Feasibility Study of Integrating Hybrid Renewable Energy Systems into a Multi-Unit Residential Building (MURB): A Case-Study in Montreal Metropolitan Area

by

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Étude de faisabilité de l'intégration de systèmes hybrides d'énergie renouvelable dans un immeuble résidentiel à logements multiples (IRLM): Une étude de cas dans la région métropolitaine de Montréal

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RÉSUMÉ

Dans un contexte d'urbanisation dense, les systèmes d'énergie renouvelable hybrides HRES pourraient constituer une alternative intéressante à la forme conventionnelle de production d'électricité et à l'amélioration du réseau correspondant. L'énergie solaire et l'énergie éolienne sont les formes les plus accessibles de ressources énergétiques ayant une capacité de complémentarité. Les systèmes d'énergie éolienne et solaire semblent être les plus appropriés parmi les sources d'énergie renouvelables pour les districts urbains. En raison de la nature stochastique des ressources éoliennes et solaires, qui réduit l'efficacité du système, un système combiné utilisant les deux technologies permettrait de combler les lacunes. Cette thèse étudie l'évaluation du rendement énergétique et la faisabilité financière de deux systèmes hybrides d'énergie solaire photovoltaïque et éolienne connectés au réseau pour un immeuble résidentiel à logements multiples (IRLM) à Montréal, Canada.

Cette recherche est menée à l'aide de l'outil d'analyse de la gestion de l'énergie RETScreen, les données climatiques externes de la NASA et de RNCan étant incorporées au logiciel pour une meilleure précision. Ces données météorologiques comprennent la vitesse et la direction du vent, la quantité d'irradiation solaire et la température de l'air à intervalles horaires. Le modèle est configuré pour une production d'énergie annuelle maximale. Deux configurations de système avec des ratios variables de capacité d'énergie solaire PV et éolienne de 90kW et 100kW ont été proposées ainsi qu'un scénario de référence. Le système énergétique est dimensionné en fonction des contraintes d'espace du bâtiment, de la demande de consommation et de considérations financières. L'éolienne et les panneaux photovoltaïques ont été sélectionnés parmi un ensemble de produits disponibles dans le commerce qui offraient la puissance de sortie la plus élevée au coût d'investissement le plus bas. Le poids et les dimensions des produits, ainsi que la logistique, ont également été étudiés. La faisabilité de la production d'énergie et les économies de coûts de la HRES sont évaluées pour toutes les provinces canadiennes et les états adjacents en ce qui concerne la production d'énergie et le prix si le système était déplacé dans ces régions.

Les économies financières ont été calculées en supposant que l'électricité produite par le système était consommée plutôt qu'achetée sur le réseau. Parmi les deux scénarios étudiés, le système ayant le coût le plus bas (0,145 $ par kWh) produit sur une durée de vie de 30 ans a été considéré comme le plus réalisable à Montréal. Les deux systèmes proposés ont couvert plus d'un tiers des besoins énergétiques du bâtiment au cours de l'année. En juillet, le système ayant la plus grande capacité éolienne a répondu à plus de 75% de la demande de la charge et a produit 3,85 % d'énergie annuelle de plus que l'autre système. Les résultats du scénario de référence éolien/PV de taille égale indiquent que l'énergie éolienne est susceptible de produire plus d'énergie que le solaire photovoltaïque dans la région de Montréal. Cependant, le système photovoltaïque semble être plus favorable pour cette étude de cas en tenant compte d'autres facteurs. La configuration du système avec plus d'énergie renouvelable hybride a produit 151 MWh d'énergie par an pour le site évalué. Au final, la suffisance des ressources en énergie éolienne et solaire est validée, mais la faisabilité d'un système hybride éolien/PV intégré au bâtiment dépend largement du coût de l'électricité dans la région.

Mots clés: énergie hybride renouvelable, l'énergie éolienne, photovoltaïque solaire, réduction des émissions

Feasibility study of integrating hybrid renewable energy systems into a multi-unit residential building (MURB): A case-study in Montreal metropolitan area

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ABSTRACT

In a context of dense urbanization, hybrid renewable energy systems HRES could be a convenient alternative to the conventional form of electricity generation and its respective grid enhancement. Solar and wind power are the most accessible form of energy resources with complementarity capability. Wind and solar energy systems seem to be the most appropriate amongst renewable energy sources for urban districts. Because of the stochastic nature of wind and solar resources which causes less efficiency of the system, a combined system employing both technologies will complement shortcomings. This Thesis investigates the energy yield assessment and financial feasibility of two proposed grid-connected hybrid solar photovoltaic and wind energy systems for a multi-unit residential building (MURB) in Montreal, Canada.

This research is conducted using RETScreen energy management analysis tool, with external climate data from NASA and NRCan being incorporated into the software for enhanced accuracy. This meteorological information includes wind speed, wind direction, amount of solar irradiance and air temperature at hourly intervals. The model is configured for maximum annual energy production. Two system configurations with varying ratios of solar PV and wind power capacity of 90kW and 100kW have been proposed as well as a reference scenario. The energy system is sized according to the space constraints of the building, consumption demand, and financial considerations. The wind turbine and photovoltaic panel units have been selected from a pool of commercially available products that offered the highest output power at the lowest investment cost. Product weight and dimensions, as well as logistics, were also studied. The feasibility of producing energy and cost savings from HRES are evaluated for all Canadian provinces and adjacent states regarding the energy output and price if the system was relocated in those regions.

The financial savings were calculated assuming the electricity generated by the system was consumed rather than purchased from the grid. Amongst two scenarios that were investigated, the system with the lowest cost ($0.145 per kWh) produced over 30-years of life span was considered to be the most feasible in Montreal. Both proposed systems covered more than a third of the building's energy needs over the course of the year. In July, the system with more wind capacity met more than 75% of the load demand and produced 3.85% more annual energy than the other system. Results from equally sized wind/PV reference scenario indicates that wind power is likely to generate more energy than solar PV in the Montreal area. However the photovoltaic system seem to be more favorable for this case-study considering other factors. The system configuration with more hybrid renewable energy produced 151 MWh of energy per year for the assessed site. In the end, the sufficiency of wind and solar power resources is validated, but the feasibility of a building-integrated wind/PV hybrid energy system is largely depends on the cost of electricity of the area.

Keywords: renewable hybrid power, wind energy, solar photovoltaic, emission reduction

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LIST OF ABBREVIATIONS AND ACRONYMS

AC	Alternating Current
AM1	Air Mass 1 Spectrum, One Atmosphere
AST	Apparent Solar Time
BAT	Battery
BESS	Battery Energy Storage System
BOS	Balance of System
CFD	Computerized Fluid Dynamic
CO2	Carbon Dioxide
Cp	Power Coefficient
CSP	Concentrated Solar Power
CUSUM	Cumulative SUM, to compare electricity production with predictions
DC	Direct Current
DNI	Direct Normal Irradiation
ECS	Energy Conversion System
ENE	East Northeast
FF	Fill Factor – Ratio between solar cell's Pmax and product Voc * Isc
GHG	Greenhouse Gases
GHI	Global Horizontal Irradiation
GIS	Geographic Information System
GWA	Global Wind Atlas
H	Radiant Power Density

HAWT	Horizontal Axis Wind Turbine
HOMER	Renewable Energy software developed by NREL
HRES	Hybrid Renewable Energy System
I_{sc}	Short Circuit Current
I-V	Current And Voltage
KW	Kilowatt
KWh	Kilowatt-Hour
M&V	Measurement and Verification
Meteo	Meteorological
MPP	Maximum Power Point
MPPT	Maximum Power Point
Mt	Million or Mega Tonnes
MT&R	Maintenance and Repair
Mtoe	Million or Mega Tonnes Of Oil Equivalent
MURB	Multi-Unit Residential Building
MWh	Megawatt-Hour
N/A	Not Applicable
NASA	The National Aeronautics And Space Administration
NE	Northeast
NNW	North Northwest
NOAA	National Oceanic and Atmospheric Administration
NOABL	Numerical Objective Analysis Boundary Layer

NRCan	National Resources of Canada
NREL	National Renewable Energy Laboratory of the U.S.
O&M	Operation and Maintenance
ODGV	Omni-Directional Guide Vane
P90	A Value that will be met or exceeded 90% of the time
Piv	Power Current-Voltage
Pmax	Nominal Maximum Power
PV	Photovoltaic Cell Technology that Converts Solar Energy in Electricity
PVOUT	Photovoltaic Power Potential
QC	Province of Quebec
QEP	Quebec Energy Policy
RE	Renewable Energy
REEEP	Renewable Energy and Energy Efficiency Partnership
REN21	Renewable Energy Policy Network for The 21st Century
RET	Renewable Energy Technologies
RETScreen	Clean Energy Management software by Natural Resources Canada
SoDAR	Sonic Detection and Ranging
SSE	South Southeast
STC	Standard Conditions, irradiance:1000 W/m2, T=25 oC, spectrum AM1.5
T	Temperature
tCO2	One Ton of Carbon Dioxide
TSG	Time Series Graph

TWh	Terawatt-Hour
VAWT	Vertical Axis Wind Turbine
V_{oc}	Open Circuit Voltage
W	Watt
WASP	Wind Atlas Analysis Program
WRF	Weather Research and Forecasting
WSW	West Southwest
WT	Wind Turbine
WTPC	Wind Turbine Power Curve

LIST OF SYMBOLS AND UNITS OF MEASUREMENT

a_P	Solar Cell Power Coefficient
A	Area
Ah	Ampere Hours
C_P	Wind Turbine Power Coefficient
DF	Dust Factor
E	Energy
H	Radiant Power Density
IR_{STC}	Standard Test Condition Solar Irradiance
KWh/yr	Kilowatt-Hour per Year
m	Meter
m^2	Squared Meter
Mtoe	Million tonnes oil equivalent: large scale unit of energy = 7.33 million barrels
MW	Mega Watt
^oC	Degrees Celsius
P	Power
PR	Performance Ratio
r	Rotor Blade Radius
TWh	Tera Watt-Hour
v	Speed of Wind
W	Watt

r	Solar Power Yield
η	Conversion Efficiency of a Solar Cell
ρ	Density of Air

INTRODUCTION

In a context of dense urbanization, hybrid renewable energy systems could be a convenient alternative to the conventional form of electricity generation and its respective grid enhancement. Universal energy resources such as solar and wind power are eco-friendly and renewable (Sumit Wagh, 2017). Solar and wind power are the most accessible form of energy resources with complementarity capability. Hence, in the absence of one source, the other source will cover the particular energy demand to some extent. Building energy consumption is responsible for 40% of global energy use; thus, reducing the proportion of conventional fuels used to power the building sector has the potential to reduce greenhouse gas emissions. The energy demand in buildings is comprised of uses such as interior space cooling and heating, hot water, and electrical loads (Lee et al, 2012). Deploying new forms of energy production, such as wind and photovoltaic, on new and existing buildings to supply demand or export electricity to the grid, is one way to reduce fossil fuel consumption and, as a result, their carbon footprint. However, the profitability of a renewable energy system appeared to be important to a building owner or investor to install a financially feasible energy system. Renewable energy project financial feasibility is determined by a number of factors such as energy resource potential, installation size, initial investment and operational expenditure (CAPEX and OPEX), electricity pricing, subsidies, and restrictions (Kelleher, 2009).

This thesis will investigate the high-level feasibility of a wind and solar photovoltaic (PV) hybrid energy system for a multi-unit residential building (MURB) in Montreal, Canada. It was intended to lower the amount of electricity purchased from the grid, with any surplus energy produced being exported back to the network. The system will then be relocated to all Canadian provinces and U.S. states of Vermont, New Hampshire and New York to investigate the effect of location in energy production and financial feasibility. In Southeastern Canada, however, wind resources have historically exceeded solar resources. The amount of power generated by photovoltaic panels and wind turbines corresponds to resource trends, with wind turbines producing more in the winter months and solar panels producing more in the summer.

Because of changes in climate, single sources of energy like photovoltaic and wind are not quite dependable and may affect by wind speed variation, sunshine hours or seasonal change in weather (Sinha, 2015), as a result, a hybrid system has the potential to deliver electricity for a building year-round while lowering electricity draw from the grid, dependent on the system's capacity and ambient resources.

In addition, operating a hybrid system will reduce the installation costs to few extent compare to a single system (Ashley Thornton, 2018)

Solar PV and wind power are two of the most promising renewable energy sources, accounting for 8.7% of global electricity energy in 2019. (REN21, 2020). Aside from the potential financial advantages of building-integrated renewable energy systems to minimize reliance on power grids or to sell excess electricity to the grid, there are numerous government incentives in Canada for implementing renewable energy equipment to increase the financial return of the projects. Figure 0.1 indicates a block diagram of hybrid renewable energy system

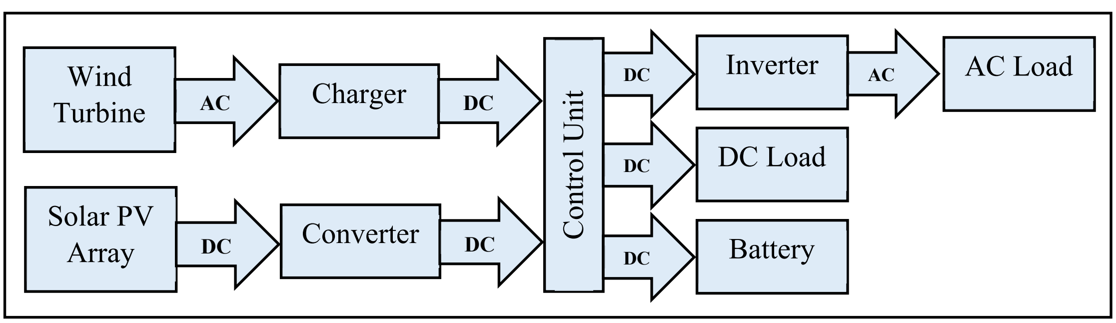


Figure 0.1 Hybrid renewable energy system supplied by solar and wind energy resources

0.1 Research motivation

The aim of this Thesis is to look at the energy production outcome and financial feasibility of the proposed scenarios for a multi-unit residential building in Montreal, Canada. The configurations will consist of varying ratio between the wind turbines and PV modules, which will then be moved to different locations to investigate the energy generation and cost. All of these with the intention to satisfy a portion of the invoiced energy consumption. The study is focused on determining to what extent a hybrid renewable energy system can meet the energy demand of a multi-unit residential building (MURB). The decision on which system is the most financially feasible will be made based only on return on investment. Given to space constraints, load demand, and capital investment considerations, system sizing will be taken into account.

The academically respected energy management analysis tool RETScreen, developed by Natural Resources Canada (NRCan) will be used to calculate the estimated electricity generation. Furthermore, a separate set of climate data from NASA and NRCan of the building's location will be introduced as an external database into the software to improve accuracy. The financial results are then compared to the cost of electricity in other Canadian provinces and bordering states considering their location specific climate data.

0.2 Research question

The aim of this thesis is to extract and analyze data to explore the advantages and disadvantages of harnessing energy from combined sustainable sources in residential buildings. Specifically, to what extent are photovoltaic and wind power resources available for a feasible renewable energy system in the Montreal urban area, as well as other mentioned locations.

0.3 Thesis outline

This thesis is organized into 6 chapters.

Chapter 1 aims to review the state of the art literature around the subject of this thesis and the respective methodologies implemented by other authors in the field of single and hybrid utilization of photovoltaic and wind power energy, as well as renewable energy resources availability analysis and management.

Chapter 2 gives theoretical content on the fundamental principles of solar and wind energy systems, covering types and configurations of renewable energy technologies, measurement techniques, and characteristics of both sustainable power sources.

Chapter 3 discusses the major factors to consider when sizing and selecting HRES components for a hybrid renewable energy system. Information regarding the acquisition of project's base load and meteorological data. Methodology for the analysis and software capabilities.

Chapter 4 describes the case study's concerns. These topics include the building's geographic location and physical measurements, electricity consumption and load profile, and environmental data. This chapter also discusses selecting the correct wind turbine and solar panel, as well as their configuration.

Chapter 5 explains the research findings. These include the amount of energy produced by each system, the renewable energy potential, the technical specifications of the system components, and the savings from energy production. This chapter also compares the production and income of the system if relocated in another region, as well as corresponding financial aspects.

Chapter 6 outlines the results discussion and highlights the energy and financial outcomes within the constraints of the research.

CHAPTER 1
BACKGROUND AND LITERATURE REVIEW

1.1 Quebec Electricity Generation and Energy State

Quebec has set a goal to increase the use of renewable resources by 60.9% in its energy system to meet the 2030 energy policy (Quebec energy, 2016). The clean power transition vision, in fact making progress in transitioning towards a low carbon future by improving non-emitting electricity generation and implementing energy efficiency techniques often known as the least expensive optimization (Canada energy regulator, 2019). Local renewable resources are responsible for a high proportion of energy production in Quebec energy system (49%). main primary energy sources that have contribution in power supply are hydraulic force, wind power and biomass (Statistics Canada, 2019. Electricity is the dominant source of primary energy for residential heating purposes in Quebec.

In 2019, Quebec produced 214 TWh of electricity, 95% from hydropower, 4.7% from wind power, and 1% from biomass, solar power and petroleum resources as stated by share in Figure 1-1A. In 2017, 54% of the energy travelling through the Quebec's energy distribution system was lost and added no value to the province's economy. Where the importance of energy efficiency come into account to be improved in both transmission and consumption sectors. At the same time 27% of energy losses in the system linked to the electrical systems and generation.

Figure 1-1B stated that in 2017, 44% of total consumed energy in Quebec was from renewable sources, including 36% in electricity form (Hydro-Québec, 2018). Due to the 2030 energy policy (QEP), Quebec province has started a rapid transition into activities with fewer greenhouse gases emissions (GHG). The need of employment new source of energy and advancing energy efficiency targets must consider to achieve this aim.

That part of electricity sector of Quebec which relies on renewable energy sources does not produces emissions. According to environment and climate change Canada, Quebec's total GHG emissions was 78 Mt CO_2 eq for 2017 while the 2030 target is 54 Mt (Statistics Canada, 2019).

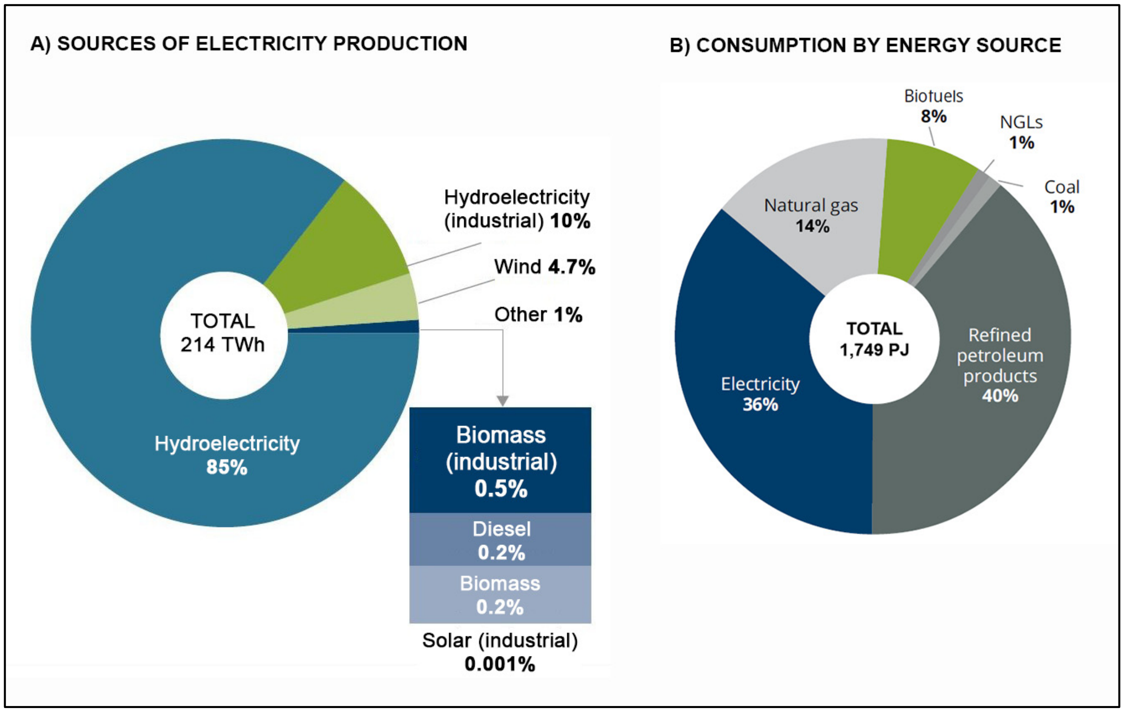


Figure 1-1 (a) Electricity production sources in Quebec (b) Total consumption
Taken from Statistics Canada (2019, Table 25-10-0015-0)

1.2 Wind-Solar Hybrid Renewable Energy Systems HRES

Utilization of renewable energy sources is a key factor in securing sustainable development with lower emissions. Numerous researches on resources analysis and development of the wind and solar hybrid system has been done thus far.

To increase the usefulness of hybrid solar-wind system many researchers have taken advantage of various combinations to gain more reliability of a system. They employed wind-solar power with other sources like wind/diesel, PV/diesel, and wind/PV/diesel (Yonghong

Kuang et.al, 2016). It is a tough mission for researchers to maximize the generated electricity output of a system with more reliability and low cost (Sunanda Sinha, 2015).

(Sumit Wagh and P.V.Walke, 2017) reviewed various aspects of hybrid solar and wind system. They discussed different theories and application associated with the development of hybrid solar and wind system and pointed out different techniques about HRES energy utilization. Thus, (Yian Tripanagnostopoulos, 2010) presented a new concept of hybrid solar and wind energy system for building application. Small wind turbines (WT) and photovoltaic panels (PV) can be mount on buildings in case of sufficient wind and solar potential, providing electricity to the building. Both PV and WT subsystems can supplement each other to cover a great part of building energy load, helping to conventional energy saving and protecting the environment. Accordingly, (Binayak Bhandari et.al, 2015) distinguishes generated power from both wind turbine and the photovoltaic regarding the condition of the weather. They noticed that it is possible to improve the system by adding storage system and to apply several optimization techniques for HRES concerning environmental crises.

In another paper author focus is on developing rural areas by using stand-alone hybrid energy system. They scrutinize electricity generation with different hybrid system combinations and considering load demand for villages (Renu Sharma et.al, 2015). In order to electrify remote areas for primary needs, design of the hybrid photovoltaic and wind system considered and the data for this research gathered from Ethiopian national agency. They concluded the study with convincing electricity coverage up to 20% using the HOMER (Hybrid Optimization Model for Electric Renewables) software to analyze the hybrid system simulation (Getachew Bekele, 2012). Consequently, in another research a vertical axis wind turbine with omni-directional guide vanes (ODGV) is combined with PV module to generate power using wind-solar system principle. To capture maximum usable of wind energy author designed the ODGV on venturi effect basis. By implementing the combined energy system they achieved an improved output power used for urban lighting (Mohammed Gwani et.al, 2014). Different from urban utilization, (Sunanda Sinha et.al, 2014) highlighted the outlook for Western Himalayas region with small scale wind turbine and PV hybrid system installation. Climate modeling of this study conducted using Artificial Neural Network (ANN) method and NASA weather database.

With attention to HRES (Luis Ramirez Camargo et.al, 2019 and 2016) conducted a study about renewable micro-generation power systems. Photovoltaic based systems with battery storage that produce more annual energy than the required demand for house owners in central Europe. These systems designed for optimized economic performance. Hybrid renewable energy systems consist of PV, wind turbine and batteries are capable to supply electricity for residential self-sufficient single family buildings (ESSSFHs) and the produced energy is highly depended on technical requirements and local weather conditions. Under off-grid circumstances, (Adel Merabet et.al, 2017) reported several advantages of the stand-alone power system in their studies for different energy applications. It can be operated independently from the network; power transmission lines loss reduction and safe operation and secure energy production during environmental hazards and storms. In like manner, (Chaouki Ghenai, 2019) investigated a HRES design for the university building in Sharjah UAE implementing integrated modeling and optimization techniques to test the performance of the system and cost. The system results prove that the stand-alone solar PV, diesel generator set and hydrogen fuel cell, meets the daily and annual AC load of the building and the proposed hybrid system is the best power system architecture to cover electrical loads. The stand-alone hybrid power system is the most suitable approach with 66.1% of renewable resource fraction. To electrify consumers with no access to the power grid (Guchhayat, 2016) addressed the optimal scheme of using off-grid hybrid wind and solar electricity system. Also, considered it as an effective solution to supply far distance consumers with continual power and reducing cost is possible by increasing the size of the energy production unit.

With the intention of combining two sustainable energy sources and their respective behavior in the system, (Sunanda Sinha, 2013) presents hybrid solar and wind systems pre-feasibility analysis for hilly terrain in northern parts of India. The study points out a meaningful potential for utilizing solar and micro wind turbines in hilly regions, While (M.A. Elhadidy and S. Shaahid, 2000) studied the effect of wind turbine generator numbers, photovoltaic array surface area and the capacity of the storage batteries on a hybrid sustainable energy system. Where the wind, PV and diesel generator were the main components.

(Shaopeng Guo et.al, 2018) provided a detailed discussion by reviewing the use of hybrid renewable energy systems for various applications. Thus they stated regional distribution, wind and solar resources periodicity, the need for proper optimization and operation strategy and inadequate support policy as future challenges for HRES. In a larger scale (Reichling and Kulacki, 2008) Analyzed the performance of a hybrid photovoltaic and wind power plant in Minnesota. They used hourly wind and solar insolation data and proved that regional solar resources has influence on financially practical aspect of the hybrid plant. The analysis show that a hybrid multi-renewable energy plant is evidently more reliable and cost effective in term of retail value of the produced energy.

For the most recent sizing methodologies (Jijian Lian et.al, 2019) provides a review respecting HRES sizing method development and classify hybrid renewable energy systems based on various energy resources type. On the same topic they mentioned a gradual replacement of conventional methods by AI and hybrid methods containing increased problem complexity. Also, for the environmental perspective part (Katsaprakakis DA et.al, 2009) scrutinized solar and wind hybrid energy system with a diesel generator as the backup of the system. The RE system overcame the power demand by 94%.

To put it differently, (Dominik Heide et.al, 2010) checked the counterbalance of both wind and solar energy for seasonal optimal mix use in the European regions to gain 100% renewable power supply scenario. The outcome of the study is a seasonal mix share of 55% wind and 45% for solar power harvesting.

(Zeyu Ding et.al, 2019) analyzed the performance of a hybrid wind-concentrated solar power (CSP) generation plant equipped with thermal storage (TSWCS) in Zhangbei China using particle swarm algorithm. A coupled wind turbine with solar thermal system investigated in this study which resulted an effective reduction of the wind curtailment and improvement in stability of the system by adding electric heater. Furthermore, an annual carbon reduction of 15,470 tons achieved.

The use of wind and solar resources to provide electricity is growing in Canada. Accordingly 49% of the primary energy in Quebec is derived from renewable energy (NRCan, 2017). A hybrid configuration of vertical horizontal axis wind turbine with variable speed generator and high efficiency photovoltaic array may be integrated to provide continuous power (P. Nema et al, 2009), many algorithms are being developed regarding the optimal energy management of such hybrid system.

1.3 Resources for Hybrid Renewable Energy Systems

Indeed understanding resources to power renewable energy production systems in various configurations is vital, henceforth (Nima Izadyar et.al, 2016) performed a major assessment on renewable energy resource availability to be used in remote areas. They summed up previously researched factors in the context of resource potential for RES. Various methodologies implemented in this comprehensive overview on solar, wind and hydropower resources ending up with emphasizing on technical, theoretical, geographical, and environmental aspects in terms of energy resources evaluation and the importance of geographic information system GIS tool that extensively used in previous studies. Comparatively, (Dong Jun et.al, 2014) performed a case study on new energy resources evaluation for seven distinct locations aimed for the micro-site selection of wind/PV hybrid power station. They used ELECTRE-II in the research to analyze the findings that concluded an improved correctness and effectiveness of the method.

Additionally, (Alessandro Bianchini et.al, 2015) presents their study on meteorological data such as wind distribution and solar irradiance for hybrid renewable energy systems to merge the produced power from the PV panel, horizontal axis wind turbine and a diesel generator. Ultimately store the energy in a battery bank with specific storage capacity. Again (Ye Ren et.al, 2015) discussed different paradigms and review both wind and solar irradiance resources forecasting and the derived output power in a state of the art approach. They conduct comparisons between two ensemble methods; the competitive forecasting which showed better performance for long-term predictions and for the shorter time scale horizon anticipation the cooperative ensemble method perform a better functionality.

Despite that, it is complicated to estimate and assess the wind power resource in built up areas. (Sara Louise Walker, 2011) reviewed multiple methods to estimate the wind resource in urban areas to install building mounted wind turbines. In this regard, (S C Pryor et.al, 2020) present a robust simulation on an assessment potential project for evaluating wind resources located in east side of the United States. This manuscript concludes that expected wind turbine gross annual power generation is modest in extreme wind speeds at spatiotemporal variability operating conditions using a model by Weather Research and Forecasting (WRF).

(Yonghong Kuang et.al, 2016) reviewed in brief the potential of alternative energy resources for islands. Furthermore, the share of electricity supply have achieved by 100% of renewable energy like wind and solar power in some islands. The study mentioned variability and randomness as major obstacles and enumerated the utilization of advanced technologies for the sector to increase the penetration level in sustainable energy for islands. It must be remembered that climatology of the area plays an important part of the resource potential analysis, thereupon (Koray Ulgen and Arif Hepbasli, 2010) performed an evaluation on the availability of combined alternative power generation in Bornova, province of Izmir, Turkey. They conducted the study on solar and wind power resources by investigating in hourly and monthly meteorological data recorded for a period of 5 years. This study states that hybrid system utilization for various application is efficient and capable to fulfill the load demand.

(M Anvari et.al, 2016) have presented a study on solar irradiance and wind power resources fluctuating behavior relying on new statistical and dynamic details. Their finding shows that by implementing a proper characterizing method on the intermittent nature of renewable energies, this trait is no longer a big problem for designing power grids with a significant electricity generation share from renewable resources. In the light of the variety forms of renewables, (Akhtar Hussain et al, 2017) analyzed the potential of in practice mainstream sustainable energy sources and harvesting methods such as wind power, concentrated solar power and marine energy as well as the under development emerging renewable energy technologies that still not widely demonstrated. Also, they presented the market share of each technology with the combined contribution of 22% for all renewable energy sources in 2014.

(Sarkar and Ajjarapu, 2011) explored the benefits of the megawatt resource assessment model (MWRAM) for the combined utilization of wind-solar renewable energy conversion system (ECS). They believe this method is appropriate for hybrid ECS performance assessment. Notwithstanding the foregoing method, (Amirsaman Arabali, 2014) studied an ideal assess on the performance of hybrid electricity generating system powered by renewable sources in a stochastic framework due to photovoltaic and wind power uncertainties. They modeled the system using autoregressive moving average simulation (ARMA) and the output enables efficiently utilization of both wind and PV generation for higher reliability in hybrid power system. To put it differently when it comes to climate change crisis, (Duy Nong et al, 2020) reviewed renewable power resources in Vietnam and challenges to tackle to be compatible with climate change policies. The author does give stress on the use of natural clean power sources toward a conventional fuel independent economy of the country.

1.4 Photovoltaic (PV) based Systems

The increasing energy demand and widely availability of photovoltaic resources prompted many researchers to conduct studies around performance improvement and developing methods to absorb more solar energy. To enumerate, (Edison Banguero et.al, 2019) performed a performance and affordability analysis on a micro grid single source solar PV renewable energy system in Chaco, Columbia for two consecutive years.

The study conducted using RETScreen tool and resulted the amount of 22.9 tCO_2 in emissions reduction. Also, the performance efficiencies related to photovoltaic panels has been recorded as 10.3% for the first year and 11.09% for the second year of the study. Another key point, is to increase the current PV system efficiency via a variety of techniques that are fast and affordable solution to provide end users with more power. To be sure (Ali Mohammadnia et.al, 2020) investigated the respond of a novel hybrid energy harvester to maximize the power production from the receiving solar irradiation.

They considered solar irradiation and concentrator separation based on the Stirling engine and solar thermoelectric generator (STEGs), the analytical results revealed a total conversion efficiency of 21.8% and indicated the enormous potential of hybrid energy harvesting systems. It can be concluded that combining another form of energy recovery and generation with an already installed photovoltaic system results in higher efficiency of the system in total.

1.5 Wind Energy based Systems

Different from solar PV, wind energy is independent from night run limitation and technically produces more power during night and wintry weather, however wind energy has suffering from its alternating nature like other forms of sustainable energies. Despite varying from daylight; it is highly rely on scholastic occurrence of air movement phenomenal to form the wind resources. With this intention, (Bhat Karthikeya et.al, 2016) examined the wind resources using on site measurements and local databases for Singapore. They also studied wind flow patterns and characteristics in built-up areas and found southern shore of Singapore is ideal for wind power harvesting. At the same time (Palash Jain, 2016) discussed on the prediction of the performance and VAWT basics for blade pitching within variable amplitude situation. They studied various design difficulties and they reached out to this conclusion that due to wide range of wind speed and tip speed ratio (TSR) the maximum wind turbine performance occurs and amplitude of blade pitching is a function of both wind speed and TSR. Thus, (Asis Sarkar, 2012) performed a practical research on wind turbine output power and efficiency at multiple tip speed ratios (TSR). The experiment showed that environmental factors such as wind direction, water vapor intrusion, climate change and corrosion are involved for the turbine performance and the amount of electricity produced. In a particular paper, author present a methodology on battery sizing of wind based power generation for isolated applications. They proposed the utilization of super capacitor or flywheel battery bank due to slow response of renewable resources output, to serve as the storage device and meet the diverse load requirements (Anindita Roy et.al, 2010).

Wind turbines are diverse in term of blade shapes and the location of the generator in accordance with the application. Point often overlooked which any of them is distinct in the way they capture wind energy, so that (Sandra Eriksson et.al, 2008) distinguished the difference between major wind turbine concepts based on the mounting axis. This comparative study went throughout a variety of aspects from the mechanical, aerodynamic characteristics to power generation and environmental impact of the designs. They concluded that the vertical axis wind turbine (VAWT) works significantly better in severe winds than the horizontal axis wind turbine (HAWT) and it is more effective. It is equally important to always consider new concepts to mature renewable energy technologies since the renewables are still standing on entry level in energy market.

Accordingly, (Kyung Chun Kim et.al, 2014) introduced a new type of HAWT for urban use and completed a study about its aerodynamics characteristics using computational fluid dynamics (CFD) so that a power coefficient (Cp) of 0.25 recorded which is high when compared with other wind turbines in the class. Based on PIV measurements and simulations the most wind energy can be captured by the design. This model is derived from the spiral blade turbine developed by Archimedes and was a proper horizontal axis for urban size wind turbine. For the accuracy of wind energy estimation of potential yield, (A Al-Quraan, 2016) did an extensive comparison between wind tunnel and onsite measurements to differentiate both types of measurements for urban wind energy calculations which resulted in a 5 to 20 percent of error in estimations.

To conclude, fluctuations in wind speed and direction highly effects the wind energy system production and a comprehensive study regarding the installation location is important. Wind energy systems perform best when included in hybrid energy systems to overcome their limitations. Vertical axis wind turbines are more suited for urban application when available, due to improved efficiency by design.

1.6 HRES Management and Efficiency

The importance of deploying various methodologies and optimization approaches has undeniable impact on the renewable energy resource management to maximize the output power. Up to the present time many researchers investigated the matter, a comprehensive review of several methodologies and optimization criteria on hybrid renewable energy system has been performed (Binayak Bhandari et.al, 2014). Authors conducted their investigation on tri-hybrid system consist of PV, wind and hydro intended to generate power for off-grid users. They also revealed which HRES is fairly cost-effective for areas that are not tied to power grid. Alongside, (Vikas Khare et.al, 2016) considered various aspects of HRES such as optimization, sizing, pre-feasibility and reliability issues. They ended up listing difficulties associated with implementing hybrid systems and emphasized required development techniques.

Among countless energy management techniques, all of them can be categorize in three main category based on the system connectivity to the network; grid-connected, off-grid and a compound utilization of both. In that case, (Torreglosa et.al, 2016) presented a comprehensive strategy in energy management for an off-grid hybrid renewable energy system feed by sustainable sources with battery and hydrogen storage systems. For the economic analysis they considered system components operating hours instead of fix lifetime values. As reported by the authors, a reliable electricity support demonstrated in the simulations. Similarly, for an off-grid system, (Anurag Chauhan et.al, 2014) reviewed number of critical issues such as, sizing methodologies, system configurations, control strategies and storage selections, all associated with stand-alone hybrid renewable systems (wind, photovoltaic etc). Their paper highlighted controlling types of flow of energy management: centralized, distributed and hybrid. Then again, (Akbar Maleki et.al, 2015) paid attention to optimal sizing and economy aspect of an off-grid hybrid system located in Iran. A combined system consist of photovoltaic, wind turbine and another sustainable power source. They optimized the proposed system regarding hourly load, solar irradiance, and wind speed. The study revealed a cost effective system size for a typical household of 3.84kW for the PV and 3kW of wind power. To emphasize the way to manage the productivity of HRES, (Lanre Olatomiwa et.al, 2016) reviewed a variety of approaches used by other authors for both grid-connected and off-grid hybrid renewable systems in the purpose of electricity generation only. Address widely used energy management techniques and features of the systems. They concluded the following by implementing management strategy: cost reduction of the generated energy, better operational efficiency, improved longevity and increase reliability of the system.

To implementing new technologic ways to assist the HRE unit with more efficient output, (Faizan A. Khan et.al, 2018) gives stress on optimization strategies for wind and photovoltaic based hybrid energy system using new techniques like artificial intelligence, graphic construction scheme, and probabilistic approach and multi objective design in their review study. They also did analysis the cost of installation and operation of renewable energy resources for ideal sizing of the system.

Besides, they find out that hybridization of multiple algorithms is recommended by many authors for RETs (Renewable Energy Technologies). Another key point to consider is the stochastic nature of renewable energies that make it necessary to analysis the energy resource availability background throughout the climatology data of the area. Therefore, (Angeliki Loukatou et.al, 2018) developed an analytically traceable model and its representative management on stochastic variations in wind speed and the associated wind power output. The proposed simulated model in this study revealed 40% of capacity factor for evening hours operation, also has potential for different scenarios where wind speed or its power density are stochastic inputs.

Finally, hybrid renewable energy system management and optimization has direct impact on production output and cost-effectively of a system. Compound utilization of both network-connected and stand-alone energy management techniques has more economic sense.

1.7 Software for Analysis

There are multiple renewable energy featured computer software that are widely in use and known for system performance analysis, feasibility study and other related aspects of new energy projects. HOMER and RETScreen are viable tools across scientific community developed by the energy sector authorities of governments of the United States of America and Canada. In other words, most research within the combined sustainable power system has used the hybrid optimization model for electric renewables (HOMER), a computer software developed by national renewable energy laboratory (NREL, 2020) in use to optimize ongoing studies about hybrid systems. (Shubhashish Bhakta et.al, 2015) used the mentioned feasibility software to perform an economic analysis, sizing and optimization of their suggested PV/wind combined energy system serving northern remote areas of India. The HOMER results revealed that the system is feasible. Another similar software being used worldwide for renewable energy, energy efficiency, performance analysis and project feasibility is RETScreen Expert developed by Natural resources Canada CANMETEnergy diversification research laboratory (NRCan, 2020).

(Kyaw Soe Lwin, 2018) analyzed a stand-alone wind turbine with 1kW of power generation capacity by deploying RETScreen software to acquire the maximum output power. The author targeted spotlight on the use of RETScreen software to make an accurate decision for real life RE systems.

1.8 Present Work

The sustainable energy resources are recognized as a new and viable source to supply the power grid using renewables. The literature review reveals that a lot has been done in terms of merging two or more of these fluctuating sources of energies into one system and implementing various utilization techniques to achieve higher energy yield. Similarly, aligning consumption patterns with energy efficiency and optimization approaches.

At the present thesis, a case-study addressing the use of renewable energy in a multi-unit residential building (MURB) has been done. The objective is to establish to what extent a HRES can satisfy the energy demand of the building that is located in Montreal metropolitan area. The size of the proposed hybrid system will be determined by the energy consumption data, space constraints and financial considerations. A selection of commercially available devices will be compared before the system's components are chosen. Therefore each considered scenario is introduced to RETScreen software to model the energy production from climatology data of the region. To perform an analysis, the selected MURB will then be relocated in all Canadian provinces and U.S. states of Vermont, New Hampshire and New York to investigate the effect of location in energy production and financial income of the system. The mentioned States has been selected due to similarities in climatic conditions to where the study is centered.

In the end, the sufficiency of wind and solar power resources, amount of energy produced and the financial feasibility of a building-integrated wind/PV hybrid energy system will be discussed.

CHAPTER 2
THEORY OF SOLAR AND WIND ENERGY

2.1 Preface

The widely called hybrid solar and wind power system HRES is a combination of solar energy and wind energy adjusted to harvest clean energy in electricity form. Hybrid systems have obvious advantages over a conventional system that is entirely dependent on one specific source of energy. In general, various parts of a hybrid wind-solar system limits to wind turbines, photovoltaic array, and controller unit and battery storage. Photovoltaic arrays consist of solar panels connected in parallel or series that convert photon particles energy into electricity through semiconductor principles. This DC form of energy needs to be stored in battery and the power inverter is in charge to supply electricity for AC or DC loads. A wind turbine acts as a transformer of wind energy into mechanical energy and into electric energy afterward. Due to variable speed of speed, generated electricity from wind turbine is inconstant and alternating. So, a set of controlling and inverter units are used for its uninterrupted storage within battery. The described system possesses high amount of daily electricity generation capacity; it requires less maintenance and low manufacturing cost (Binayak Bhandari et.al, 2014).

2.2 Solar Energy

The sun is the ultimate source of many renewable energy forms, sunlight energy can get transformed into electrical energy in a direct way using photovoltaic panels. A part of solar radiation is electromagnetic wave and PV cells inside the PV panel obtain energy from incident of these waves to its surface. This effect is called photovoltaic and lets the electric current flow and produces electricity.

2.2.1 Photovoltaic system

A photovoltaic system consists of solar panels with other complementary components such as an inverter, battery and more elements based on the configuration. The PV system can operate alone as off-grid systems or integrated with power network as grid-tied PV systems. Solar power systems can vary in size from small-scale to utility-scale production plants.

2.2.2 Types of PV Systems

A photovoltaic system generates power during daylight to supply connected loads. The system may have another form of power generation as backup. There are three types of configurations: Stand-alone, grid-connected and hybrid. The basic components and principles are the same in all configurations. PV systems are modular to increase capacity by adding more PV modules in case of change in demand.

2.2.3 Stand-Alone System

Stand-alone systems can consist of PV modules and the load, or they may have batteries included in the circuit for energy storage. The batteries' capacity must be compatible with the system's nominal power to store the energy produced during the day so that it can be used at night or in poor weather conditions. When having batteries in the circuit, the charge regulators are also included that are responsible to switch off the PV modules off the load when batteries are charged. They can cut off the load to prevent batteries from being discharged to increase the battery lifespan and system reliability. Figure 2-1 shows schematic example of a stand-alone system with DC and AC load, supported with energy storage part.

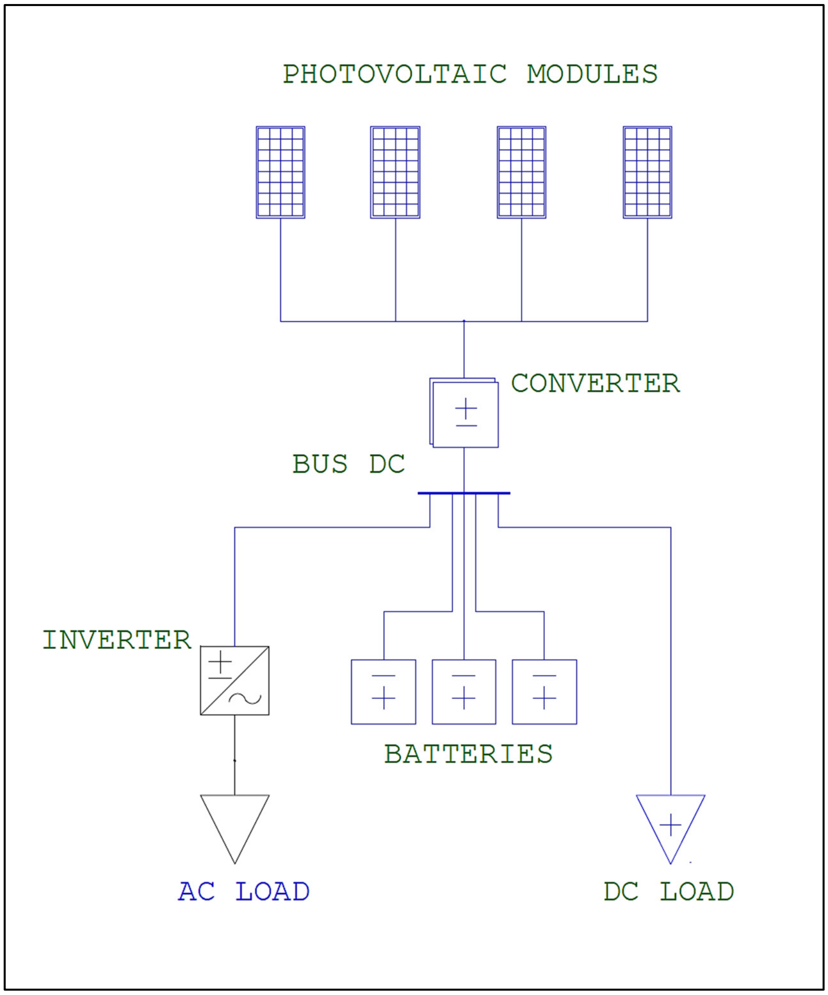


Figure 2-1 Stand-alone solar system schematic with battery and load

2.2.4 Grid-Connected System

As illustrated in Fig. 2-2, a grid-connected PV system has a link to the power network via inverter and distribution panel to export PV-generated energy to the grid or to supply the AC load when needed. These systems are popular for building integrated applications and they do not require batteries due to connectivity to the electricity grid. In the time of insufficient PV power production, the grid also supplies the AC load. This configuration can transport the energy directly into the grid which makes it suitable for large PV fields.

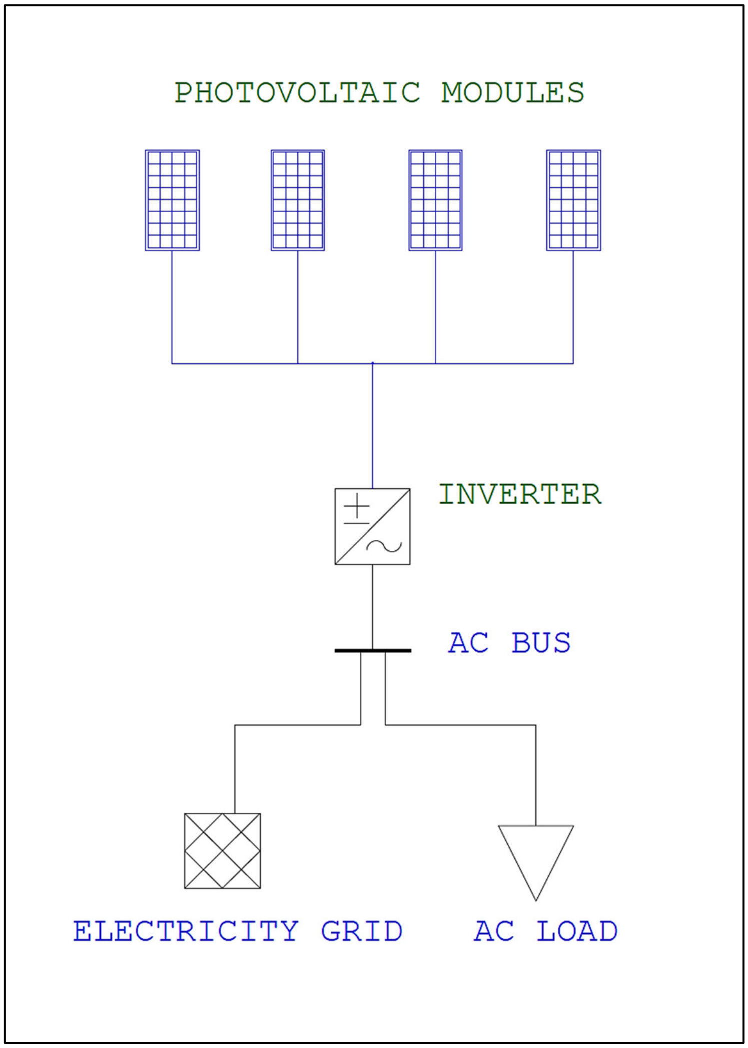


Figure 2-2 Grid-connected (on-grid) photovoltaic energy system without batteries

2.2.5 Hybrid System

A photovoltaic energy system combined with a complementary method of power generation such as wind energy shown in Fig. 2-3. The purpose of this combination of PV modules and wind turbine is to optimize the electricity production method. Hybrid renewable energy systems (HRES) typically involve more sophisticated controllers compared to other types of

PV systems. Since producing energy from both renewable resources is stochastic, a diesel generator or any other sort of energy generator can be used to recharge the batteries as a back-up system.

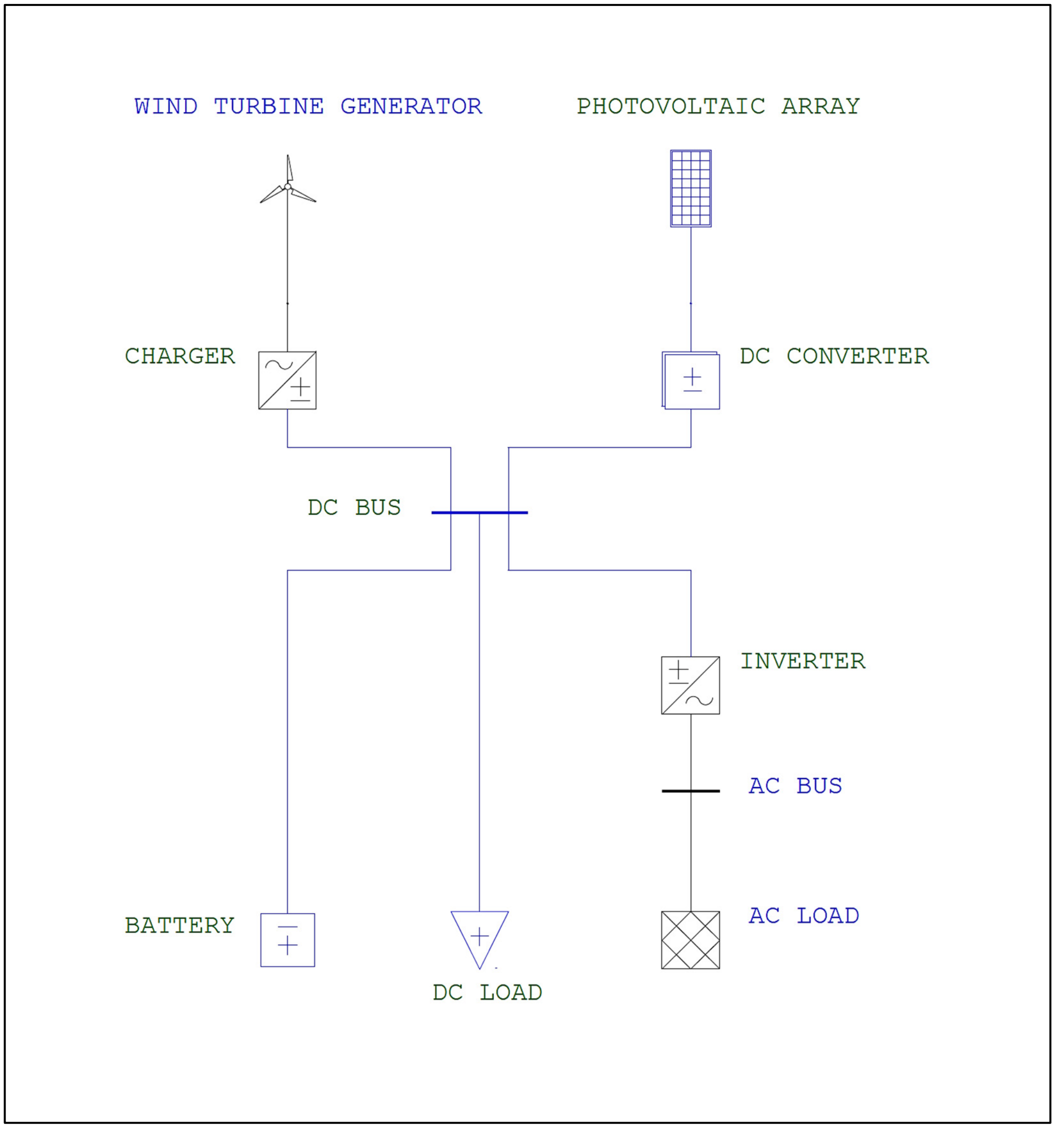


Figure 2-3 Hybrid renewable energy system consists of PV and wind turbine generator with energy storage, supplying DC and AC loads

2.2.6 Components of a PV System

Because of the size limitation of a solar cell, it only delivers a limited amount of power under fixed current-voltage conditions that are not suitable for many applications to operate with it. To use the energy contained in solar radiation into electrical power, solar cells must be connected to form a panel that generates enough current-voltage to drive applications operational. Although PV panels are the core of a solar power system, a variety of different components are required to bring the system into working and to feed the grid. Together, these elements are called balance of system (BOS). Their use and number depend on whether the system is on-grid or off-grid. The main components of the mentioned BOS are:
The structure to mount and fix the PV modules and aim them toward the sunlight. An energy storage system which is vital to off-grid configurations because it assures that the system will get electricity during the absence of solar irradiance. Converters (DC-DC) task is to convert module output, due to its variable voltage occurring at different light intensities. Inverters (DC-AC) are used in systems with power grid connectivity to convert DC power from PV into AC electricity to feed the network. Transmission cables connect the whole electrical system to each other and the load. The cables are responsible for a part of system losses due to their inner resistance.

2.2.7 Photovoltaic Effect

To produce electric power in a photovoltaic cell, both voltage and current need to be generated. The process is known as the photovoltaic effect. The energy from photon absorption excites electrons to a higher level of energy in a semiconductor. The collection of light generates charge carriers because of photon absorption in the material and forming a junction that causes electrons to move. In this movement, electrons travel to the n-type side and holes to the p-type side of the junction throughout the so-called depletion region. Then photo-generated charge carriers start to separate in the junction that creates an electric field. Next, photo-generated charge carriers appear to accumulate at the terminals of the junction. There is no charge build up when terminals are connected in short circuit condition as current can flow in the circuit. In open circuit circumstance there is no cell current.

2.3 Photovoltaic Module Placement and Orientation

The solar panel will harvest most energy when solar irradiance hits its surface perpendicularly. To ensure maximum power generation it is important to ensure the photovoltaic module faces the correct direction and the appropriate tilt angle as well as to be exposed to the high intensity sunlight for the greatest period. The use of solar tracking systems increases the energy production by the PV module significantly compared to the fixed or non-tracking configuration. For PV applications in the northern hemisphere, solar panels should face true south. By the same reasoning, in southern hemisphere, the panel should instead face in the direction of true north. By this method solar panels receive direct sunlight during the day. It is vital to consider the angle or tilt of the PV module, this parameter is determined by geographical latitude of the installation location. The solar panel facing angle toward the sun can also influence the output power of the system in many ways. Figure 2-4 pictures the orientation of a PV module toward the sun. The celestial sphere shows the motion of the sun which is arbitrary radius and concentric to the earth. The azimuth is the angle between the line of sight projected on the horizontal plane and due north.

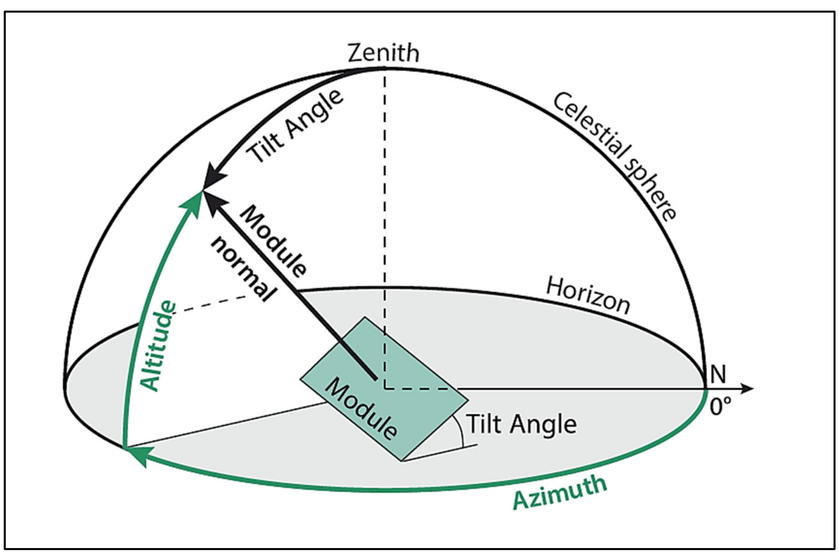


Figure 2-4 PV Orientation, arrows indicates the position of the sun.
Taken from Klaus Jäger et al. (2014, p. 226)

2.4 Measuring Solar Radiation

The solar radiation on a plane surface like photovoltaic modules is measured using a pyranometer device. Different methods are available to measure this amount: instantaneous or integrated over a period; over horizontal or tilted surfaces; beam, diffuse, or global. Most recorded quantities for these data are in global radiation form measured at a horizontal surface. Information about this data is provided by Environment Canada. Also, when light passes through the atmosphere, it becomes slightly scattered and causes the direct beam light to attenuate. So, it is important to evaluate the strength of both direct and diffuse components of the light beam, for PV application because the scattered light also reaches on earth surface and collisions the panels.

2.5 Location of the Study

There are few issues related to the installation location of the photovoltaic system which are the position of the sun, the sun path at various locations, the equation of time, irradiance intensity level on PV module, direct and diffuse irradiance, and shadowing. The sun position is relative to an observer on horizontal plane that defines with three main factors, zenith angle, azimuth angle and altitude (Fig. 2-4). The sun path diagram is a sun-movement base visual aid that has been designed to determine the solar position and solar time easily for any day year-round (A.S. Roy, 1979). In solar resource assessment there are multiple factors involved, such as meteorological data collection including solar irradiance. The solar irradiance is the amount of sunlight received on a horizontal plane. The two types of solar irradiance are direct and diffuse radiation. Diffuse radiation refers the scattered sunlight in the atmosphere and direct radiation is photons traveling straightly toward the earth surface. Fig. 2-5 shows the solar path, the position of the sun and solar time throughout the year at the location of study. Note that times are given in apparent solar time (AST). It is crucial that the PV modules are exposed to sunlight without shadowing at least from 9 a.m. to 3 p.m. (Soteris A. Kalogirou, 2014).

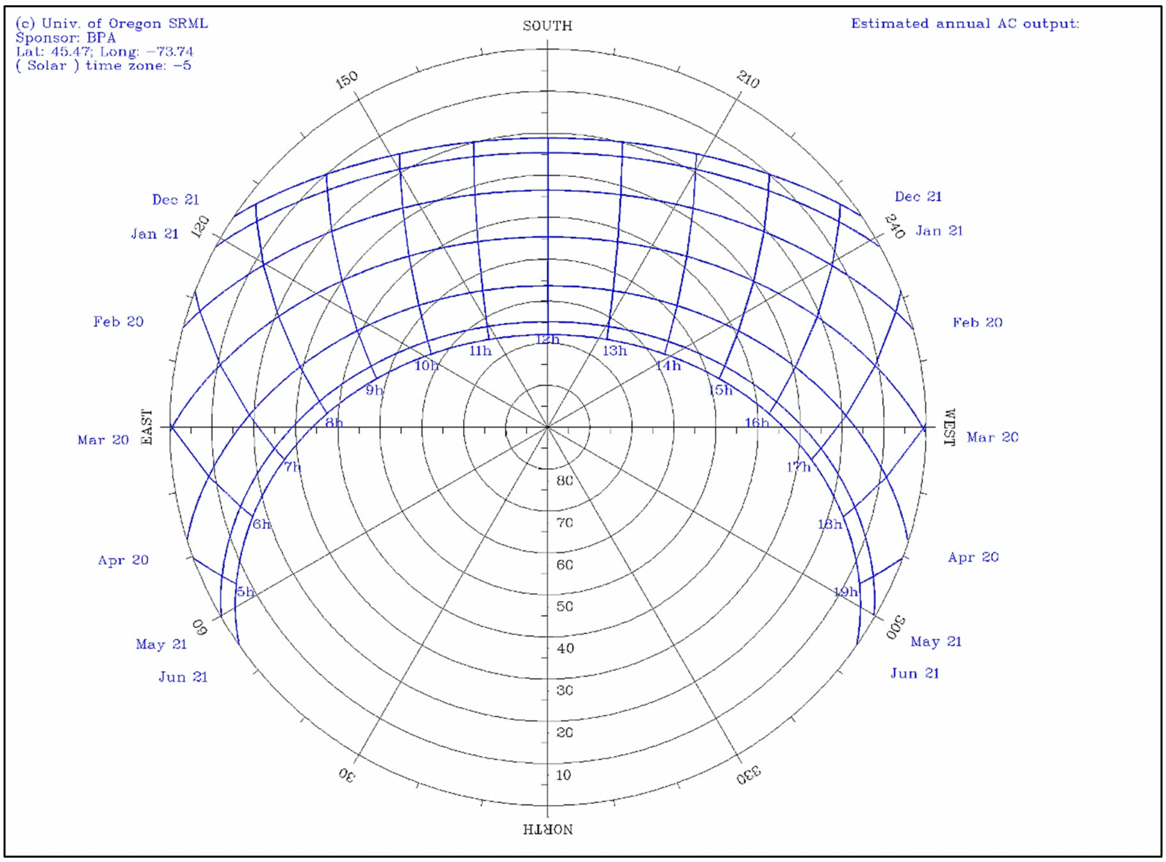


Figure 2-5 the sun path in apparent solar time in Montreal, Canada.

Taken from University of Oregon - Solar Radiation monitoring Laboratory

2.6 Wind Energy

Wind energy feasibility analysis is considered as primary to study the availability of wind energy resources. This form of energy is utilized globally due to its reliability. Wind speed is the main factor of wind power production. In long term study, the averaged wind speed is reviewed because the power is proportional to the cube of wind speed. Wind speed varies over time, so it is essential to study its behavior for long durations and multiple height points. To determine wind force of an area, a fundamental study should investigate for at least one year. Furthermore, there are a few types of wind energy potential parameters to differentiate from one another as follows: meteorological potential, site potential, technical potential, economic potential and implementation potential. The wind information of this study is collected from NASA databases.

2.6.1 Wind Energy Systems Classification

All wind systems produce power from pressure differences or the potential energy, rather than from the kinetic energy of the moving air. Such a machine works with basic aerodynamic principles applied on turbine blades. The fact that potential energy in the air caused by pressure differentials is vastly larger than kinetic energy at moderate wind speeds, promises larger energy output in wind energy system deployment in less elevated locations such as urban areas. As every batch of air flows over the airfoil shaped blade, airfoil generates lift power which forces the blade to rotate around the turbine's hub axis. The section rotates perpendicular to the distant oncoming wind of speed. Therefore, a classification of wind machines is given in association with the rotating axis of the blades: Horizontal Axis Wind Turbines (HAWT) and Vertical Axis Wind Turbines (VAWT).

2.6.1.1 Horizontal Axis Wind Turbines (HAWT)

The rotation axis of these turbines is placed horizontally which means the turbine shaft is parallel with the ground. The blades on the rotor can be mount upwind (in front) or downwind (behind) of the tower while the wind blows in a horizontal plane causing the rotor to rotate. The most generic form of HAWTs (Horizontal Axis Wind Turbines) is two- and three-bladed turbines in power generation (Fig. 2-6). Three-bladed turbines produce less noise, and they operate more quietly compared to two-bladed versions. The more blades installed on rotors the larger the starting torque would be in light winds. The main parts of a HAWT are the rotor, drive train, nacelle, tower, control, and electrical unit. Airfoils in horizontal axisWTs (Wind Turbines) often are designed to be used at low angles of attack, where lift coefficients are high and drag coefficients are low (John Twidell, 2015).

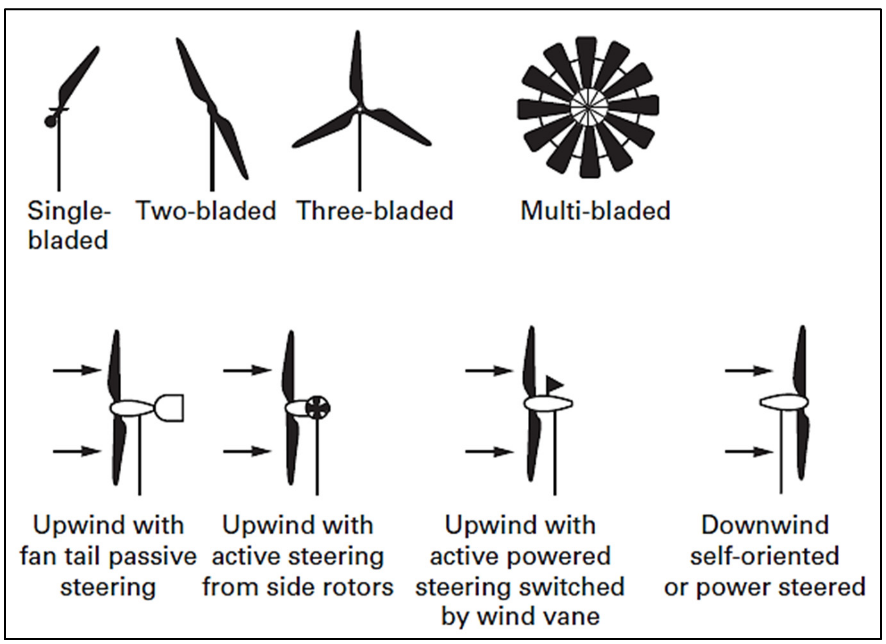


Figure 2-6 diverse types of horizontal axis wind turbines and the mounted blades configurations.
Taken from John Twidell (2015)

2.6.1.2 Vertical Axis Wind Turbines (VAWT)

The shaft of this kind of wind turbine rotates around the vertical axis against the ground. Vertical axis wind turbines are omni-directional in accepting winds (Fig. 2-7). The position of the generator and gearbox room is under the turbine blades at ground level, owing to that, the machine eliminates gravity induced stress on blades. On the other hand, vertical axis wind turbines have suffered from fatigue failures due to many natural resonances. In brief, vertical axis wind turbines have either drag driven or lift driven rotors. Typically, there are two types of blade configuration in VAWT, straight blades and curved blades. In most electrical power generation applications, lift driven rotors have been used. These machines do not need a yaw mechanism for heading the blades into the wind direction.

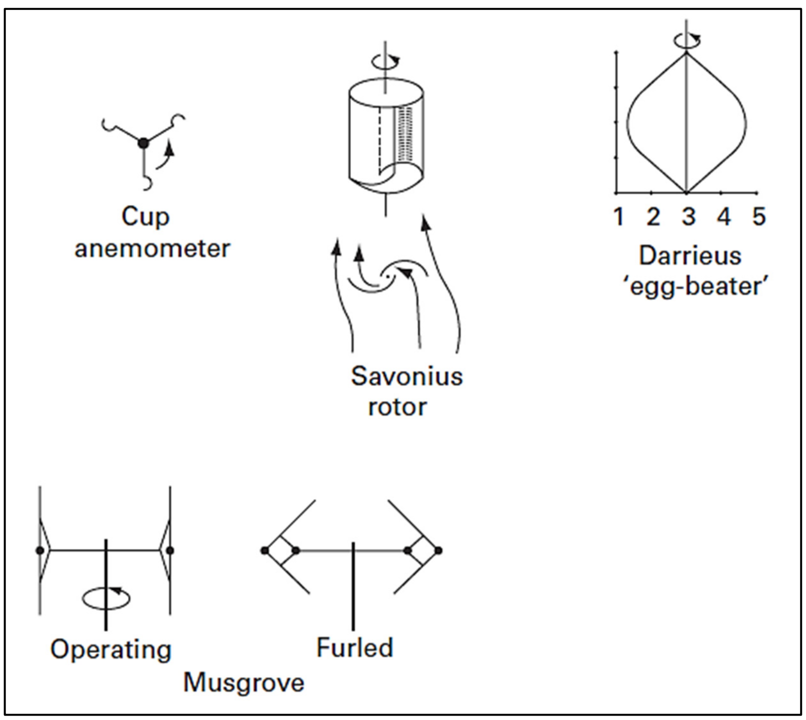


Figure 2-7 Types of vertical axis wind turbines and blade shapes.
Taken from John Twidell (2015)

2.6.2 Characteristics of the Wind

In most cases the wind speed measured at a standard height of 10m at weather stations. This kind of measurements are not enough for detail wind energy planning, and they serve as primary estimates so to anticipate the wind power potential for a specific location, it is needed to measure wind speed at several heights for a particular wind turbine. Such a measurement should last for a few months but best for one year. A standard meteorological method for hourly wind speed is measuring the length of the wind passing at 10 meters to get the idea about wind velocity fluctuation. The wind direction refers to the compass bearing from which the wind comes. Wind data usually be given in the form of a wind rose showing the average wind speed for every direction as well as the distribution of the winds for a specific height.

2.6.2.1 Variation with Height

The wind speed is a function of height, and it varies significantly with altitude above the ground. This is also referred to as wind speed shear which means winds above other obstacles are stronger. Wind speed at local obstructions level changes erratically and rapid fluctuations occur in any direction in windy circumstances. To study this behavior of the wind, wind speed time and frequency plots and wind roses are being used.

2.6.2.2 Wind Speed Probability and Prediction

Because of the stochastic nature of wind, information about future wind speed and its occurrence is required for every specific site location. This knowledge can be extracted from statistical analysis, time series measurements and climatology of the location using logged meteorology data to understand the wind speed probability. Studying wind speed and its variables is indispensable to calculate the available wind power from basic measured wind data on the distribution of wind speed for area.

2.6.2.3 Wind Speed Distribution

For understanding wind performance for wind energy systems, the wind speed distribution for a given area and time should investigate. By knowing the wind speed probability distribution, the wind speed distribution will be obtainable as a result. Such analysis depends solely on measured field data and other calculations. So specific numerical equations have been developed for this aim.

2.6.2.4 Wind Speed Variation with Time and Distance

The instantaneous movement of rapid wind speed and its fluctuations at 10 seconds or less intervals are important. This happens with turbulence most of the time. If changes in wind speed correlate beyond about 10 s, this is usually described as a gust wind. The importance of being aware of turbulence and gusty winds is because they may lead to damaging stress cycles on the wind turbine blades and other machinery.

2.6.3 Wind Instrumentation

For wind power operation and meteorological services, a variety of standardized measurement devices and instrumentation is required. Measurements for wind energy resources assessment for a particular location is an inseparable part of the study. Measuring method must be considered carefully for wind turbine operations. Today’s reliable instrumentation and their modern robust technology is highly dependent on solid-state physics. Acoustic and electromagnetic interactions, wireless communication and computerized data analysis and recordings. All these measuring instruments have their own inaccuracy and need annual calibrations. The World Meteorological Organization recommends a set of conventional instruments for measuring horizontal wind speed and direction at the height of 10 meters with no obstacle within the 100 meters (about 328.08 ft) of radius (WMO, 2008).

These traditional instruments include wind vanes, cup anemometers and recording information in written or digital format in data storage (see Fig. 2-8). Because wind turbine towers are high and wind speed and direction are measured at blade-tip height of the intended wind turbine, such height is not realistic for a wind measurement tower. So, most instrument towers height is limited to between 50 meters to 100 meters for wind energy potential purposes.

Most utility-scale and research use wind turbines are equipped with anemometer, wind vane and thermometer mounted at the rear of the turbine nacelle. Several types of wind speed and direction instruments are being used such as: mechanical instruments, sonic instruments, Doppler instruments, and other instruments. For mechanical instruments, propeller anemometers are often preferred while cup anemometers are common. Sonic wind instruments are like ultra-sonic anemometers which calculate the wind speed and direction using its three displaced sound emitters and receivers. And acoustic resonance anemometers are robust devices, measuring wind specification after detecting ultra-sonic waves of passing wind through the gap distorts of the instrument. Wind measurement devices based on Doppler Effect (sound back scattered method, see Fig. 2-9) are expensive and need expert calibration, but the benefits are the absence of towers and accurate sampling to monitor oncoming wind to a wind turbine. The working principle is the sophisticated instruments propagate signals from ground level (omnidirectional) and record the backscattered signal back from dust that is always in the air. There are also numerous other ways of assessing wind speed, such as the Pitot tube, hot wire sensor, windsock and drag spheres.

Figure 2-8 Cup anemometer and wind direction vane mounted on a pole
Taken from National Oceanic and Atmospheric Administration NOAA

Figure 2-9 Acoustic-Doppler SoDAR (Sonic Detection and Ranging)
Taken from https://www.windpowerengineering.com

2.6.4 Wind Power Potential Tool

Measuring wind power potential for a whole region is possible via computer modeling is the only method of assessment and anticipation, with the model calibrated from a set of measured data. Furthermore, for predictions on complicated wind properties within an actual site, two modeling methods can be considered. Numerical objective analysis boundary layer modeling and Wind atlas analysis and application program. A significant handicap of NOABL method is ignoring local distribution effect in the model. The WasP method is based on trustworthy wind data from an established meteorological station, then applying effects like altitude, topography, and obstruction in the model and finally an average wind speed and power prediction as the outcome of the simulation.

2.6.5 Short term predictions

The importance of wind speed prediction is uncovered when having a significant wind power capacity installed at the site. For a range of purposes such anticipations are needed: providing wind information of some minutes ahead for individual wind turbine control systems; hours ahead for electrical network operators' short-term planning; few days ahead for network operators' power station scheduling; few months ahead for power maintenance scheduling; few years ahead for wind power plant financing (John Twidell, 2015). To ensure that total wind generation supplies the varying demand, power grid operators need wind information to plan for input. The uncertainty about wind power generation is not the condition of wind turbines, but the state of the wind. For weather prediction from hours to days ahead, the meteorological services deploy massive computing capacity using established weather models. Such models range from post-prediction correlations with past recorded wind speed to hydrodynamic models calculating how air pressure differences and heat inputs cause masses of air to move. Such analysis provides exceptionally reliable information for the areas covered by grid networks.

2.7 PV and Wind Turbine Size Selection

The size of a renewable energy system is the very first subject to be questioned when studying the feasibility of the project. Application and number of loads connected to the system defines its size.

2.7.1 Size Selection of the PV System

For an estimate on size selection of a photovoltaic system, there are few required information to be considered. These details are around the type of application for which the systems to be installed is intended, the amount of energy required in watt-hour per day, elements that need to be electrified and the grid connectivity of the system (NRCan, 2002).

2.7.2 Size Selection of the Wind Turbine

Selection of the wind turbine size is a function of energy needed by the consumer and the wind energy resource availability. The Size of the wind turbine has impact on electricity generation as well as potential GHG reductions. Rotation of wind turbine blades around hub axis create a disc and the sweeping area of that circle determines how much energy is harvestable in a year. Indeed, a large wind generator requires more power (here intense winds) which also requires high elevated locations and larger diameter of the turbine rotor.

2.8 Summary

The main principles of two forms of renewable energy, including wind power and solar power have been investigated to accurately assess the ways of harvesting energy likely to be produced. Furthermore, the required technology to capture power from these resources is explored. Each solar and wind power generation technologies are categorized on a different basis which are based on the application and efficiency.

Solar cells generate electricity from the photovoltaic (PV) effect by absorbing light within semiconductor materials. There are a few advantages of PV include its universal applicability, modular character to increase the power production capacity, reliability, and long life due to no moving parts, ease of installation, and silent operation as well as zero emissions. One major drawback of solar energy systems is that electricity generation only happens during daytime. Therefore, use of batteries as energy storage solution or power grid connecting is common. Also, the hybrid configuration of PV and another form of renewable energy is often considered to improve the electricity production rate.

When it comes to wind energy harvesting, vital measurements should take place to assess the power that is likely to be produced by a particular wind turbine at a specific site. These on-site measurements should be performed over at least 12 months at several heights. This is because wind speed varies over time in matter of seconds to seasons or years. So then, to harvest wind energy the technical characteristics of a wind turbine including aerodynamics of the blades with airfoil shape carefully chosen to maximize the lift force and to minimize the force of drag. Many working wind turbines are horizontal axis, not vertical. With two or three blades and a radius ranging from 5 m to about 60 m. In practice, vertical axis turbines have not been used as widely as have horizontal axis turbines. A minimum wind speed of 12 to 14 km/h is needed for wind turbine to start rotating and to generate low-level power. Wind speeds ranging from 50 to 60 km/h are require for full capacity power generation of wind turbines. Additionally, to prevent equipment failure, power production should cease in winds about 90 km/h or more.

CHAPTER 3
METHODOLOGY

3.1 Preface

In this chapter a distinct approach toward energy potential yield from sustainable power sources serving Montreal is performed. A computerized methodology for renewable energy here refers to photovoltaic and wind power using the state-of-the-art developed software tools and satellite derived data analyzers. The outcome of the following method for energy resource potential analysis could be put to practical use and critical decision making in many urban applications, in this case residential consumers. Although, the technique is expandable to other non-residential utilization purposes. There is a vast variety of factors to be considered when it comes to analysis energy potential and electricity generation capabilities for a specific location by scrutinizing accurate data from prestigious databases.
Weather phenomena such as air mass movement (wind) and radiation from sun considered as the fuel to run machines that does the energy conversion act for the power grid and local electrification. This gives enough reason to investigate the climatology of the area for a reliable and dependable energy source to check if the region is suitable for investment. Utilizing two or more forms of energy makes this goal possible for continuous power generation with minimum alternation in energy production by overcoming on each source shortages. Before supplying wind-solar system equipment, a resource potential analysis is needed. In the current study the RETScreen Expert energy management software is the primary tool for the proposed research.

The procedure to HRES resource assessment including system configuration, databases for raw climate information, deemed capacity, studied methods and emissions reduction capacity etc. stated in this part.

3.2 Energy Calculations

The initial stage will be to determine the projected building's energy consumption, from which a system capacity will be determined. Following that, two system configurations with same capacity will be designed, consisting of a solar photovoltaic system with fixed tracking mode and wind turbine. The total capacity will be determined by the amount of space available on the building's roof. The study site is a multi-unit residential building (MURB), which will be discussed in the following chapter.

The generation estimation of the hybrid system will be done using data from the RETScreen climate database, which is provided in the software. RETScreen has a database of weather data for tens of thousands of locations all over the world. This information is a combination of measured data from weather stations and estimated data from NASA's satellite/analysis database (RETScreen Expert, 2022). The nearest site to the planned project location will be determined, and the data in the database for these sites will be utilized as a basis for the calculations. When this is accomplished, the energy generation calculations for the identified systems can be conducted in RETScreen, yielding the amount of expected energy produced by the system at each site. RETScreen accomplishes this by running a series of calculations using the input measurement data as well as other user-defined variables (Natural Resources Canada, 2005).

Figure 3-1 shows a flow chart that details the methodology analysis.

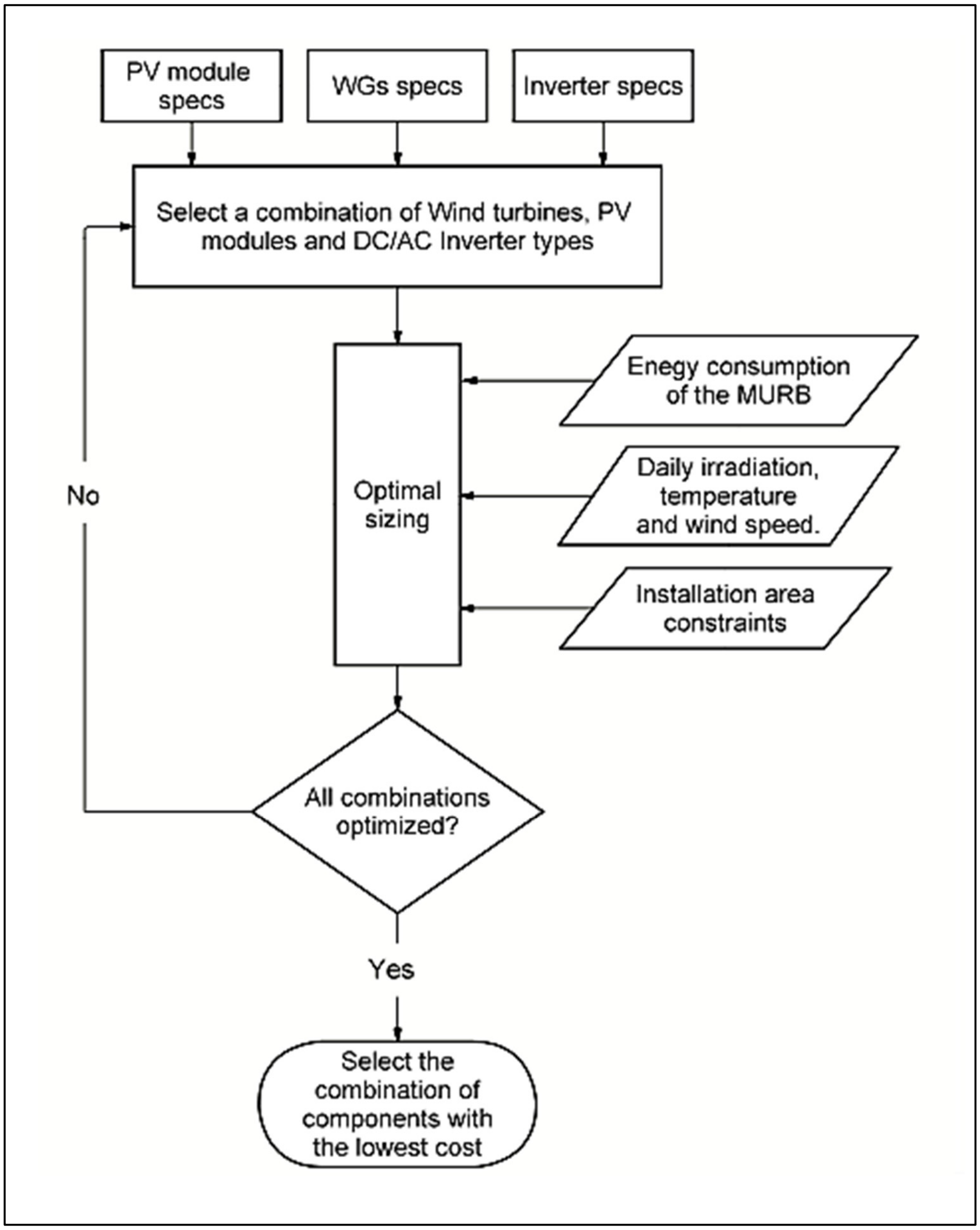


Figure 3-1 Method for hybrid Wind/PV energy system sizing and optimizing in MURB that stands for multi-unit residential building

3.3 Requirement for Wind-Solar Energy System Implementation

To analyze the sustainable power resources to investigate enough harvestable energy for minimum performance of the system. Various models of combined system have been covered in literature review with the following aspects.

3.3.1 Weather Data

Measuring solar irradiance and wind intensity data is considered as the main input of a hybrid energy system. It is an inseparable part of the PV/Wind resource analysis to address measured hourly, monthly and annual climatology parameters of the proposed location.

3.3.2 System Sizing

It is important to determine the generating capacity of the system for a proper analysis and design. The operational size of the HRES should be compatible with the demand factor of end user load. The load fluctuation is not a plateau year-round and complicated to predict for every season, so to fulfil existing requirements a nominal system capacity of close to or more than the load demand is preferred.

3.3.3 System Layout

Since producing electricity from sources like photovoltaic and wind power is highly dependent on the location to be selected. And due to the environmental conditions and gathered data such as solar radiance, wind speed and load demand, a desired configuration must be chosen with an appropriate selection of equipment.

3.4 Method for Wind Power Potential

In order to analyze the wind energy production potential, the wind speed climatology data from 1984 to 2020 provided from NASA are used in this study for the Montreal area. The forming process of wind energy starts from temperature difference between two points that leads air to flow and create wind. The collision of sun rays with air molecules raises the kinetic energy and temperature of the moving air, it forces the air to climb. Conversely, by dropping temperature a low-pressure zone will form. The higher amount of pressure difference means faster wind movements. Once air mass speeds up (v) toward an area (A), the respective bulk air movement power at time (t) can be calculated by the given relation:

$$P_{(t)} = \frac{1}{2}\rho A v_{(t)}^3 \tag{3.1}$$

Where air density is 1.225 kg/m^3 corresponding to dry air and 15ºC of temperature at sea level standard pressure (Martin Hansen, 2008). The amount of energy unit (kWh) is the outcome of power and time:

$$E = P_{(t)}T = \frac{1}{2}\rho A\Delta t \sum_{i=1}^{N} v_i^3 \tag{3.2}$$

The energy derived from cube of averaged wind speed differs from energy from wind speed, as the energy in cube of wind speed is obtained from the summation of several wind speeds over a time divided into small intervals. In most cases, average wind speed is measured every single hour by the meteorological stations. Thereby, 24-time scoops are available for wind speed each day of the year. Despite the constant amount of air density, there are two parameters to keep an eye on, wind speed (v) and the wind-swept area (A).

Power generated from a wind turbine is affected by various parameters. Including the scale, design specifications and the weather characteristics of the installed environment. The radius is the length of the rotor blade (r) and (v) refers to a momentary speed in time and not the average speed. The efficiency factor indicates that to what extent the rotor sweep area is converting wind energy into electricity (η), which 59.26% is the maximum theoretic limit for typical horizontal axis wind turbines according to Betz law. The following equation discloses the measured electrical output power of the wind through a circular cross section in W (Watt):

$$P = \frac{\pi}{2} r^2 v^3 \rho . \eta \tag{3.3}$$

Where:

P refers to the wind turbine's power.
r is the radius of the rotor blade.
v stands for wind speed, ρ is the density of air and η counts as an efficiency factor.

3.5 Method for Solar Power Potential

The RETScreen photovoltaic power model can be globally employed to evaluate solar energy applications due to the extensive access of databases. Solar panels or photovoltaic modules (PV) absorb solar energy to generate electricity using photovoltaic principle. There are a few elements influencing on photovoltaic system performance like: level of solar radiation, efficiency, operating and coefficient temperature, physical orientation of the collector and other factors like the use of invertor and the connected or isolated grid solar electric system. But tracking mode of solar panels is one of the many important conditions which locates the way they face toward the sun. Namely, fixed type, one and two axis trackers (azimuth). Calculations associated with solar PV power understanding is given by:

$$P_{PV} = P_{STC} DF \left(\frac{IR}{IR_{STC}}\right) [1 + a_P (T_{mod} - T_{mod,STC})] \tag{3.4}$$

Where in the above equation, the standard test conditions STC of the photovoltaic power are considered as P_{STC} ($T_{mod,STC}$ = 25ºC, IR_{STC}=1000W/m^2 and no blowing wind). There is a factor for dust accumulations on the surface of solar panels that causes reduction in power production DF, as well as shading and wiring losses. Power coefficient a_P, PV module temperature T and solar irradiance (IR) are all efficacious on the output power.

Where:

P_{PV} :Photovoltaic output power

P_{STC} : Power in standard condition

DF: Dust factor

IR: Receiving solar irradiance

IR_{STC}: Solar irradiance in standard condition

a_p: Power coefficient

T_{mod}: PV module temperature

$T_{mod,STC}$: Module temp in standard condition

The Photovoltaic module efficiency at maximum power point is also known as the conversion rate of sunlight into electric power. This factor depends on the spectrum and intensity of sun radiation as well as the temperature. It is determined by the following relation:

$$\eta_{m,STC} = \frac{P_{m,STC}}{A_{PV} IR_{STC}} \tag{3.5}$$

Where:

$\eta_{m,STC}$: Module efficiency in Standard condition

$P_{m,STC}$: Power in standard condition

A_{PV}: Photovoltaic panel area

The radiant power density H (In Wm^{-2}) emitted from the sun spectral irradiance $F(\lambda)$ overall available wavelengths $d\lambda$ on tilted panels, is calculated as follows:

$$H = \int_0^\infty F(\lambda) d\lambda \tag{3.6}$$

With the purpose of estimating the output energy (kWh) from a photovoltaic system for electricity generation, the below equation is taken into consideration:

$$E = A \times r \times H \times PR \tag{3.7}$$

Where PR is the performance ratio and r is the solar panel yield (in %).

A : Area of the PV module

H: Radiant power density

The photovoltaic resource assessment part of the RETScreen follows a similar approach to the wind resource data evaluation but with different criteria available in two levels of scrutiny. In the first level a simplified analysis based on the PV system power capacity and capacity factor is performed. While in the second level, more details are engaged to run the analysis in accordance with monthly climate data (i.e., daily horizontal, and tilted radiation) and photovoltaic equipment information. In this study, level 2 of analysis is investigated with a focus on maximizing the incident of solar beam radiation on the collector surface by using Azimuth solar tracking method whereas a fixed slope angle is prescribed, and the rotation is around a vertical axis to always position the panels normal to the solar beams.

3.6 Financial Investigation, Economic Indicator

The maximum annual financial income for each system will be computed over a 20-year period by combining the energy delivered with the price of electricity for Montreal. The average lifespan of small-scale wind turbines is around 20 to 30 years (Tremeac & Meunier 2009; Nugent & Sovacool 2014), and the average lifespan of PV solar panels is around 30 years (Tremeac & Meunier 2009; Nugent & Sovacool 2014). (Nugent & Sovacool 2014). As a result, the wind turbine component's shortest lifecycle is assumed for the entire system.
It is difficult to precisely determine the financial return criteria since the purchase prices for wind turbines and solar panels varies, as well as the installation, are not available for an academic study due to commercial considerations. As a result, the goal of this research is to determine the average purchase and installation costs that fulfil a defined internal rate of return (IRR). This will be accomplished by applying the equation stated in Equation 1 to calculate net present value (NPV). The discount rate used to assess the financial viability of a given project is sometimes called the "hurdle rate," or the "required rate of return." However, as previously mentioned, the initial investment of the projects is an averaged cost, so in this instance a discount rate of 9% will be defined which recommended by RETScreen as common value. The base reasoning behind the defined hurdle rate for this project is that in North American electric utilities currently use discount rates ranging anywhere from 3 to 18% with 6 to 11% being the most common values.

$$NPV = \sum_{T=0}^{N} \left\{ \frac{Period\ Cash\ Flow}{(1+R)^T} \right\} - Initial\ Investment \quad (3.8)$$

$$NPV = \sum NPV_{income} + \sum NPV_{end} - C_{investment} - \sum NPV_{OM} - \sum NPV_r \quad (3.9)$$

Where:

NPV= Net Present Value

R= Discount rate / Hurtle Rate

N= Number of Time Periods

T= Timing of Periodic Cash Flow

$C_{investment}$= Initial investment

NPV_{OM}= future O&M cost

NPV_r= future replacement cost

NPV_{income}= income from electricity export

NPV_{end}= end of life value of components

3.7 Graphical Representation of Methodology

The process of this study is schematically shown in the figure 3-2, it starts with the analysis of two sets of data. It contains the total energy consumed by the building, as determined by electricity bills, and the amount of solar and wind energy resources available at the location, as determined by climatology records. The choice of system components is made based on technology, cost, and logistics. Two system configurations are then presented to show how additional wind energy performs. Then each system designed independently is included in the software. The final step will involve financial analysis and energy potential.

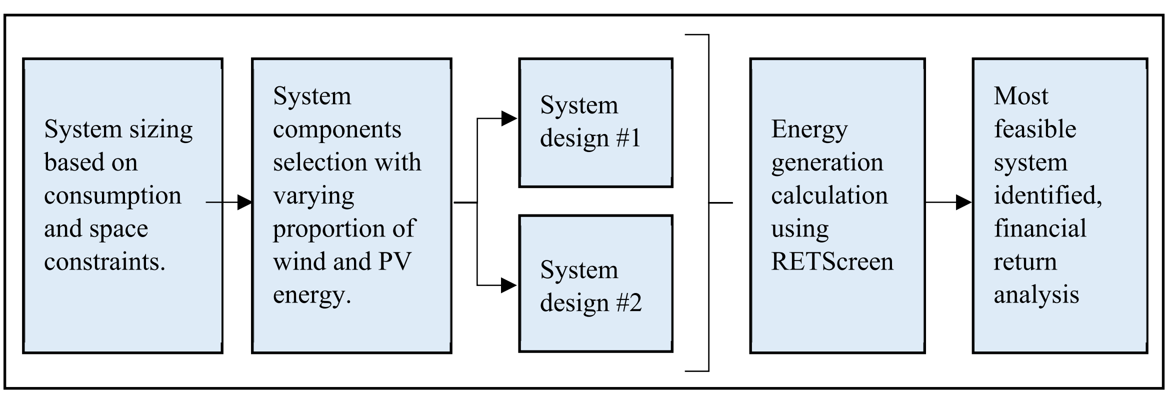


Figure 3-2 Graphical Representative of Methodology

3.8 Chapter Summary

This chapter identifies essential research data and energy calculation methods for both solar PV and wind systems. Also, the methodology for this research and the tools used to analyze the findings are thoroughly discussed. Locational factors like wind speed, wind direction, temperature, and solar radiation quantities will be discussed in the following chapter, alongside with energy consumption data and load demand of the building. Also included in the next chapter is a review of the optimum commercially available solar panels and wind turbines for the case study.

CHAPTER 4
CASE STUDY

4.1 Case Study Overview

The site that will be investigated for this case study is a multi-unit residential building (MURB). The building has five levels and electricity consumption is invoiced on a bi-monthly basis. The building was recently built in 2021 and is privately owned. To simplify the text, this building will be referred to as MURB in the remainder of this text.

It has been decided that the renewable energy system shall consist of both small-scale wind turbine and solar PV technologies connected to an internal load and to the power grid. This is to enable the maximum amount of energy to be generated, as weather patterns suggest that solar resources tend to peak when wind resources are at their lowest, and conversely wind resources tend to peak when the solar resources tend to be at the lowest. As a result, the hybrid system should generate more consistently throughout the year than installations of the same capacity that use either solar PV or only wind power systems when compared with each other (Ma et al. 2014; Bhattacharjee & Acharya 2015).

This section will describe the location and usage of this mid-rise building, the energy consumption since after opening in 2021 for one year period, the peak and base load calculations, and the system design and system components.

4.2 Location and Building Utilization

The location of the proposed project is a five-story residential building which is in Montreal urban areas. The building is newly constructed and employs the latest energy efficiency and monitoring technologies. The building is situated on inclined land, surrounded by woods from the northwestern side and only 70 meters from rail tracks on the southern side. The MURB is approximately 15.3 meters high with 1162 m^2 flat roof area. The internal area of the building is 5613 m^2 including residential units, parking, gym, storage, and shared areas. The isometric view of the building and its geographical location can be seen in Figures 4-1 and 4-2.

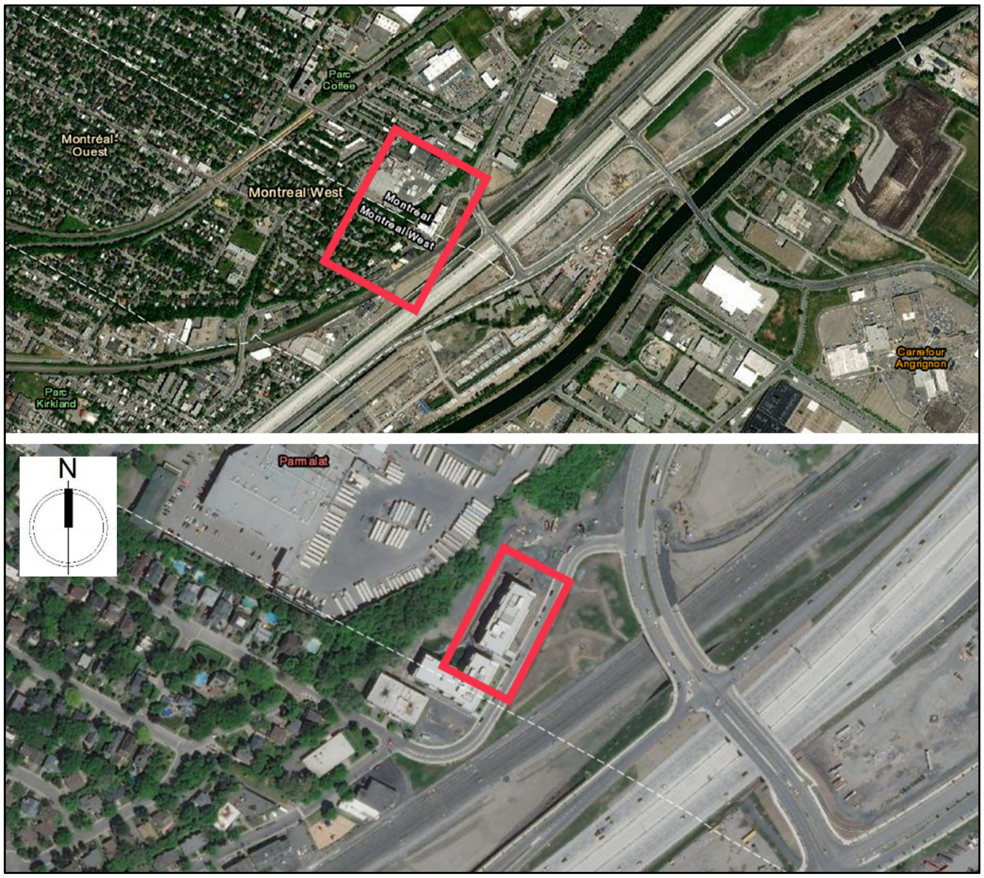


Figure 4-1 (a) 3D view of the proposed building and (b) location of the site Taken from Open Street Map (2022)

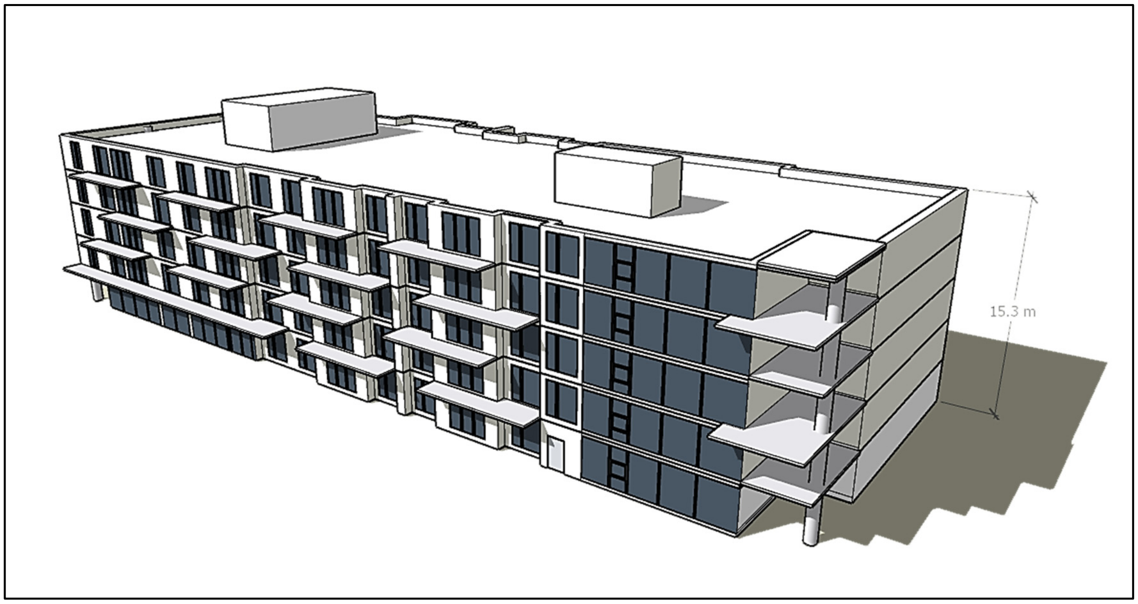


Figure 4-2 Isometric view of the studied Multi-Unit Residential Building (MURB)

4.3 Building Electricity Consumption

The electricity price paid by this multi-unit residential building complex is dynamic and fluctuates throughout the year, however a value of 0.053 Canadian dollar per kilowatt hour (5.3 ¢ / kWh) have derived from the building's hydro bills. For this MURB, average values for power factor and duty cycle are 98.2 percent and 46%, respectively. Since this building is opened in early 2021, the available electricity consumption data covers a one-year period as shown in Table 4-1 and Figure 4-3. This information is recorded by Hydro Quebec and has been provided by Bellevue Limited Partnership Inc. which owns the building.

Table 4-1 Monthly Energy Consumption from 2021-07 to 2022-06
Taken from Hydro Quebec (2022)

Monthly Energy Consumption (kWh) 2021-22											
Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
15428	15428	15142	30285	56571	63142	64857	63142	48571	34285	32000	30857

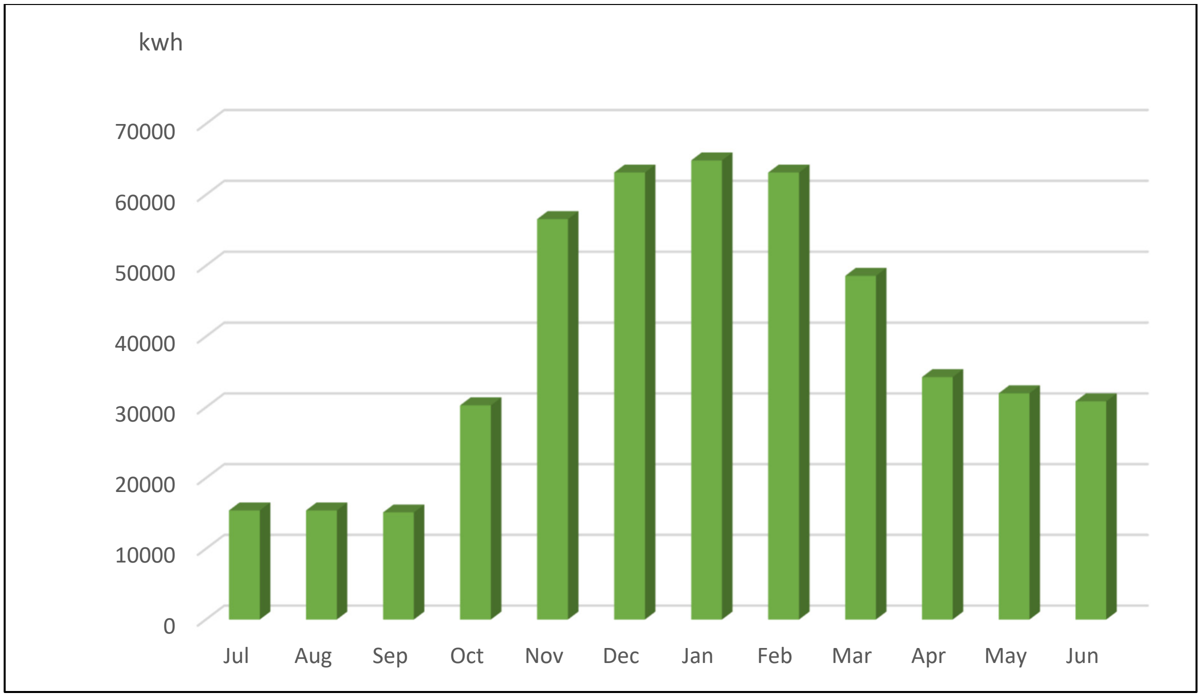


Figure 4-3 Monthly Energy Consumption of the MURB 2021-22

It can be seen in the data in Table 4-1 and Figure 4-2 that there is a general trend that the months of November to May have higher electricity consumption due to cold weather. Utilization of heating equipment, less daylight and tenants' tendency to stay indoors in the winter are main reasons for higher power consumption. There is generally a smaller amount of energy used in the summer months June, July, August and September. This is because heating systems are disconnected from the circuit and energy-efficient air conditioning systems are used. The need for interior illumination is at its lowest during this time period because the days are longer. Due to the vacation season occurring around this period, lower occupancy levels are most likely anticipated, leaving some residential units temporarily vacant.

The electricity consumption from July to September throughout the past year was rather constant. After this, the consumption tends to act in a variable manner.

Based on the temperature data for the study year provided by Hydro Quebec, see Table 4-2. The amount of electricity used, and the outside temperature appear to be related. Since December, January, and February have much higher electricity consumption than other months, their corresponding temperatures are the lowest of the year. Similarly, July and August have the highest recorded temperatures and the least amount of electricity used. Both Fig. 4-3 and Table 4-2 show that January was the coldest month of the year, and that month also had the highest power consumption. Since the building uses natural gas-powered boilers to heat the water, the increase is likely the result of increased use of heating systems to control the interior temperature.

Table 4-2 Average temperature in °C provided by Hydro Quebec 2021-07 to 2022-6

Recorded Data for the Average Temperature (Unit: °C)											
Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
21	23	17	11	2	-4	-13	-8	1	8	17	20

4.4 Building Peak Load and Base Load

For this thesis, there was no information on the daily consumption and peak load for this MURB. However, Hydro Quebec bills can be used to obtain information on the monthly base load. These are important considerations when designing a renewable energy system, in terms of capacity and size of the inverter that must be employed to meet the peak demand.

The usage of the building has been deemed to follow the activity level of a residential environment: with weekday energy use plateauing and rising on the weekends. Based on these assumptions, the electricity consumption of a residential unit over the course of one week has been used as basis and it is shown in Figure 4-4 which demonstrates household load profile. This data comes from a study carried out by Anna Marszal et al. (2016) which includes the high-resolution electricity consumption for each day of the week taken at 1-minute intervals.

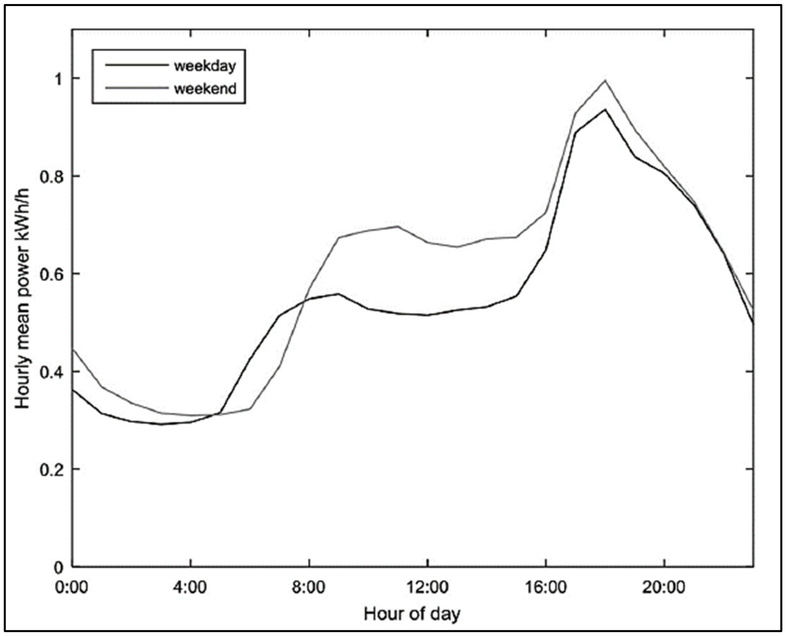


Figure 4-4 hourly mean load profile for a weekday and weekend

Taken from Anna Marszal et al (2016)

Table 4-3 from the building's utility bill shows the daily load consumption of the MURB, and it estimates an amount of 1630 kWh per day that translates into 67.8 kW/d of load. Based on a study done by David Lee in 2016, the weekend peak load of a residential building could increase by 50 percent higher than the daily base load. Considering Lee's research and to cover weekend's peak loads, the system size requires to be 50% greater than the building's average base load. This increases the 67.8 kW base load to 101kW as the possible system size.

Sizing techniques that take average values or the worst-case scenarios into account have a tendency to oversize system components. Because either the average value fluctuates over time or the worst scenario has a low probability of happening (R. Luna-Rubio, 2012). There are two common sizing techniques; annual monthly average sizing and the most unfavorable month technique. The average annual monthly values of energies statement is used to determine the system. This calculation is based on annual monthly solar radiation and wind speed data.

In the most unfavorable month strategy, The PV and wind turbines are calculated in the least favorable month. In general, the month with the least favorable wind is the month with the most favorable irradiation, When the system functional in these months, it automatically works in the rest of the months (A. Al Busaidi, 2015). To set the system dimension based on this statement, December has the least favorable solar irradiance as stated in Table 4-4, and the corresponding average energy consumption for this month is 106 kW (Tables 4-3 and 5-7).

A system size of 100 kW derived from the discussed methods is validated by the commonly referenced national energy code of Canada for buildings guide published by National Research Council Canada (NRC Can, 2020) which provides guidelines for installed capacity of electrical equipment in the buildings per square meter.

Table 4-3 Mean Daily Power Consumption for each Month in kW/Day

Average Energy Consumed (kWh/Day) of the MURB												
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann.
2636	2841	1974	1440	1300	1296	627	627	636	1192	2457	2566	1630

4.5 Environmental Data

The RETScreen climate database provided the environmental information used in this study. The nearest site to the MURB with weather data is in Montreal Int'l airport, with the latitudinal and longitudinal coordinates of 45.47, -73.72. It is located approximately 6 Km from the proposed multi-unit residential building.

It can be seen from Table 4-4 that the wind data is recorded from an anemometer located 10 meters above the ground level. The data on solar radiation is acquired from the ground meteorological station because the chosen weather station has solar measurement equipment. In the absence of ground solar measurements, NASA surface meteorology data that are derived from satellite measurements could be used in their place. As can be seen in Table 4-4 below and as stated in earlier literature, the wind resources are at their peak in the winter and the solar resources are at their highest in the summer.

Table 4-4 Calculation Input Data

Month	Air temperature	Relative humidity	Precipitation	Daily solar radiation (horizontal)	Atmospheric pressure	Wind speed	Earth temperature	Heating degree-days	Cooling degree-days
	°C	%	mm	kwh/m^2/d	kPa	m/s	°C	°C-d	°C-d
Jan	-10.3	69.5%	66.03	1.52	101.2	4.7	-11.6	877	0
Feb	-8.8	66.6%	54.04	2.43	101.2	4.5	-9.8	750	0
Mar	-2.4	64.3%	67.27	3.57	101.1	4.5	-3.1	632	0
Apr	5.7	61.5%	82.2	4.41	101.0	4.5	5.8	369	0
May	12.9	63.3%	89.59	5.34	101.0	3.9	13.1	158	90
Jun	18	66.9%	101.4	5.77	100.9	3.9	18.5	0	240
Jul	20.8	69.0%	98.58	5.85	100.9	3.3	21.3	0	335
Aug	19.4	71.1%	97.03	4.84	101.1	3.1	20.7	0	291
Sep	14.5	73.8%	91.5	3.74	101.3	3.3	15.8	105	135
Oct	8.3	73.6%	92.69	2.31	101.3	3.9	8.2	301	0
Nov	1.6	74.4%	82.2	1.29	101.2	4.5	0.9	492	0
Dec	-6.9	73.7%	78.43	1.11	101.3	4.5	-7.5	772	0
Ann.	6.1	69.0%	1000.96	3.52	101.1	4.0	6.1	4,457	1,091
Src.	Ground	Ground	NASA	Ground	Ground	Ground	NASA	Ground	Ground
Measured at						10 m	0 m		

4.6 System Design

As outlined previously there will be two different proposed systems and each of which will be composed of parts from both wind turbines and solar PV components. These are described in subsection 4.6.1 and 4.6.2 with the overall system design described in subsection 4.6.3

4.6.1 Wind Turbines

Although there have been some stated advantages to employing the VAWT design, the system design for this study will instead use micro-mid-scale HAWT concepts. This is due to the HAWT concept having more of a proven design outlined in the Literature Review of this thesis. Two wind turbines have been chosen to be used in the proposed systems. This includes a 10kW Zenia Energy wind turbine and a 5kW Magnum Tesup wind turbine. (Figures 4-5 and 4-6)

The 10kW Zenia Energy was chosen because of its favorable power capacity and sizing in terms of yearly production and overall performance (Figure 4-5). Furthermore, the turbine was designed for the Nordic climate of Denmark, which means that it is theoretically expandable to the Canadian winter climate (see Appendix II). When these two turbines are compared, the Zenia Energy turbine is heavier and less suitable for rooftop installations. Moreover, it necessitates more maintenance as well as a higher initial investment, making it an expensive option that is not economically viable. Because of this reasoning, the 5kW Magnum Tesup (Fig. 4-6) is advantageous for this research to be considered. The wind turbine that has been selected for use within the proposed system is a 5kW rated power Magnum 5 wind turbine by TESUP Canada.

The TESUP Magnum 5 has been chosen due to its favorable weight and sizing, both in terms of logistics, and with respect to obtaining planning permission. In addition, the turbine has been designed for cold climates, meaning that any snow or icing experienced on the blades should, in theory, not increase the amount of maintenance required compared to other turbines.

According to the manufacturer, the turbine is specifically made for residential applications, and its mechanism is designed to be lighter, quieter, and more durable. The turbine's advertising materials state that it can produce 5kW of power at 15 m/s of wind speed. However, the turbine's maximum output is 5.2 kW at higher wind speeds. The power curve data for this turbine used as inputs for RETScreen energy generation calculations can be found in Appendix III.

The tower of this turbine will be simulated to elevate the hub height to 5 meters above the surface of the roof. This height of tower has been used as a method of raising the hub height to account for the resistance effect the building has on the wind, as well as take into consideration the relationship between the hub height and the rotor diameter of the turbine. At the same time there has been an attempt to keep the tower relatively low to reduce the visual impact and to increase the chance of planning permission will be granted.

When multiple turbines are installed at the same site, there is a potential for losses due to 'wake effects'. This is because one turbine stands downwind of the other due to the direction of the wind, which reduces the wind resources available to this turbine. In the energy calculations, a value of 4% has been included when 2 turbines are in the system, as this value falls within the recommendations in the RETScreen software (RETScreen International, 2013). Because wind speed data from measurements for calculations are not directly related to the proposed location, a wind shear component of the site must be taken into consideration. The wind shear component relates to the surface roughness of the surrounding area. Due to the location of the building being in the urban area, a wind shear component of 0.4 has been used in the calculations. This is a conservative wind shear component value for urban environments, and 0.1 for a smooth surface such as the sea (RETScreen International, 2013).

In order to support structures required for securing the wind turbine, a 3m x 3m area has been set aside for each turbine on the roof of the MURB.

Figure 4-5 Proposed horizontal axis wind turbine, Tesup Magnum 5kW

Figure 4-6 A Zenia Energy 10kW wind turbine

4.6.2 Solar Photovoltaic

Due to the findings in the literature review, it has been determined that the solar panels type for this hybrid system analysis will be made from the monocrystalline silicon material.
For this study, two different brands with the same output power and similar dimensions were investigated. The Canadian Solar HiKu and LG NeON each have a peak power of 435W. Their surface areas are 2.2 and 2 square meters respectively. By performing a comparison between these two modules (detailed specifications in Appendix IV), the Canadian Solar HiKu CS3W-435 solar panel not only takes up more space on the roof, but it also weighs more than the LG NeONR 435QAC panel by a substantial margin of 3.8 kg per module. Because there is limited space at the rooftop of MURB, the space occupied by the panels becomes an important parameter to the decision on. The most suitable option will be a panel with a smaller area and higher efficiency. In this case, the LG module's efficiency is 21.9%, while the Canadian solar module's efficiency is 19.7%. And this is all while the maximum output power of both panels is the same.
The chosen model for use in this feasibility study is a LG NeON® R LG435QAC-A6 with 435 watt per panel. The selected panel offers greater output power per unit area and an industry-leading efficiency of 21.9 percent, making it a suitable option for residential applications with constrained space. Due to their accessibility and logistics on the Canadian market, these panels are a logical option. Panels will be secured to the rooftop in a fixed position (i.e., the panels will not track the path of the sun). They will be in a fixed position in order to simplify the installation and maintenance of the system. The angle of elevation (slope) from the floor of the installation will be 37º as the optimal year-round tilt angle of the site calculated by RETScreen, which generally maximizes the annual solar radiation in the plane of the solar collector (RETScreen International, 2013). The orientation of the MURB means that the most surface area of the roof can be utilized when the solar panels face the south, meaning that the azimuth angle used in the calculations will be 0º, with zero due south. The preferred orientation should be facing the equator (RETScreen International, 2013).

It can be seen from Appendix IV that the dimension of each solar panel is 1910mm x 1042mm. It will be assumed that the solar panels will be mounted in a portrait orientation, two panels high. Using basic trigonometry as shown in Appendix V, this means that the required roof surface area for two solar panels is 3m x 1m (32.3 sq.ft).

4.6.3 System Design for the Study

The proposed system design has the goal to cover the base load of the MURB in question. This is primarily because the amount of area available on the rooftop of the proposed MURB has a significant impact on a system's potential capacity. As a result, it is unlikely that any system configuration will be able to completely meet the needs of this multi-unit residential building. It has been determined to exclusively use the non-elevated part of the flat roof of the building to position the wind turbines and solar PV panels in order to reduce the complexity of installation and maintenance. The area of the roof has been appraised using the provided floor plan by the building's developer, combined with physical measurements. The entire area of the building's roof is approximately 1162 m^2. However, there are raised portions of the roof totaling about 81m^2 that have not been considered for the installation of the renewable energy equipment. The usable area is about 1081m2 for implementing wind turbines and solar panels. A total of 276 m^2 has been designated for the solar power installation, and 9 m^2 has been set aside for each turbine erected, considering the expected shade areas as well as access to the turbines, solar panels, and roof maintenance.

The photovoltaic allocation is divided into 4 sections with the dimensions of 23m x 3m each, which translates into 184 solar panels or 80kW of installed capacity. Configurations are sized according to the load demand of the least favorable month in terms of energy consumption.

The plane area of the roof has produced using SketchUp Pro, computer-aided design (CAD) software to illustrate the proposal positioning of the wind turbines and solar panels. This is shown in Figure 4-7. Additionally, the PV arrays are positioned to provide the most power annually, and receive a minimum amount of shade from surrounding elevated structures using sun trajectory simulation during the year.

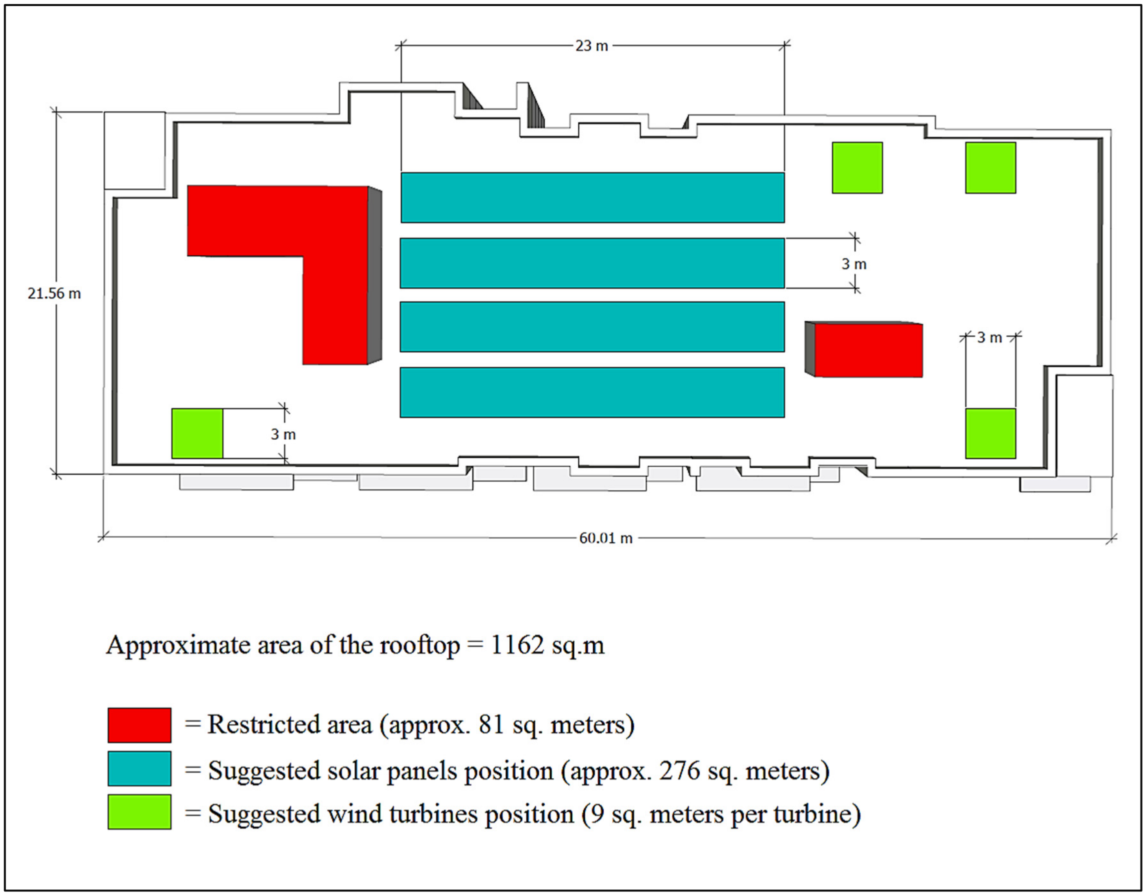


Figure 4-7 Layout of the hybrid wind and solar energy system

The following system configurations will be examined, considering the technology stated in the preceding subsections and the above dimensions. Capacity distribution between each technology is based on building's structural limits, field measurements, optimization factors and operational simplicity.

1. 2x 5kW wind turbine and 80kW of installed solar photovoltaic (90kW total)
2. 4x 5kW wind turbine and 80kW of installed solar photovoltaic (100kW total)
3. 9x 5kW wind turbine and 45kW of installed solar photovoltaic (90kW total)
   This scenario is presented as a reference point only and will not be used to investigate in different locations, since such a configuration is not technically and economically feasible for this case study.

CHAPTER 5

METHODOLOGY APPLICATION AND RESULTS

5.1 Introduction for Energy Calculation

Estimates of energy production for each of the defined system configurations that are analyzed by RETScreen are presented in this chapter. As stated in earlier sections, the data gathered and analyzed by RETScreen software is on a daily and monthly average basis, and as such estimations could not be shown in daily hourly amounts during energy production. Accordingly, the total estimated energy generated in one month is presented.

Furthermore, the amount of energy produced is compared to the building's base load, and the maximum initial investment and resulting cost per MWh are shown for each system.

5.2 Photovoltaic System Results

This section shows the RETScreen estimated solar photovoltaic energy production using the methodology described in the previous chapter.

Important data, such as daily solar irradiance on a horizontal surface, are extracted from the NASA database, and to calculate daily solar radiation on the PV flat face, angles of azimuth and elevation of the PV panels are introduced into the software for the most optimum production.

Table 5-1 shows the solar radiation at the site as well as the solar PV system's estimated monthly energy generation. Table 5-2 provides an overview of the hybrid system's solar PV component, while Table 5-3 provides an annual overview of efficiency and energy generation.

Table 5-1 Available solar resources and output of the proposed system

	Daily solar radiation – horizontal kWh/m²/d	**Daily solar radiation – 37 ° Slope kWh/m²/d**	**Estimated Generated Energy MWh (Tilted)**
January	1.52	2.79	7.1281
February	2.43	3.88	8.8348
March	3.57	4.60	11.2827
April	4.41	4.72	10.8835
May	5.34	5.18	11.9688
June	5.77	5.35	11.7277
July	5.85	5.54	12.3536
August	4.84	4.96	11.158
September	3.74	4.37	9.7181
October	2.31	3.16	7.5099
November	1.29	1.98	4.7235
December	1.11	2.00	5.0803
Annual	3.5208	4.0438	112.369

Table 5-2 Photovoltaic module specification data

Type	Mono-Si
Power capacity (kW)	80
Manufacturer	LG Solar
Model	LG435QAC-A6
Number of units	184
Efficiency (%)	21.9%
Nominal operating cell temperature (°C)	45
Temperature coefficient (%/°C)	0.4%
Solar collector area (m^2)	365
Miscellaneous losses (%)	1%

Table 5-3 Summary of annual PV production

Overview		
Capacity factor	%	16
Electricity delivered to load	MWh	112,369

Table 5-1 represents the energy production amounts by the solar PV system in relation to the amount of solar radiations in horizontal and tilted formats. These energy quantities have been calculated by RETScreen according to the specifications of the proposed system for each month as well as the annual amount in MWh by linking the solar radiation values derived from climatology information of the studied location. July has the highest amount of solar radiation in both horizontal and tilted forms, with corresponding values of 5.85 and 5.54 kW per square meter per day. Because of this power peak in radiations, the PV system produces the most energy this month.

Based on the research findings and the annual average of radiation of 3.52 kWh/m^2 per day, the period between March and September produced more energy than the median line. This confirms the photovoltaic system promising energy production during the summer season. In contrast, the lowest amount of radiation occurs between October and February, with a minimum value of 1.11 kWh/m^2 per day in December.

Table 5-2 shows the technical specifications of the studied solar PV system, which has a module efficiency of 21.9% and an installation area of 365 square meters. Table 5-3 estimates 112.369 megawatt hours of energy for one year based on the technical specifications in Table 5-2 and the energy production values in Table 5-1.

In addition, a capacity factor of 16% was obtained, implying that 16% of the system's nominal capacity was converted into energy in one year.

5.3 Wind Energy System – Set of Two and Four Turbines

This section shows the RETScreen estimated wind energy generation using the methodology described regarding the wind energy calculation in the previous chapter. The primary inputs of the calculations are the average wind speed measured at the nearest meteorological station for each month of the year, which is then processed through power curve data and specifications of the Tesup wind turbine to estimate the monthly and annual amount of energy production. Thus, the output multiplies by the number of installed turbines. The advantage of using several turbines is that the output fluctuations of the total wind energy project are reduced, and they may lower the cost of per kW power. Table 4-5 shows the average monthly wind speed and the estimated production amount of both wind energy systems with two and four turbines. An overview of the settings for wind turbine components can be found in Table 5-5, while Table 5-6 differentiates the annual energy production of each system.

Table 5-4 Available wind resources and output of the proposed systems

	Wind speed m/s	2X turbine - generated energy MWh	4X turbine - generated energy MWh
January	4.7	2.1033	4.2067
February	4.5	1.7817	3.5634
March	4.5	1.9239	3.8477
April	4.5	1.8048	3.6096
May	3.9	1.4924	2.9848
June	3.9	1.4175	2.8351
July	3.3	1.1654	2.3308
August	3.1	1.0791	2.1582
September	3.3	1.1563	2.3126
October	3.9	1.5213	3.0426
November	4.5	1.8358	3.6715
December	4.5	1.9591	3.9182
Annual	4.1	19.2407	38.4813
Measured at	10 m		
Wind shear component	0.4		

Table 5-5 Wind turbine specification data

Power capacity per turbine (kW)	5
Manufacturer	TESUP
Model	MAGNUM
Number of turbines	2 and 4
Power capacity (kW)	10 and 20
Hub height (m)	20
Rotor diameter per turbine (m)	2.5
Swept area per turbine (m^2)	19.6
Energy curve data	Standard
Shape factor	2

Table 5-6 Wind turbine summary with two and four units

Overview		
Number of turbine	2	4
Capacity factor	22 %	22 %
Electricity delivered to load	19.2407 MWh	38.4813 MWh

Table 5-4 represents the energy production amounts from wind turbine systems of two and four units, in relation to the averaged wind speed. These energy generation quantities have been calculated by RETScreen according to the system configurations and wind speed values derived from weather information databases. Output results are in MWh and are on monthly and annual basis. The highest value of wind speed occurs in January, implying the highest amount of power generation from wind in this month. According to these data, the average wind speed per year is 4.1 m/s. Table 5-4 also shows that a period between November to April have winds that are faster than the annual average, which peaks in January. This justifies that highest amounts of wind energy generated are related to the coldest months of the year. On the other hand, the Wind energy production is unfavorable from July to September due to lower wind speeds than the rest of the year. August has the lowest at 3.1 meters per second and the system produces the least amount of energy in this month. The total energy produced by system equipped with two wind turbines is estimated to be 19.24 megawatt hours and system with four wind turbines generates 38.48 MWh. Both systems carry a capacity factor of 22% (see Table 5-6).

5.4 Climate Data Graphs of the Study

The wind and solar data based on which the research was conducted are shown in the Figures 5-1a and 5-1b. This information includes the distribution of wind speed and direction in percentage, as well as averaged solar radiation and temperature over the course of the year. Raw data derived from Environment and natural resources of Canada. The analysis of Figure 5-1a, which illustrates wind speed, direction, and probability of occurrence, shows that the prevailing direction of the wind is from the southwest to the northeast of Montreal most of the time. Following that, the southeast to northwest direction has a great chance for wind to blow. This diagram also supports the significant potential of the wind energy in the area.

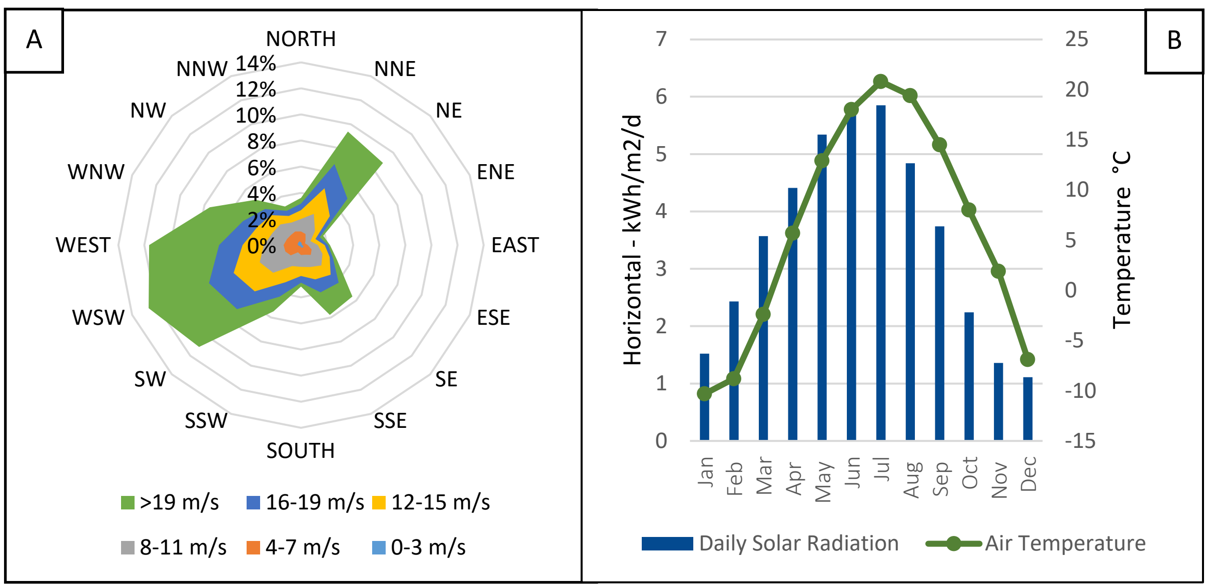


Figure 5-1 (a) Wind direction in Montreal based on data from 1983 to 2020 (b) Monthly solar radiation and temperature

Figure 5-1b displays the average temperature and solar irradiation, with January being the coldest month (-10.3°C) and July being the warmest (20.8°C). In addition, the highest amount of solar radiation occurred in July 5.85 kilowatt hours per square meter and the lowest solar irradiance is recorded in December 1.11 kilowatts per square meter per day. The energy production profile of the PV system should follow this pattern throughout the year.

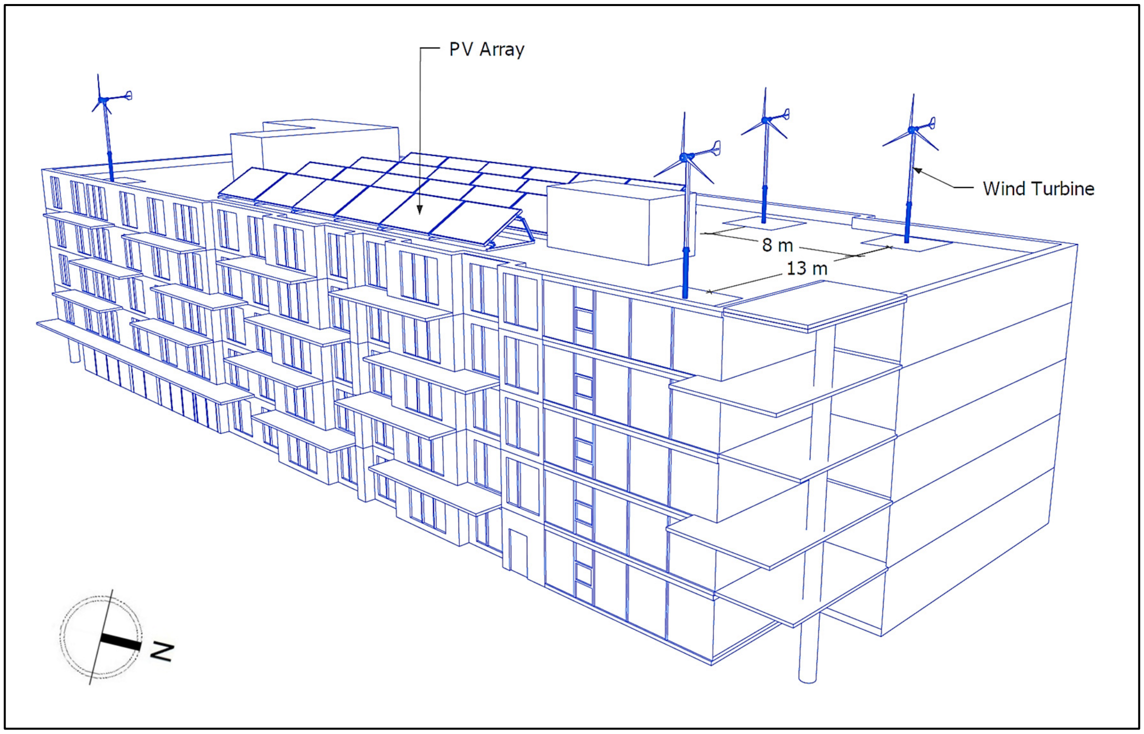


Figure 5-2 Location of the wind turbines on top of the MURB

Each turbine produces a wake that affects downstream turbines, which causes issues such as production loss, blade loading, and fluctuating electrical output. By using the wind direction and its distribution information of the area, the correct placement of each wind-turbine is verified. Winds from the northeast direction, can align rear turbines in a straight line. Due to the space constraint these turbines have close placement with each other which may affect production output. It is estimated that mixing wakes from turbine blades occurs at approximate distance of $1.6 \times Turbine\ Diameter$ (Michael McKinnon, 2019). In this study, the turbulent wakes merge at a distance of 4 meters, with a diameter of 2.5 meters. As shown in Figure 5-2, 8 meters is the shortest lateral separation between wind turbines, ensuring no disruption from wakes of surrounding turbines.

5.5 Electricity Production, Demand and Income

Table 5-7 shows that System 2 is estimated to cover 75.6% of the average load base in June and has slightly better energy production capability throughout the year. Both systems are expected to meet a portion of the MURB's demand shown in Table 5-10 for each month. System 1 can meet 31.20% of the average load base, while System 2 can meet 35.05% of demand.

As shown in Table 5-7, System 2 is capable to produce more electricity than System 1 by having two more wind turbines. The largest difference between production and demand occurred in February, while the greatest demand coverage occurred in July. This means that most of the energy consumption in this MURB is for heating purposes, which is at minimal level in the summer. In the best of these results, system 2 supplied approximately 76% of building demand in July, while system 1 supplied 70% in the same month. In general, system 2 will supply the required load 3.85% better than system 1 over the course of a year.

Table 5-7 Daily variations in power production and demand

Month	Avg. Daily Generated Load in kW		Recorded Consumed Based Load (kW)	Difference in kW		Demand Coverage in %		
	System 1	System 2		System 1	System 2	System 1	System 2	Diff.
Jan	12.40	15.24	109.83	97.43	94.59	11.30	13.90	2.6
Feb	15.8	18.45	118.39	102.59	99.94	13.35	15.6	2.25
Mar	17.75	20.34	82.25	64.50	61.91	21.6	24.73	3.13
Apr	17.62	20.13	60.00	42.38	39.87	29.37	33.55	4.18
May	18.10	20.10	54.19	36.09	34.09	33.4	37.1	3.7
Jun	18.26	20.23	54.00	35.74	33.77	33.81	37.47	3.66
Jul	18.17	19.74	26.12	7.95	6.38	69.6	75.6	6
Aug	16.45	17.90	26.12	9.67	8.22	62.98	68.53	5.55
Sep	15.10	16.71	26.50	11.40	9.79	56.99	63.06	6.07
Oct	11.76	13.74	49.68	37.92	35.94	23.68	27.66	3.98
Nov	9.50	12.12	100.65	91.15	88.53	9.44	12.04	2.6
Dec	9.46	12.10	106.93	97.47	94.83	8.85	11.32	2.47
Annual	**15.03**	**17.23**	**67.88**	**52.85**	**50.65**	**31.20**	**35.05**	**3.85**

In December, both system generations are at their minimum capacity, which is 8.85% for system 1 and 11.32% for system 2. Furthermore, the demand is highest in February and lowest in July and August, with a size of 26.12 kW. System 2 outperforms System 1 in terms of energy production, producing an additional 2.2 kilowatts per month on average.

Table 5-8 Monthly power production and income at Quebec price 0.073$/kWh

Month	System 1 – 90kW nominal power		System 2 – 100kW nominal power	
	Energy Produced (kWh)	Potential Savings (CAD) @ $0.073 kWh	Energy Produced (kWh)	Potential Savings (CAD) @ $0.073 kWh
Jan	9,231	674	11,335	828
Feb	10,616	775	12,398	905
Mar	13,206	964	15,131	1,105
Apr	12,687	926	14,493	1,058
May	13,461	983	14,953	1,092
Jun	13,145	960	14,563	1,064
Jul	13,518	987	14,684	1,072
Aug	12,237	893	13,316	973
Sep	10,874	794	12,031	879
Oct	8,749	639	10,223	747
Nov	6,840	499	8,727	637
Dec	7,039	514	9,000	657
Annual	131,603 kWh	$9,607	150,854 kWh	$11,013

Table 5-9 Monthly power production and income at Canada average price 0.179$/kWh

Month	System 1 – 90kW nominal power		System 2 – 100kW nominal power	
	Energy Produced (kWh)	Potential Savings (CAD) @ $0.179 kWh	Energy Produced (kWh)	Potential Savings (CAD) @ $0.179 kWh
Annual	134,874 kWh	$24,143	153,360 kWh	$27,452

Table 5-8 and 5-9 depicts the impact of both systems in terms of annual income when comparing with the cost of electricity in Quebec and the average cost of electricity across Canada. System 2 saves around $1406 more annually than System 1 does at the current electricity pricing of $0.073 per kilowatt hour. While this difference is about $3,500 at $0.179 for each kWh. The month of May saw the highest amount of energy production for both systems, with 13461 kilowatt hours for system 1 and 14953 kilowatt hours for system 2.

As a result, the savings from not importing electricity from the grid at a price of $0.073/kWh in Quebec will be assumed. Table 5-9 highlights the financial savings at 17.9 cents per kilowatt hour rate, when the system produces the energy output that is averaged across Canadian regions.

The average amount of energy produced and related cost savings are determined by relocating the MURB into the most populated city in each Canadian province (Fig 5-3). The Canada average-price is resulted by recalculating monthly energy generation based on specific regional weather conditions and different geographic coordinates of each province. Energy data regarding each month can be found in Appendix VI for all Canadian provinces.

System 1 has a nominal capacity of 90 kilowatts and can produce approximately 132 thousand kilowatt hours per year, while System 2 has a nominal capacity of 100 kilowatt hours and can produce approximately 151 thousand kilowatt hours in Montreal.

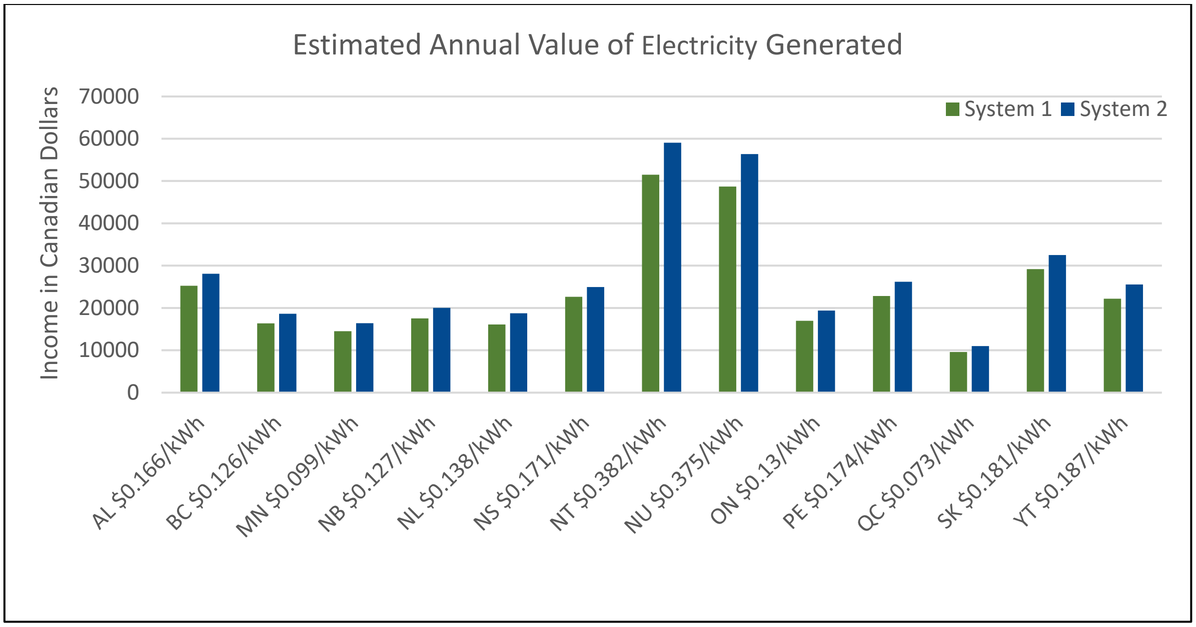


Figure 5-3 Annual savings of the proposed systems when relocated into a different Canadian province. Electricity rates derived from provincial power companies, refer to Appendix VI for monthly power production results of each province

Figures 5-3 and 5-4 indicate the revenue these systems would save if the MURB were situated in a different province or state, while system performance is calculated according to the local climatology of each region. This includes all provinces in Canada, as well as neighboring U.S states with comparable climate. Quebec has the lowest electricity rates among them. Appendix VI shows the electricity production for each month of the year in all locations.

Figure 5-3 illustrates a comparison of the energy system production based on each province electricity tariffs. Here, using the data of energy production in each region, how much could be saved on the utility bill, if the residential building under study were situated in a different province. When electricity production and rates in Canadian provinces are compared, Quebec has the lowest, with $9,607 in system 1 and $11,012 in system 2. The Northern Territories will save the most, with $59,036 in system 2 and $51,502 in system 1, owing to the high cost of energy carriers in this province. If this hybrid energy system is located in the neighboring province of Ontario, it could save $19,389 in system 2 and $16,952 in system 1, which, compared to Quebec, is almost $8,000 higher per year.

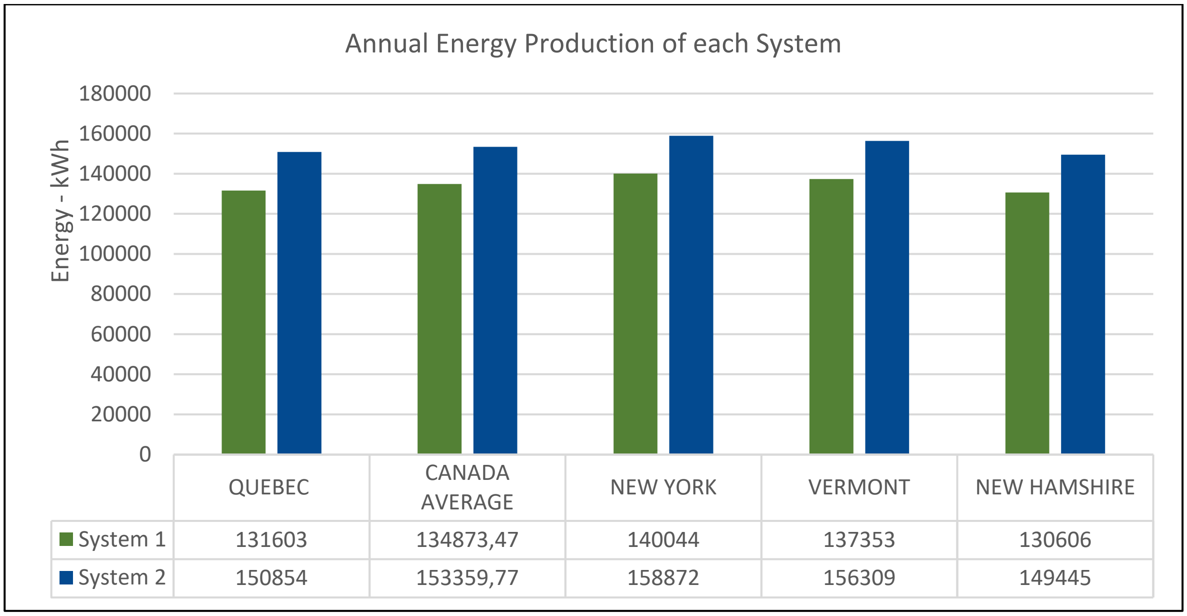
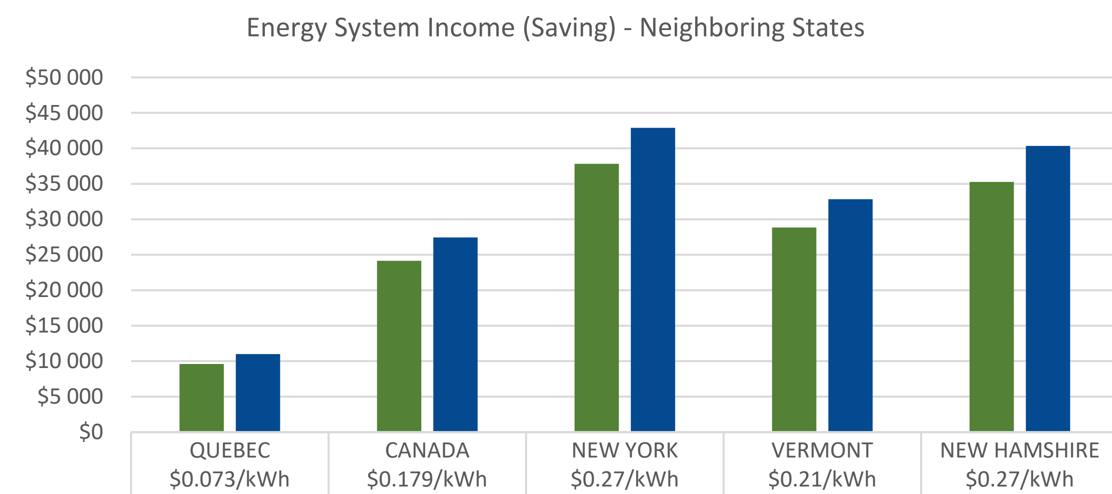


Figure 5-4 the energy production of the suggested systems when placed in the neighboring States is shown in this graph

Graph 5-4 which shows subtle variations in the system's energy generation, is the outcome of relocating the MURB to a site in the most populous city of the selected States. This can be justified given the similarities in climate and geographic coordinate. Despite the energy production results of each site are very close to one another, but incomes varied significantly due to difference in cost of electricity. This affects the return on investment in each region.

Figure 5-5 displays the corresponding cost savings to Fig. 5-4 energy production results for the States surrounding the project. Therefore, the states of New York and New Hampshire, which have the highest electricity rates among the states studied, have the greatest amount of savings. Consequently, they have a slightly shorter payback period (Fig. 5-5). The next-highest rate for power is in Vermont, where it costs $0.21 per kWh, and Canada's average electricity cost ($0.179/kWh) follows. On the other hand, Quebec province has the lowest savings due to its inexpensive electricity cost from readily accessible hydropower source.



	QUEBEC $0.073/kWh	CANADA $0.179/kWh	NEW YORK $0.27/kWh	VERMONT $0.21/kWh	NEW HAMSHIRE $0.27/kWh
System 1	$9 607	$24 142	$37 812	$28 844	$35 264
System 2	$11 012	$27 451	$42 895	$32 825	$40 350

Figure 5-5 Energy income comparison based on system performance in the environment of neighboring States to Quebec. The graph shows the effect of electricity price in correlation to amount of energy produced in each region. The cost of electricity in the nearby States was converted to 1.28 Canadian dollars for every US dollar at the time of this study

5.6 Initial Capital Expenditure for System Installation

The capital expenditure for system procurement is the figure used to compare the proposed configurations. In addition to the electricity production calculations, financial savings and revenue, renewable energy subsidies are used to determine the initial investment to achieve a hurdle rate of 9%. The incentives for renewable energy in Quebec applicable for the proposed systems are limited to exporting surplus power into the Hydro-Québec grid in exchange for credits in kilowatt-hours (Hydro Quebec, 2022). The Canadian government provides a tax incentive for clean energy equipment to fully expense clean energy production. This means a capital cost allowance (CCA) rate of 100% and the abolishment of the first-year rule (Canada Revenue Agency, 2021). The maximum initial investment to achieve a 9% return rate has been calculated for each system using the RETScreen default values for the study location, from the monthly savings from Table 5-8, and the equations highlighted in the methodology. Table 5-10 has shown each technology's respective savings for both system configurations.

Table 5-10 Investment costs and financial viability in Quebec

	System 1 90kW	System 2 100kW
Total Generated Energy (MWh)	131.603	150.854
Lifetime Generated Energy (MWh)	3948.09	4525.62
Hybrid Annual Savings	9,607	11,012
Wind Annual Savings	$1,404	$2,809
Photovoltaic Annual Savings	$8,203	
Initial Wind Investment	$20,000	$40,000
Initial PV Investment	$168,000	
Energy Production Cost from the System	$0.149/kWh	$0.145/kWh
Simple Payback	17.3 yr	16.7 yr
** Prices are in Canadian dollar (CAD)*		

According to the financial analysis of this study, both systems have similar investment payback durations, 17.3 years for system 1 and 16.7 years for system 2. Besides that, system 2 can produce 577 MWh more than system 1 over its lifetime. Which can be viewed as a compensation for the higher initial cost of the wind system.

Table 5-11 Initial cost per kilowatt for each energy technology

	Price per kilowatt ($)	Installed Capacity (kW)	Total Initial Cost
Wind power	2,000	10 / 20	$20,000 / $40,000
Photovoltaic power	2,100	80	$168,000

As confirmed with the manufacturer, the initial purchase cost per kilowatt for each wind turbine is $2000 at the time of study. According to the RETScreen's cost database, each kilowatt of the solar energy costs $2,100 for a system with 80 kW of photovoltaic output (Table 5-11).

5.7 Reference Configuration, Energy Production

Table 5-12 presents the result of Scenario III energy generation. This configuration has equal power capacity for each of the technologies used in the study, for use as a comparison indication. The wind power system produces noticeably more energy than the PV system. Table 5-12 indicates that wind power offers 37% more energy compared to a photovoltaic energy system of the same capacity in Montreal. The complexities of implementing such a system have not been considered and this comparison has only been intended to show the resource potential of the region.

Table 5-12 Energy production from Reference scenario in Montreal, Quebec

	Capacity (kW)	Electricity (MWh)	Initial Costs ($)
Wind turbine	45	86.6	90,000
Photovoltaic	45	63.2	94,500
Total	90	150	184,500

CHAPTER 6

DISCUSSION AND ANALYSIS

Because the system was sized based on space constraints, load demand, and capital investment considerations, the simulated results obtained in the previous chapter show that the system successfully covered one-third of the MURB's energy demand throughout the year.

The cost of energy production in this project is lower than the average cost of energy in Canada (Fig. 5-5 and Table 5-12). The project promises a return on initial investment in 16.7 years and amount of $0.145 for each kilowatt hour of generated energy over the system's 30-year life time. Feasibility of the system is greatly dependent on the availability of renewable resources and it was observed that areas with similar climatic conditions produce similar amounts of energy while the system is unchanged. However, those locations that were studied with less capacity for energy production are compensated for by higher energy costs. In terms of the maximum investment required to achieve a 9% hurdle rate, the system that produces more power through wind turbines appears to be more feasible. The ratio between sizing of wind and PV energy systems could be used as a model for freshly built multi-unit residential buildings because it is optimized to partially meet the load demand.

In terms of resource potential, the selected building appears to be better suited to wind power generation than solar power generation when a simulation was executed with both wind and PV systems of the same size. In the event that nominal capacity of the wind and photovoltaic systems were of equal size. The annual energy output from the wind power system could be 1.375 times greater than the photovoltaic energy system. This assertion is valid given the chosen components and location of this study. However, although being less expensive and marginally more efficient, such a wind energy system is not practical due to space limitations, building structural considerations, noise level, turbine wake effect, cost and maintenance as well as environmental factors. This confirms that the proposed photovoltaic system is more feasible and cost effective in this case study. PV system is less complicated to maintain and its rectangular fixtures make them easy to be fitted on the roof area.

The amount of electricity generated by photovoltaic panels and wind turbines follows the trend of the resources, with wind turbines producing more in the winter months and solar panels producing more in the summer. Wind turbines nevertheless produce a sizable amount of power in the summer when compared to the solar PV energy produced in the winter. Due to the low cost of energy in the province of Quebec, such an energy system has the lowest income from production and is not cost effective in this province. Not to mention that a battery bank would not be an effective means to store electricity for later use because there was never a time when the proposed system produced excess energy. The system's connectivity to the power grid and the high cost of purchasing a battery storage unit of a suitable size will therefore corroborate the statement of inefficiency. Meanwhile, areas with higher energy costs and similar climatology to this province are better areas to place this system from an economic point of view.

This is despite the fact that a government subsidy is available for solar but not wind. If the Canadian government implements a wind and solar PV incentive program, wind and solar PV systems may become more affordable in the future. If this is the case, a hybrid solar PV and wind system may become a more financially viable solution than current estimates.

CONCLUSION AND PERSPECTIVE

- Conclusion

The objective of this thesis was to determine to what extent a hybrid renewable energy system can meet the energy demand of a multi-unit residential building (MURB) in all Canadian provinces where most populated urban areas are located. A newly constructed building located in Montreal metropolitan area used as a model for this study. American states of Vermont, New Hampshire and New York were also added due to similarities in climatic conditions to where the study is centered. The clean energy management tool RETScreen is used to model different scenarios as well as the financial feasibility of a building-integrated wind/PV hybrid energy system. The investigation was accompanied by unavoidable realistic limitations such as space constraints, load demand, and capital investment considerations, which led to the methodology improvement and, subsequently, the selection of the proposed configurations. This study has compared the amount of energy produced and the corresponding cost savings across all Canadian provinces and bordering states. It has been assumed that the same building would be relocated to each study area, an energy estimation would then be calculated according to the meteorological data and energy prices of the location.

A literature review was conducted to look into the available solar and wind energy generation technologies, the energy generation software tool RETScreen, and hybrid renewable energy management. In addition, previous studies that investigated the potential of energy generation using small-scale wind and solar power and combined wind/solar power systems have been cited. Following that, a methodology based on the case study inputs was developed. First, the monthly energy consumption of the building was determined employing Hydro Quebec utility bills. Using this information, and the physical dimensions of the MURB's roof top, two configurations of hybrid wind and solar PV energy system with varying capacity ratios, and an equally sized reference system were proposed. The systems were proposed in such a way that, according to the base load and the limited space available, they produce the highest power possible for the least investment cost.

Computer analysis was performed using RETScreen software in accordance with components specification and climatology data from NASA and Natural Resources Canada.

The potential financial savings were calculated assuming that the electricity generated by the system was consumed rather than purchased from the grid, with excess energy exported back into the network. According to this principle and the investment cost marketplace of renewable energy technologies, the median costs that would satisfy a 9% hurdle rate were calculated. The system with the $0.145 cost per kWh produced over 30-years life span considered to be the most feasible, despite the differences are insignificant.

Both proposed systems covered more than a third of the building's energy needs over the course of the year. In July, the system with more wind capacity met more than 75% of the load demand and produced 3.85% more annual energy than the other system. In this study, no extra energy was generated. The system with the highest wind power capacity was found to be the most feasible. When wind and solar technologies are sized equally in the reference scenario, it is evident that wind power is likely to generate more energy than solar PV in the Montreal area. Due to the building's flat rooftop and structural challenges with securing wind turbines on the roof, solar PV was determined to be the most financially feasible and advantageous option for the site evaluated in this case study. Sum up, the system configuration with more hybrid renewable energy produced 151 MWh of energy per year for the assessed site. It was found that location and climatology have meaningful effect on renewable energy system production and revenue as stated in the literature review. However, financial return for sites with least potential for energy production are compensated for by higher energy costs.

- **Perspective**

This Thesis work showed that wind-solar renewable resources have adequate potential to partially supply energy demand of a Multi-Unit Residential Building in Montreal. The analysis tool, RETScreen has a meticulous method for energy saving with different factors involved. It has been recommended that if this work is to be pursued further, a system equipped with an energy storage system (battery bank) should be investigated to increased independence from the power grid. This will provide the consumer with better power quality and extended reliability. Due to the limited availability of data in RETScreen, the forecasted daily electricity produced from wind and solar resources was averaged over a 24-hour period. As a result, it is suggested to have anemometers and pyranometers installed above the roof surface to measure actual wind speed and solar irradiance resources for minimum of one year with 30 minutes intervals. This will provide a better understanding of wind and solar resource availability on a daily, weekly, and monthly basis. Also, the effect of wake turbulence from surrounding obstacles and snow-covered photovoltaic panels can be covered in future study.

As a supplement to this work and to create a customized load profile, the proposed building could be equipped with an online metering system to keep a record of actual electricity consumptions, peak and base load readings. It should be noted that default software values were used for system operation and maintenance costs, and there is room to investigate this issue further. This study did not take into account concerns such as urban planning permits, noise, and vibration which may affect building's residents. Additionally, an analysis of the annual emissions that could have been avoided by implementing this renewable energy system can be conducted. Much work remains to be done concerning performance optimization, implementing newer technologies and energy management techniques for the current study.

APPENDIX I

ELECTRICITY CAPACITY FROM PRIMARY SOURCES OF ENERGY

- Distribution of primary fuel sources in Canada and Quebec province

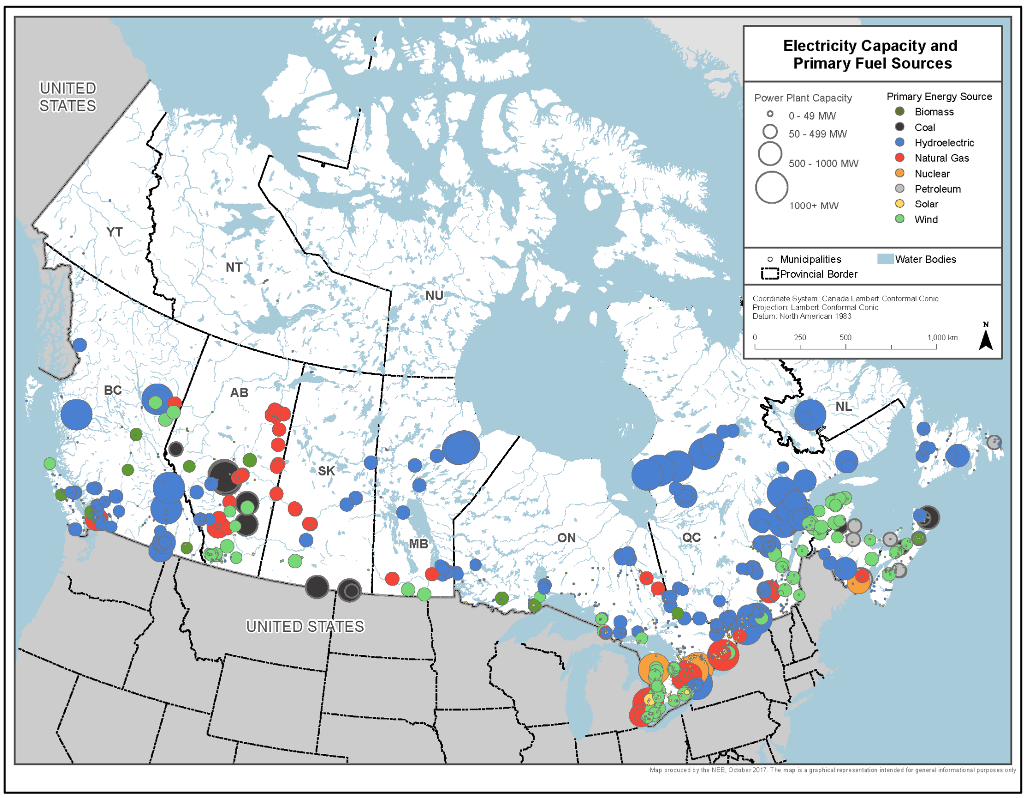


Figure-A I-1 Electricity capacity and primary fuel sources in Canada

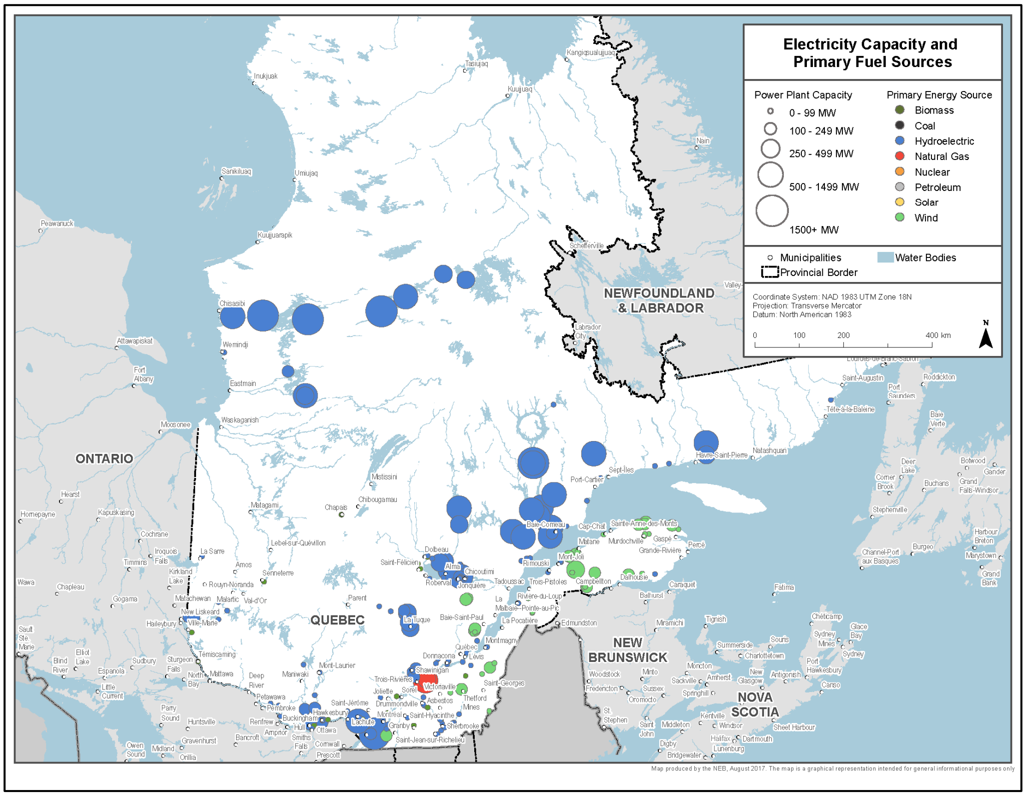


Figure-A I-2 Electricity capacity and primary fuel sources in Quebec

APPENDIX II

DATASHEET OF ZENIA 10KW WIND TURBINE

- 10kW wind turbine information

Special ZENIA options:
- Data transfer via GPRS
- On-line surveillance of turbine
- View your data on PC or smart phone
- Easy installation and service

Controller
Orbital (DK)

Gear
Benzler (SE)

Generator
VEM (D)

Wings
Olsen Wings (DK)

ZENIA WIND 10kW	
Type	Upwind
Effect (kW)	10
Voltage (V)	3 X 400
Generator type	4-pole generator
Estimated yearly production (kWh)	Up til 30.000
Wings (stk.)	3
Hub height (m)	18
Rotor diameter (m)	7,1
Swept area (m^2)	39,98
Start-/min. productionswind (m/s)	3,0/1,8
Cut out wind speed (m/s)	30
Survival wind speed (m/s)	70
Norminal RPM	110
Nacelle weight (t)	0,5
Tower type	Galvanised tube tower, sectioned
Foundation (m^3)	10
Yaw system	Electronic
Lifting/Service	Hydraulic tilt function
Safety	Fail-safe brake system / Tip brake
Noise (db)	From 35

Figure-A II-1 Danish build Zenia Energy 10kW wind turbine specifications

APPENDIX III

DATASHEET OF TESUP ENERGY 5KW WIND TURBINE

- **5kW wind turbine information**

4.1 PARAMETER & DIMENSIONAL DETAILS

TESUP DANGER UP TO 120V DURING STORMS

SPECIFICATIONS	
DESIGNATION	12V to 48V
GENERATOR	
TYPE	5KW horizontal axis wind permanent magnet generator
WEIGHT	10kg (22lbs)
MAX. POWER	5kW
OPERATING CIRCUIT VOLTAGE	0-100V
CURRENT	3-Phase
START OF CHARGING	3m/s
BASE PLATE MATERIAL	Metal
DIRECTION OF ROTATION	Clockwise
TEST STANDARDS	EN 61000-6-1 (electromagnetic compatibility – immunity) EN 61000-6-3 (electromagnetic compatibility – emissions)
ROTOR BLADES	
MATERIAL	Composites
HUB FLANGE	Aluminum
DIAMETER	2500 mm (8.2 Feet)
WEIGHT PER ROTOR BLADES	200 g (0.44 lbs)
DIRECTION OF ROTATION	Counter-Clockwise
STARTING WIND SPEED	3 m/s
NO. OF BLADES	3
MAX RPM	1500
MAX SPEED	50m/s
NOISE	35 dB

Figure-A III-1 Tesup 5kW wind turbine specifications

APPENDIX IV

DATASHEET OF THE SOLAR MODULES LG AND CANADIAN SOLAR

- Solar panels information

LG NeON®R

LG435QAC-A6 Preliminary

66

435W

LG NeON® R is powerful solar module that provides world-class performance. A new cell structure that eliminates electrodes on the front maximizes the utilization of light and enhances reliability.

LG NeON® R is a result of LG's efforts to increase customer's values beyond efficiency. LG NeON® R features enhanced durability, performance under real-world conditions, an enhanced warranty and aesthetic design suitable for roofs.

25 YEAR PRODUCT • PERFORMANCE • LABOR WARRANTY

Features

Roof Aesthetics

LG NeON® R has been designed with aesthetics in mind: the lack of any electrodes on the front creates an improved, modern aesthetic.

25-Year Limited Product Warranty

The NeON® R is covered by a 25-year limited product warranty. In addition, up to $450 of labor costs will be covered in the rare case that a module needs to be repaired or replaced.

Enhanced Performance Warranty

The LG NeON® R has an enhanced performance warranty. After 25 years, LG NeON® R is guaranteed at least 92.5% of initial performance.

More generation per square meter

The LG NeON® R has been designed to significantly enhance its output, making it efficient even in limited space.

When you go solar, ask for the brand you can trust: LG Solar

About LG Electronics USA, Inc.

LG Electronics is a global leader in electronic products in the clean energy markets by offering solar PV panels and energy storage systems. The company first embarked on a solar energy source research program in 1985, supported by LG Group's vast experience in the semi-conductor, LCD, chemistry and materials industries. In 2010, LG Solar successfully released its first MonoX® series to the market, which is now available in 32 countries. The NeON® (previous MonoX® NeON), NeON®2, NeON®2 BiFacial won the "Intersolar AWARD" in 2013, 2015 and 2016, which demonstrates LG's leadership and innovation in the solar industry.

LG Life's Good

Figure-A IIV-1 LG solar panel information

LG NeON®R

Preliminary

LG435QAC-A6

General Data

Cell Properties (Material/Type)	Monocrystalline / N-type
Cell Maker	LG
Cell Configuration	66 Cells (6 x 11)
Module Dimensions (L x W x H)	1,910mm x 1,042mm x 40mm
Weight	20.5 kg
Glass (Material)	Tempered Glass with AR Coating
Backsheet (Color)	White
Frame (Material)	Anodized Aluminium
Junction Box (Protection Degree)	IP 68 with 3 Bypass Diodes
Cables (Length)	1,250mm x 2EA
Connector (Type/Maker)	MC 4 / MC

Certifications and Warranty

Certifications**	IEC 61215-1/-1-1/2 : 2016, IEC 61730-1/2: 2016, UL 61730-1 : 2017, UL 61730-2 : 2017
	ISO 9001, ISO 14001, ISO 50001
	OHSAS 18001
Salt Mist Corrosion Test	IEC 61701:2011 Severity 6
Ammonia Corrosion Test	IEC 62716 : 2013
Hail Test	25mm (1") diameter at 23m/s (52mph)
Module Fire Performance	Type 1 (UL 61730)
Fire Rating	Class C (UL 790, ULC / ORD C 1703)
Solar Module Product Warranty	25 Years
Solar Module Output Warranty	Linear Warranty*

*Improved: 1st year 98.5%, from 2-24th year: -0.25%/year down, 92.5% at year 25
**In Progress

Temperature Characteristics

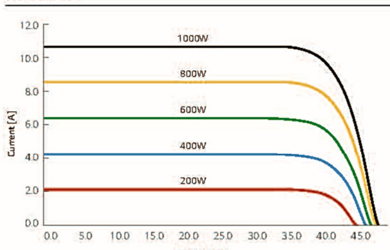
NMOT*	[°C]	44 ± 3
Pmax	[%/°C]	-0.29
Voc	[%/°C]	-0.24
Isc	[%/°C]	0.04

*NMOT (Nominal Module Operating Temperature): Irradiance 800 W/m², Ambient temperature 20°C, Wind speed 1 m/s, Spectrum AM 1.5

Electrical Properties (NMOT)

Model		LG435QAC-A6
Maximum Power (Pmax)	[W]	330
MPP Voltage (Vmpp)	[V]	38.8
MPP Current (Impp)	[A]	8.49
Open Circuit Voltage (Voc)	[V]	45.8
Short Circuit Current (Isc)	[A]	9.02

I-V Curves



Electrical Properties (STC*)

Model		LG435QAC-A6
Maximum Power (Pmax)	[W]	435
MPP Voltage (Vmpp)	[V]	41.1
MPP Current (Impp)	[A]	10.59
Open Circuit Voltage (Voc,± 5%)	[V]	48.0
Short Circuit Current (Isc,± 5%)	[A]	11.20
Module Efficiency	[%]	21.9
Power Tolerance	[%]	0 ~ +3

*STC (Standard Test Condition): Irradiance 1000 W/m², Cell temperature 25°C, AM 1.5
Measure Tolerance: ± 3%

Operating Conditions

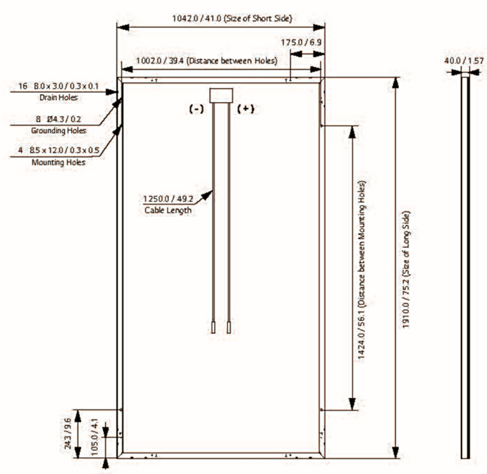
Operating Temperature*	[°C]	-40 ~ +85
Maximum System Voltage	[V]	1,000
Maximum Series Fuse Rating	[A]	20
Mechanical Test Load** (Front)	[Pa/psf]	5,400
Mechanical Test Load** (Rear)	[Pa/psf]	4,000

*The operating ambient temperature of these devices may exceed 40°C at full load for all wire sizes if is determined suitable in the field use application.
**Based on IEC 61215-2 : 2016 (Test Load = Design Load x Safety Factor (1.5))

Packaging Configuration

Number of Modules per Pallet	[EA]	25
Number of Modules per 40' Container	[EA]	600
Number of Modules per 53' Container	[EA]	TBD
Packaging Box Dimensions (L x W x H)	[mm]	1,960 x 1,120 x 1,221
Packaging Box Dimensions (L x W x H)	[in]	77.2 x 44.1 x 48.1
Packaging Box Gross Weight	[kg]	549
Packaging Box Gross Weight	[lb]	1,210

Dimensions (mm/inch)



LG Life's Good

LG Electronics USA, Inc.
Solar Business Division
2000 Millbrook Drive
Lincolnshire, IL 60069
www.lg-solar.com

Product specifications are subject to change without notice.
LG435QAC-A6.pdf
121020

Figure-A IIV-2 LG solar panel specifications

CanadianSolar

HiKu

HIGH POWER MONO PERC MODULE

435 W ~ 465 W

CS3W-435|440|445|450|455|460|465MS

MORE POWER

26 % more power than conventional modules

Up to 4.5 % lower LCOE
Up to 2.7 % lower system cost

41°C
Low NMOT: 41 ± 3 °C
Low temperature coefficient (Pmax): -0.34 % / °C

Better shading tolerance

MORE RELIABLE

Lower internal current, lower hot spot temperature

Minimizes micro-crack impacts

Heavy snow load up to 5400 Pa, wind load up to 3600 Pa*

* For detailed information, please refer to Installation Manual.

12 Years — **Enhanced Product Warranty on Materials and Workmanship***

25 Years — **Linear Power Performance Warranty***

1st year power degradation no more than 2%
Subsequent annual power degradation no more than 0.55%

*According to the applicable Canadian Solar Limited Warranty Statement.

MANAGEMENT SYSTEM CERTIFICATES*

ISO 9001:2015 / Quality management system
ISO 14001:2015 / Standards for environmental management system
ISO 45001: 2018 / International standards for occupational health & safety

PRODUCT CERTIFICATES*

IEC 61215 / IEC 61730 / CE / MCS / INMETRO / UKCA
FSEC (US Florida) / UL 61730 / IEC 61701 / IEC 62716
UNI 9177 Reaction to Fire: Class 1 / Take-e-way

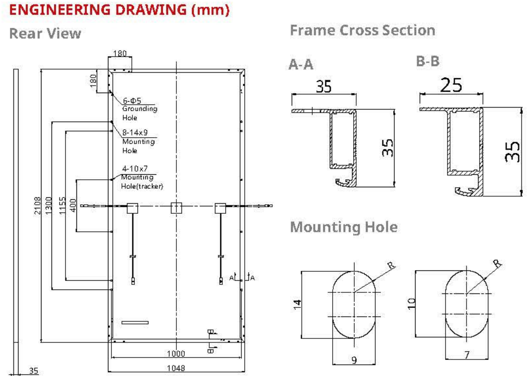
* The specific certificates applicable to different module types and markets will vary, and therefore not all of the certifications listed herein will simultaneously apply to the products you order or use. Please contact your local Canadian Solar sales representative to confirm the specific certificates available for your product and applicable in the regions in which the products will be used.

CSI Solar Co., Ltd. is committed to providing high quality solar photovoltaic modules, solar energy and battery storage solutions to customers. The company was recognized as the No. 1 module supplier for quality and performance/price ratio in the IHS Module Customer Insight Survey. Over the past 20 years, it has successfully delivered over 70 GW of premium-quality solar modules across the world.

CSI Solar Co., Ltd.
199 Lushan Road, SND, Suzhou, Jiangsu, China, 215129, www.csisolar.com, support@csisolar.com

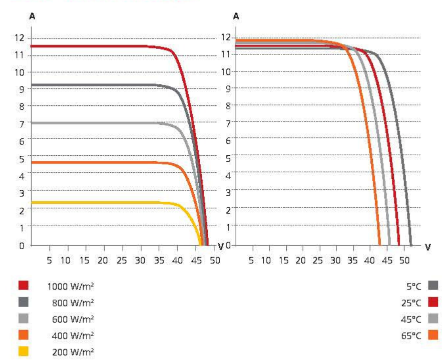
Figure-A IIV-3 Canadian solar panel information

ENGINEERING DRAWING (mm)



Length: ±2mm Width: ±2mm
Height: ±1mm Row Pitch: ±2mm

CS3W-435MS / I-V CURVES



ELECTRICAL DATA | STC*

CS3W	435MS	440MS	445MS	450MS	455MS	460MS	465MS
Nominal Max. Power (Pmax)	435 W	440 W	445 W	450 W	455 W	460 W	465 W
Opt. Operating Voltage (Vmp)	40.5 V	40.7 V	40.9 V	41.1 V	41.3 V	41.5 V	41.7 V
Opt. Operating Current (Imp)	10.75 A	10.82 A	10.89 A	10.96 A	11.02 A	11.09 A	11.16 A
Open Circuit Voltage (Voc)	48.5 V	48.7 V	48.9 V	49.1 V	49.3 V	49.5 V	49.7 V
Short Circuit Current (Isc)	11.42 A	11.48 A	11.54 A	11.60 A	11.66 A	11.72 A	11.78 A
Module Efficiency	19.7%	19.9%	20.1%	20.4%	20.6%	20.8%	21.0%
Operating Temperature	-40°C ~ +85°C						
Max. System Voltage	1500V (IEC/UL) or 1000V (IEC/UL)						
Module Fire Performance	TYPE 1 (UL 61730 1500V) or TYPE 2 (UL 61730 1000V) or CLASS C (IEC 61730)						
Max. Series Fuse Rating	20 A						
Application Classification	Class A						
Power Tolerance	0 ~ + 10 W						

* Under Standard Test Conditions (STC) of irradiance of 1000 W/m², spectrum AM 1.5 and cell temperature of 25°C.

MECHANICAL DATA

Specification	Data
Cell Type	Mono-crystalline
Cell Arrangement	144 [2 X (12 X 6)]
Dimensions	2108 X 1048 X 35 mm (83.0 X 41.3 X 1.38 in)
Weight	24.3 kg (53.6 lbs)
Front Cover	3.2 mm tempered glass with anti-reflective coating
Frame	Anodized aluminium alloy
J-Box	IP68, 3 bypass diodes
Cable	4 mm² (IEC), 12 AWG (UL)
Cable Length (Including Connector)	500 mm (19.7 in) (+) / 350 mm (13.8 in) (-) or customized length*
Connector	T6 or T4 series or MC4-EVO2
Per Pallet	30 pieces
Per Container (40' HQ)	660 pieces

* For detailed information, please contact your local Canadian Solar sales and technical representatives.

ELECTRICAL DATA | NMOT*

CS3W	435MS	440MS	445MS	450MS	455MS	460MS	465MS
Nominal Max. Power (Pmax)	326 W	330 W	334 W	338 W	341 W	345 W	349 W
Opt. Operating Voltage (Vmp)	38.0 V	38.2 V	38.3 V	38.5 V	38.7 V	38.9 V	39.1 V
Opt. Operating Current (Imp)	8.59 A	8.65 A	8.71 A	8.76 A	8.82 A	8.87 A	8.92 A
Open Circuit Voltage (Voc)	45.8 V	46.0 V	46.2 V	46.4 V	46.6 V	46.8 V	47.0 V
Short Circuit Current (Isc)	9.21 A	9.26 A	9.31 A	9.35 A	9.40 A	9.45 A	9.50 A

* Under Nominal Module Operating Temperature (NMOT), irradiance of 800 W/m² spectrum AM 1.5, ambient temperature 20°C, wind speed 1 m/s.

TEMPERATURE CHARACTERISTICS

Specification	Data
Temperature Coefficient (Pmax)	-0.34 % / °C
Temperature Coefficient (Voc)	-0.26 % / °C
Temperature Coefficient (Isc)	0.05 % / °C
Nominal Module Operating Temperature	41 ± 3°C

PARTNER SECTION

* The specifications and key features contained in this datasheet may deviate slightly from our actual products due to the on-going innovation and product enhancement. CSI Solar Co., Ltd. reserves the right to make necessary adjustment to the information described herein at any time without further notice.
Please be kindly advised that PV modules should be handled and installed by qualified people who have professional skills and please carefully read the safety and installation instructions before using our PV modules.

CSI Solar Co., Ltd.
199 Lushan Road, SND, Suzhou, Jiangsu, China, 215129, www.csisolar.com, support@csisolar.com

Figure-A IIV-4 Canadian solar panel specifications

APPENDIX V
SOLAR PANEL INSTALLATION DIMENSIONS

According to RETScreen, the optimum solar power happens at a tilt angle of 37 degrees for the location of study. Using trigonometry and the known height and width of each solar module of 1910mm and 1042mm, it is possible to determine how much of flat area required to mount two modules on top of each other. The total length of two panels placed one on top of the other is:

1910mm x 2 = 3820mm

The figure below shows an illustration of the mounting rack:

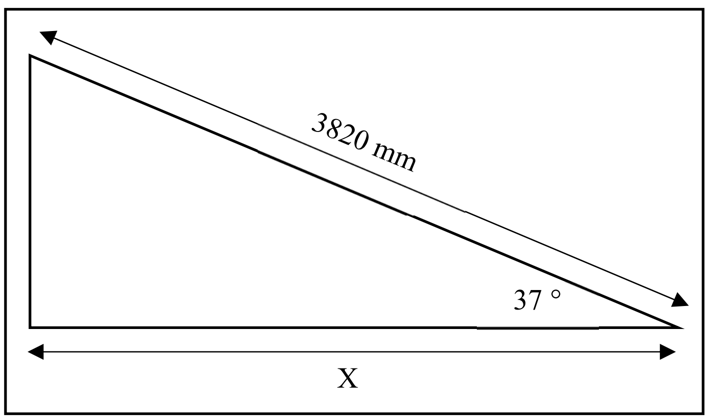


Figure-A V-1 Trigonometry method for PV panel sizing

The two-dimensional length of the floor space will be calculated using trigonometry as follows:

$$\cos 37 = \frac{x}{3820} \xrightarrow{Therefore} x = 3050\ mm \approx 3\ meters \qquad \text{(A V-1)}$$

The area occupied by two solar modules

$$3\ m\ (length) \times 1\ m\ (width)\ = 3\ m^2 = 32.29\ sq.ft$$

APPENDIX VI

MONTHLY AVERAGE SAVINGS IN DIFFERENT CANADIAN PROVINCES

Table-A VI-1 Savings from System 1, prices are in Canadian dollars (CAD)

System 1	A.L.	B.C.	M.N.	N.B.	N.L.	N.S.	N.T.	N.U.	O.N.	P.E.	Q.C.	S.K.	Y.T.
Jan	1532	1163	913	1172	1273	1578	3526	3461	1200	1606	673	1670	1726
Feb	1762	1337	1050	1348	1465	1815	4055	3981	1380	1847	774	1921	1985
Mar	2192	1663	1307	1677	1822	2258	5044	4952	1716	2297	964	2390	2469
Apr	2106	1598	1256	1611	1750	2169	4846	4757	1649	2207	926	2296	2372
May	2234	1696	1332	1709	1857	2301	5142	5047	1749	2342	982	2436	2517
Jun	2182	1656	1301	1669	1814	2247	5021	4929	1708	2287	959	2379	2458
Jul	2243	1703	1338	1716	1865	2311	5163	5069	1757	2352	986	2446	2527
Aug	2031	1541	1211	1554	1688	2092	4674	4588	1590	2129	893	2214	2288
Sep	1805	1370	1076	1380	1500	1859	4153	4077	1413	1892	793	1968	2033
Oct	1452	1102	866	1111	1207	1496	3342	3280	1137	1522	638	1583	1636
Nov	1135	861	677	868	943	1169	2612	2565	889	1190	499	1238	1279
Dec	1168	886	696	893	971	1203	2688	2639	915	1224.	513	1274	1316
Ann.	21846	16581	13028	16713	18161	22504	50272	49351	17108	22898	9607	23820	24609

Table-A VI-2 Savings from System 2, prices are in Canadian dollars (CAD)

System 2	A.L.	B.C.	M.N.	N.B.	N.L.	N.S.	N.T.	N.U.	O.N.	P.E.	Q.C.	S.K.	Y.T.
Jan	1881	1428	1122	1439	1564	1938	4329	4250	1473	1972	827	2051	2119
Feb	2058	1562	1227	1574	1710	2120	4736	4649	1611	2157	905	2244	2318
Mar	2511	1906	1497	1921	2088	2587	5780	5674	1967	2632	1104	2738	2829
Apr	2405	1826	1434	1840	2000	2478	5536	5434	1884	2521	1057	2623	2710
May	2482	1884	1480	1899	2063	2556	5712	5607	1943	2601	1091	2706	2796
Jun	2417	1834	1441	1849	2009	2490	5563	5461	1893	2533	1063	2635	2723
Jul	2437	1850	1453	1864	2026	2510	5609	5506	1908	2555	1071	2657	2745
Aug	2210	1677	1318	1691	1837	2277	5086	4993	1731	2316	972	2410	2490
Sep	1997	1515	1191	1527	1660	2057	4595	4511	1564	2093	878	2177	2249
Oct	1697	1288	1012	1298	1410	1748	3905	3833	1328	1778	746	1850	1911
Nov	1448	1099	863	1108	1204	1492	3333	3272	1134	1518	637	1579	1631
Dec	1494	1134	891	1143	1242	1539	3438	3375	1170	1566	657	1629	1683
Ann.	25041	19007	14934	19158	20817	25796	57626	56570	19611	26248	11012	27304	28209

APPENDIX VII

SOLAR RESOURCE MAP OF CANADA – DIRECT NORMAL IRRADIATION

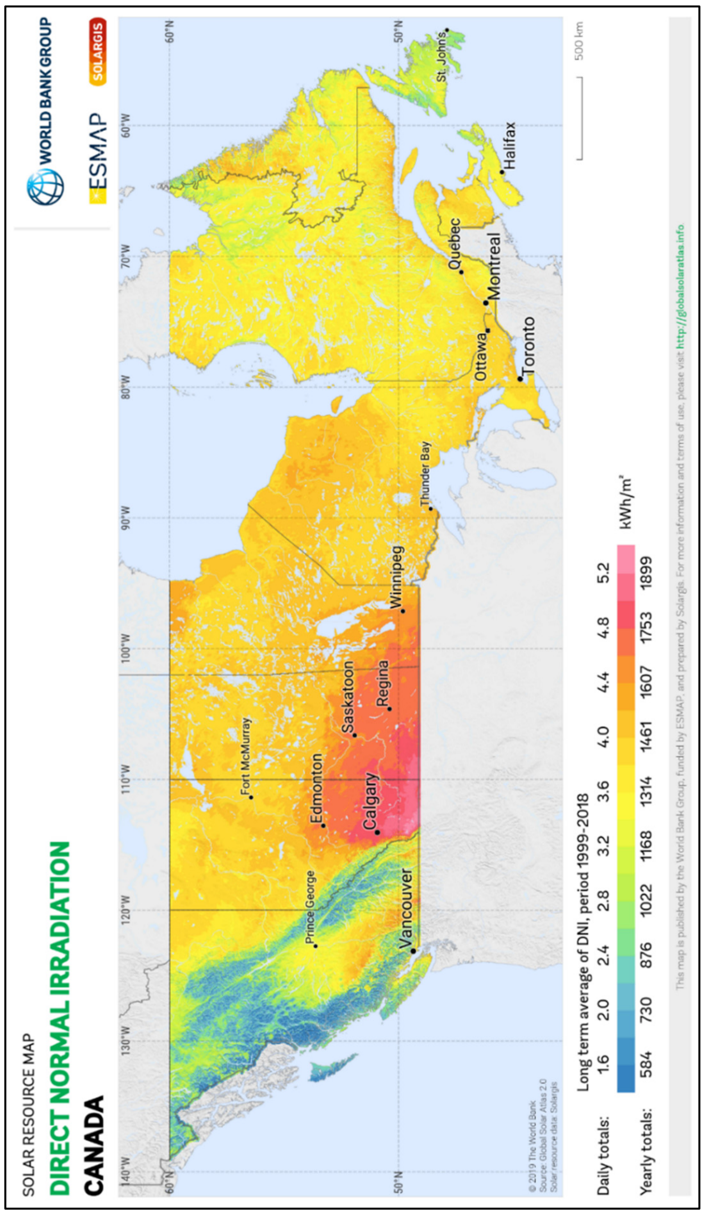


Figure-A VII-1 direct normal irradiation

SOLAR RESOURCE MAP OF CANADA – GLOBAL HORIZONTAL IRRADIATION

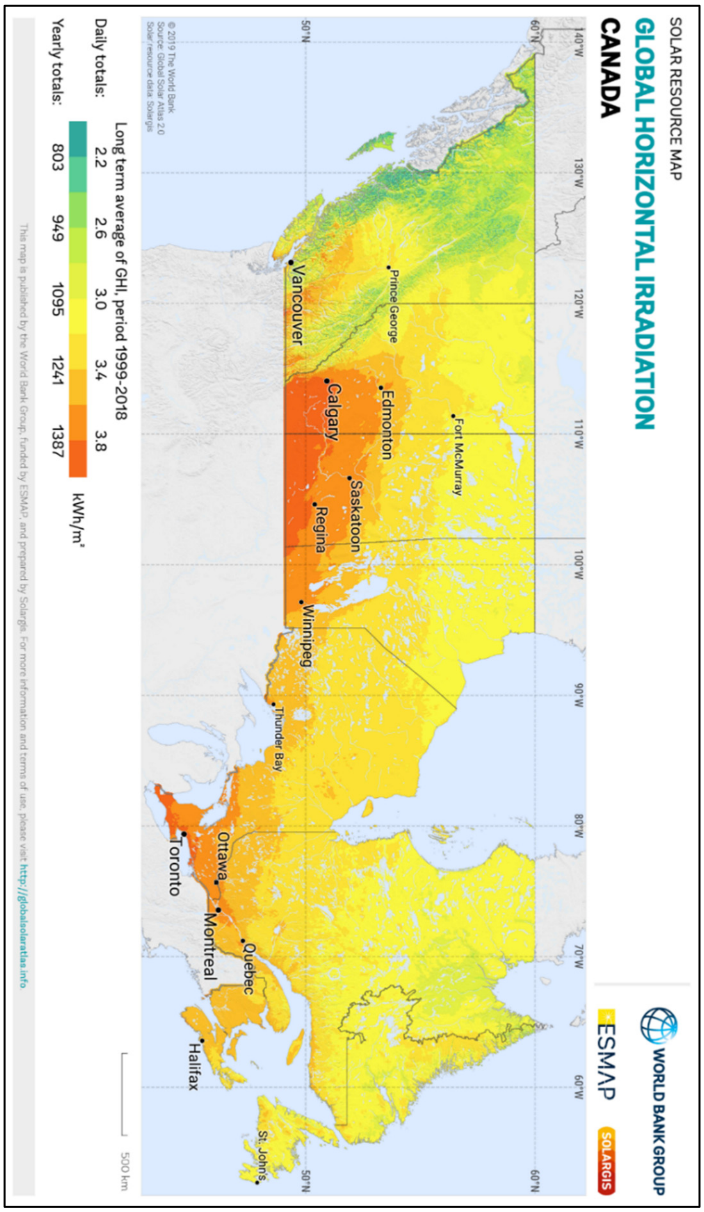


Figure-A VII-2 global horizontal irradiation

SOLAR RESOURCE MAP OF CANADA – PHOTOVOLTAIC POWER POTENTIAL

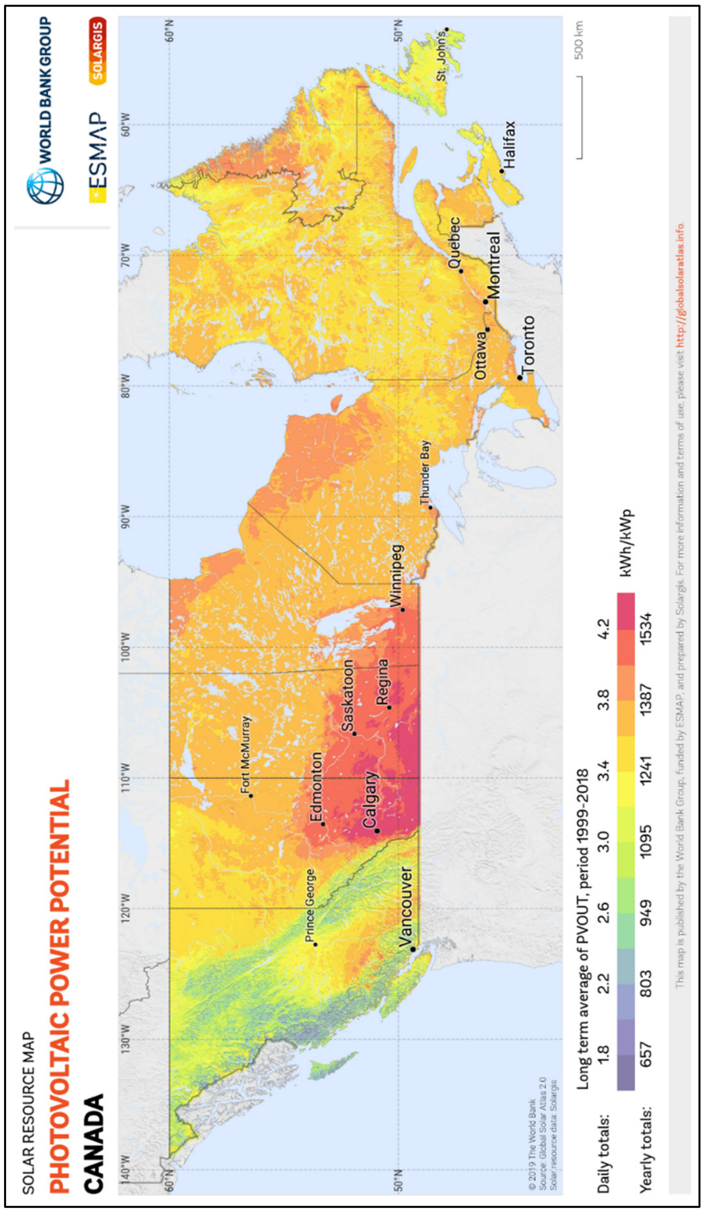


Figure-A VII-3 photovoltaic power potential

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