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# Innovations in Distributed Energy Resources

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# Innovations in Distributed Energy Resources

By

**Sarah Nichol**

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Submitted to the Faculty of Graduate Studies
through the Department of Civil and Environmental Engineering
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Windsor, Ontario, Canada

2021

# Innovations in Distributed Energy Resources

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# DECLARATION OF CO-AUTHORSHIP AND PREVIOUS PUBLICATION

## I. Co-Authorship

I hereby declare that this thesis incorporates material that is result of joint research, as follows:

*Chapters (II) and (IV) of the thesis were written under the supervision of Dr. Lindsay Miller and Dr. Rupp Carriveau. In all cases, the key ideas, primary contributions, experimental designs, data analysis, interpretation, and writing were performed by the author.*

*Chapter (III) of the thesis was co-authored with D. S-K. Ting, Djordje Romanic, Adrian Costache, and Horia Hangan under the supervision of professors Rupp Carriveau and Lindsay Miller. In all cases, the key ideas, primary contributions, experimental designs, data analysis, interpretation, and writing were performed by the author, and the contribution of co-authors was primarily through: Djordje Romanic contributed to the designs of the wind profiles and written description of the WindEEE dome; D. S-K. Ting, Rupp Carriveau and Lindsay Miller provided feedback on refinement of ideas and editing of the manuscript and experimental design, Adrian Costache provided training and feedback on the experimental design.*

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| Thesis Chapter | Publication title/full citation | Publication status* |
|---|---|---|
| *Chapter [II]* | "Should Canada Pursue or Support Offshore Wind Development?," S. Nichol, L. Miller, R. Carriveau, in: Sustainable Engineering for Life Tomorrow, Editors: D.S-K. Ting and Stagner J.A., Lexington Books, 2020. | *Accepted for Publication.* |
| *Chapter [III]* | S. Nichol, R. Carriveau, L. Miller, D. S-K. Ting, D. Romanic, A. Costache, and H. Hangan, "Experimental Investigation of the Movement of an Offshore Floating Platform in Straight Wind, Tornadic Wind, and Downburst Conditions,". | *Prepared for submission to Wind Engineering in January 2021.* |
| *Chapter [IV]* | S. Nichol, L. Miller, R. Carriveau, J. Fonger and S. Costa, "Financial model of a carbon-neutral microgrid at an Ontario high school," International Journal of Environmental Studies, 2020. | *Published.* |

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# ABSTRACT

The demand for energy is continuously increasing, but the ability to meet it is becoming challenging. Distributed Energy Resources (DERs) will be key players in the future energy mix. This work considers innovations in DERs, and key factors in their developments.

This thesis first presents an analysis of the best options for Canada's involvement in the offshore wind scene. It compared three different scenarios which considered drivers, barriers, support, incentives, and technology advancements. The most favorable scenario is to export Canadian expertise, as the country's experience in the offshore oil and gas industry can be transferred to offshore wind projects. Installation in Canadian waters is suggested only after developing further understanding of requirements in similar waters.

This research also includes the results and analysis of a 1:150 scaled experimental study on the dynamics of a floating offshore platform model under extreme wind conditions. Four configurations were tested under straight wind (ABL), tornado (TLV), and downburst (DB) conditions. It was observed that motions varied greatly when the platforms were subjected to different wind conditions. In general, the TLV and DB flows caused the greatest instability and loosely moored platforms experienced movements of higher magnitude and frequency than tightly moored ones.

A major factor in any new project is the financial aspect and business case associated. The final study completed within this thesis is the generation and analysis of a 30-year financial model of a carbon neutral microgrid. Case and location specific factors are considered as well as non-monetary benefits. Ontario-specific policies and incentives are also discussed, and it is determined that presently, they are a major factor in the feasibility of a large microgrid project such as the one presented here.

# DEDICATION

This thesis work is dedicated to my family and friends for all their confidence, love, and encouragement. I would especially like to recognize my fiancé, Aaron, for his unwavering support and for always inspiring me.

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I would like to express my sincerest appreciation to everyone who has provided their insight, knowledge, and assistance with this work.

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# Chapter 1 : Introduction

## Background and Motivation for Research

According to the International Energy Outlook report of 2019, it is predicted that the world's energy consumption will increase by nearly 50 percent between 2018 and 2050 [1]. The demand for energy is continuously rising, while the ability to meet this demand is challenging. Technological innovations and advancements to the current electrical infrastructure are necessary to keep up with the rising energy needs. Historically, electricity was solely supplied by generation at large scale power plants, transmission lines, and distribution services. More recently, North American industry leaders have expressed concerns for the current state of aging electricity infrastructure and the reliability of bulk energy distribution [2], [3]. These concerns are also true of energy systems in other locations worldwide. The use of these "traditional" technologies to meet energy demand has led to unreliability, losses, and even blackouts in electricity supply. Additionally, there are still many locations globally that do not have access to reliable energy sources.

The integration of Distributed Energy Resources (DERs) into the current and future electrical supply mix could provide a potential solution to the abovementioned concerns. DERs are decentralized generation or storage units and controllable loads that are connected to a local distribution system or host facility. There are many types of distributed energy resources, including renewable and non-renewable generation, such as: solar, wind turbines, battery storage, or electric vehicles and their chargers. With their modular integration ability, DERs can significantly delay or even replace the needs for new transmission infrastructure in the future. These systems can address the major concerns surrounding the future of North American utilities and provide flexibility in balancing generation and demand needs. Storage can be included for backup power, providing resiliency in times of shortages, losses, or a blackout. Different combinations of DERs can be optimized for a specific project, location, environmental factors, and demand. Distributed energy resources, therefore, are a potential solution to providing energy to remote locations currently in need.

A microgrid is a small network of interconnected distributed energy resources, storage, and loads that can be either connected to or islanded from the main electrical grid. Microgrids can be found in: residential or commercial areas, schools, military bases, and remote locations. Some of the major barriers to the integration of microgrids are economic and technical limitations. The integration with the central grid can be difficult, especially for large projects. Incidentally, these projects must be fully defined and approved before they can move forward. They also have high upfront costs, which could be offset if additional support were supplied in the form of incentives, or programs. There is a lack of understanding of business models for microgrid systems, and the effect of support measures for increased integration of distributed energy systems.

With larger distributed energy systems like solar farms or wind turbines, social aspects and large land use have become barriers to deployment. Large amounts of land can be very costly and likely sometimes unavailable. This is a major challenge in areas such as Europe and the UK, where there is not an abundance of land for large, distributed energy farms. In these areas, offshore structures, such as wind turbines, are enabling a shift to green energy and distributed energy systems. Since 2013 the global offshore wind market has grown 24% each year, on average, resulting in total installations of 29.1 GW at the end of 2019 [4]. Most installations are off the coast of European countries with the UK and Germany accounting for 59% of total global installations. However, recently many installations have been added in Asia. It is predicted that over 205 GW of new offshore wind will be installed over the next decade [4].

The growth of offshore wind is not as prominent in North America to date, although there have been some recent developments in the United States (US). Currently, Canada does not have any turbines in its waters, despite the nation's significant resource potential for offshore wind and the major potential benefits. Even with the availability of terrestrial land within Canada, the nation can still benefit greatly from involvement in the offshore wind industry. Aside from the obvious opportunity of implementing offshore wind turbines within Canadian waters to meet its energy needs, there are many opportunities for Canada in the offshore energy markets. The nation is rich in experience, expertise, and capabilities in the energy sector, as well as in the offshore oil and gas industry. Expertise in both industries is extremely important to the development of offshore wind systems, which will benefit both the developments of offshore wind farms globally, as well as Canadian developers. However, there are still many barriers to the development of offshore wind turbines, especially in North American waters conditions, rendering the best option for Canadian involvement in the offshore scene to be unclear.

Another barrier faced in the increase of implementation of offshore energy systems is the lack of understanding of the effect of harsh weather conditions on offshore system stabilities. The US Federal National Offshore Wind Strategy states that a gap remains in the understanding and development of design practices for extreme weather conditions at offshore sites in the US [5]. As climate change continues and the weather becomes less predictable, extreme weather conditions will become more frequent and more powerful [6]. Additionally, the locations with high wind resource potential in North America are located mostly in areas with deep waters. Many projects in countries with a more established offshore wind scene are moving into deeper waters to benefit from higher wind speeds and larger turbine possibilities. Sea-bed fixed turbine foundations cannot be used in deep waters. Instead, floating offshore foundations have become a necessary component for the support and stability of offshore wind turbines in deepwater applications. To fully develop these floating offshore wind turbine foundations and understand their potential role both within North America and globally, it is necessary to consider the response of these systems under a variety of possible conditions they could be subjected to, including extreme environmental conditions.

Parallel to the major success of the offshore wind industry, applications for offshore floating platforms has expanded far beyond oil and gas production systems or offshore wind turbines

[7]. Multi-purposed floating platforms are being used for many applications, including offshore greenhouses or food production [8], solar farms [9], [10], residential real estate [11], floating airports [12], or entertainment facilities [13], and holding compressors for underwater compressed air energy storage. They are becoming essential for some island living. The floating foundation platforms can also host a variety of distributed energy systems to increase energy generation and storage abilities, as well as dependability.

Due to the embryonic state of these newly developed multi-purposed floating platforms, few studies have considered the dynamics of such systems under different harsh environmental conditions. There is a lack of understanding of offshore floating platforms under extreme weather conditions. There is also insufficient standards for the design and implementation of such systems [14]–[16]. Both developers and governments agree that research must be completed for a greater understanding and development of design standards for offshore floating structures under extreme weather conditions [5].

## Objectives

The objective of this thesis is to address some of the barriers to the growth of innovations and the penetration of distributed energy resources. This objective will be met by means of the following deliverables:

- Generate an evaluation of the current opportunities in the Offshore Wind Industry, with a focus on the potential of implementing Offshore Wind in North America.
- Propose the best methods for Canadian involvement in the Offshore Wind Industry, which is an important DER market.
- Evaluate the effect of different weather conditions on the dynamics and stability of floating offshore multi-purposed platforms for use in various DER applications.
- Develop financial models for evaluation of the feasibility of implementing distributed energy systems.
- Outline the importance of considering non-monetary benefits in the development of business cases of systems with distributed energy resources.

The work presented within this thesis provides evaluations and insight, which can contribute to eliminating major barriers that are restricting the current integration of distributed energy resources in energy supply mixes, both within Canada and globally.

### Thesis Organization

Chapter II focuses on conducting a comprehensive literature review of the current state of the offshore wind industry, with a focus on the potential involvement of offshore wind projects in North America. Currently, offshore wind is a major energy market contributor in the UK, Europe, and Asia; however, there are very few installations in North America and zero in Canada. This study evaluates the reasons for barriers to offshore wind installations in Canada and presents suggestions for the nation’s involvement in the industry. This contributes to the overall objective of this thesis by determining what barriers are present in such an important DER market, and by providing a plan for overcoming these barriers to allow integration of the Offshore Wind market in Canada without initially installing turbines in Canadian waters.

The applications for offshore floating systems reach far beyond the offshore wind industry. These platforms are being used as the foundations for many different projects, including energy generation and storage systems, aquaculture, agriculture, and even residences. Multi-purpose offshore floating platforms can be used for numerous applications at once. Many applications of these multi-purposed platforms could be in areas of deep waters or harsh environmental conditions. Chapter III evaluates the experimental results of a floating platform subjected to Tornado-Like Vortical (TLV), Downburst (DB), and Straight-Line Atmospheric Boundary Layer (ABL) winds. There is an obvious gap in the literature pertaining to the understanding of reactions of floating offshore platforms to extreme weather conditions. Experimental testing of such data is difficult, as there are limited resources available able to generate the necessary conditions for obtaining data related to both extreme wind conditions and water. Following the major successes of the offshore wind industry, further applications are underway for offshore structures, including multi-purposed, light-duty, and floating platforms to host a variety of distributed energy systems. Integration of such systems in deep waters requires an understanding of floating structure stabilities in all sorts of environmental conditions that could arise. This includes extreme wind. This chapter presents the findings of an initial experiment conducted on a simple floating platform structure under different loadings and design conditions.

The experiment presented in Chapter III provides an initial insight to the effects of different winds on various designs of offshore structures and contributes to the overall understanding of the variation in stability caused by wind loadings on floating structures. Additionally, the results provide direction for developing designs and standards for stable offshore structures in conditions requiring deep waters. A future research avenue to be directed by these experiments is to generate design requirements for deep water offshore structures. In deep waters, fixed sea-bed foundations cannot be used for turbine stability. Instead, they require floating platform foundations. Confidence is lost in these projects due to the lack of understanding of how these floating structures will react to extreme environmental conditions. Design standards have not yet been developed for such systems, as the dynamics of floating structures subjected to unpredictable and harsh conditions are not yet understood.

Another barrier to further penetration of distributed energy resources is the high costs associated with such technology. This study recognizes the importance of economic feasibility in the promotion and use of distributed energy resources as an innovative energy solution. Although there are many obvious benefits to the use of distributed energy resources, for the use of these technologies to really grow, they must be economically feasible first. Chapter IV presents a 30-year financial model and business-case investigation of a system of distributed energy resources. It breaks down the necessary components when considering a financial model for DERs and describes the necessary details (project and location-specific) for a true representation of the business cases for such projects. It presents barriers to economic feasibility, as well as potential opportunities and cases which can lead to an economically feasible system of DERs, such as: various government incentives, policies and level of support, or increases in electricity and carbon tax pricing, and a decline in technology costs. As well, this chapter provides an evaluation of non-monetary benefits to DERs, such as improved system resiliency, emissions reductions, or contributions to research and education programs. Taken together, the contribution of this chapter to the overall objective of this thesis is addressing one of the biggest barriers to the growth of DERs, economics.

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# Chapter 2 : Should Canada Pursue or Support Offshore Wind Development?

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## Chapter Summary

Installed offshore wind capacity surpassed 29 GW at the end of 2019, with the majority being off the coast of European countries such as the UK and Germany. Canada is a massive nation rich in energetic natural resources, and yet, there are no offshore wind turbines in Canadian waters. Past research has revealed that Canada has significant resource potential for offshore wind and has illustrated the areas where installations would deliver the greatest benefits. However, such opportunities must be economic to be pragmatic. This paper explores options for Canada's involvement in the offshore wind industry. Barriers to offshore wind implementation in Canada include the high costs compared to onshore wind, adequate onshore space, relatively clean energy supply, opposition, lack of incentives and policies, as well as uncertainties in necessary technologies for Canadian waters. Drivers of offshore wind elsewhere are surveyed to evaluate whether Canada has similar support for an offshore market. Three scenarios are considered to determine how Canada should proceed within the offshore wind industry: (I) install in Canadian waters and sell power to Canada or export power, (II) do not install in Canada and instead focus on exporting Canadian expertise and supporting the international supply chain, or (III) do not involve Canada in the offshore industry at this time. It was determined that currently there are too many barriers for feasible implementation of offshore wind projects in Canadian waters for the sale of energy to Canada. The most favourable scenario based on existing findings is to export Canadian expertise, as the country's vast experience in the offshore oil and gas industry can be transferred to offshore wind projects. Immediate contribution to offshore wind energy projects internationally, and especially within North America is important for Canada to be recognized as a leader in the offshore wind supply chain. Following this, with advancements in government support and funding of offshore wind, as well as advancements in the necessary technologies, the next recommended step is to install offshore wind along Canada's coastlines and sell energy to bordering US states at competitive pricing.

# Introduction

Wind energy is a clean and cost-effective solution to meet increasing energy demands while facing climate change challenges. In areas where terrestrial space is becoming scarce, offshore installations are becoming popular due to significant energy potential associated with higher wind speeds and vast offshore areas. Since 2013 the global offshore wind market has grown on average 24% each year, resulting in total installations of 29.1 GW at the end of 2019 [1]. Most installations are off the coast of European countries with the UK and Germany accounting for 59% of total global installations. However, in the past few years many installations have been added in Asia, with China now accounting for 24% of total global offshore wind installations. It is predicted that over 205 GW of new offshore wind will be installed over the next decade [1]. While Canada is a massive nation rich in energetic natural resources, there are currently no offshore wind turbines in Canadian waters.

Although offshore growth is not as prominent in North America as it is in Europe, there have been some recent developments of offshore wind in the United States (US). The first US offshore farm came online in December 2016 and there are now over 25,000 MW of offshore wind in the U.S. pipeline [1]. The first offshore project in the Great Lakes is currently under development and is expected to be operational by the end of 2022 [2]. There has been significant policy support for offshore wind in the U.S. over the last few years and growth of offshore wind in the US is expected to continue as renewable energy targets increase while costs of offshore projects decline.

Research has revealed that Canada has significant resource potential for offshore wind and has illustrated the areas where installations would deliver the greatest benefits [3], [4]. However, such opportunities must be economic to be pragmatic. Offshore wind projects face higher costs of installation and operating and maintenance due to access challenges and the need for large crane vessels along with the potential for environment impacts on marine ecology. In Canada, a country with vast terrestrial area available for onshore installations, the business case for offshore installations is very challenging. Compared to its onshore counterpart, offshore wind has greater resource potential due to stronger and steadier winds, and has the opportunity for installation of large turbines, up to 8 MW, while minimizing noise and visual impacts. Currently, several offshore wind projects are in the planning stages in Newfoundland, Nova Scotia, New Brunswick, Prince Edward Island, and in British Columbia. Although Ontario has been identified as having significant potential for offshore installations, a moratorium is in place on all offshore wind projects and has been since 2011, halting offshore development plans for the time being.

Canada is also a nation rich in experience, expertise, and capabilities in the energy sector. Offshore global capacity is expected to approach 234 GW by 2030 [1] and Canadian businesses can capitalize on the CAD$350 billion that will be invested to support this growth through provision of services and expertise to the sector. Some Canadian companies have realized this and have recently become involved in the offshore scene. Exciting business opportunities for

Canadian companies will be available to those who can strategically position themselves and closely follow the global offshore progress.

There are many opportunities for Canada in the offshore energy markets, however, the best option is not clear. The purpose of this study is to determine how Canadian stakeholders can best position themselves to become key players in the rapidly growing offshore wind industry. With the potential for such large investments in this industry, and the major benefits of offshore wind technology, it is important to consider if and how Canada should be involved. The study pulls information from many sources to lay out the barriers, drivers, support, and courses of action available to Canada regarding the offshore wind industry. The comparisons of these to other offshore wind projects and markets will provide insight to how Canada should proceed in the industry. With various opportunities available for Canada's involvement, a plan must be determined, in which the areas of best practices are considered. Immediate action is required if Canada is to become involved in the offshore scene, as developments are rapidly expanding, and the US is beginning to search for contributors to their offshore wind supply chain.

This paper first identifies drivers and barriers to offshore wind development with a focus on relevance to Canadian projects. Then an overview of North American policies relating to offshore wind are summarized, considering both the US and Canada. Following this, global offshore activities, with a focus on recent U.S. developments are explored, followed by Canadian developments.  Furthermore, this paper presents an examination of options for prioritizing the next steps for Canada to capitalize on offshore wind opportunities.

# Offshore Wind Drivers and Barriers

## Offshore Wind Drivers

Offshore wind has several advantages over its onshore counterpart, the greatest being that offshore wind has a greater resource potential.  Winds blow stronger and more consistently over water than over land, and are greatest during the day when energy demands are highest [5]. When winds are varying offshore, they are more easily predictable, with the potential to be forecasted days in advance [6]. Higher wind speeds imply higher productivity which can partially offset the higher capital costs.  Higher capacity factors are also a benefit of offshore wind compared to onshore [7].  If installed sufficiently far from shore, offshore installations can avoid many of the conflicts posed by land-based wind projects, including visual impacts, noise, and shadow flicker.  In areas with scarce land, offshore wind can provide an obvious option for additional energy production with minimal terrestrial footprint. Furthermore, there is virtually no limit on the size of the turbines since there are no concerns with road limit restrictions as there are with onshore transportations [8]. Due to the ease in transportation of large structures by water, offshore turbines can be much larger than onshore, allowing for much greater energy production potential [6].

Offshore wind energy is a clean and sustainable source of energy with the potential for very large-scale projects to significantly reduce the use of carbon emitting energy supplies. Under the Paris Agreement, Canada committed to reducing its greenhouse gas emissions to 30% below the levels of 2005 by the year 2030. The country also is generating a plan for a net-zero emissions future by the year 2050 [9]. The integration of offshore wind into Canada's energy sector could help the country meet these goals as targeted.

Likewise, smaller scale offshore wind farms could power remote communities, reducing the use of diesel fuel [6]. There are over 292 remote communities in Canada which are often supplied with diesel-dependent imported energy. Many of these communities have access to renewable energy resources, including waters and offshore wind. Indigenous communities pose an ideal community space for these wind farms to be located. Indigenous participation in the clean energy sector within Canada has rapidly increased over the past two decades. Over the next few years continuous participation in clean energy projects by Indigenous communities is expected as they move away from the use of diesel-reliant energy [10]. Smaller scale offshore wind project installations within these communities can provide a transition to cleaner energy increased community self-reliance, as well as job and skill developments [6]. Remote communities, especially coastal areas, also suffer from frequently compromised transmission lines and unreliable energy [6]. The integration of offshore wind in these areas would also be beneficial, with point of use generation improving the reliability of energy and reducing maintenance on transmission lines [6].

## Offshore Wind Barriers

Although there are many advantages to offshore wind turbines, there are also disadvantages that pose as challenges to implementation. A large barrier in implementing offshore wind turbines are the associated construction, maintenance, and transmission costs, as they are significantly greater than the costs associated with onshore wind turbines [11]. The weather, winds, waves, and water currents experienced by offshore turbines require a different approach in terms of technology, support structures, electrical infrastructure resulting in higher investments in towers, foundations, and underwater cabling. Construction of offshore wind farms also requires use of materials that can resist the corrosive marine environment. Costs of offshore wind in North America are about twice that of onshore wind [8], [12]. A major challenge is access to offshore site for maintenance and repairs. Offshore turbine repairs can be 5 to 10 times more expensive than onshore, largely due to the need for expensive crane vessels [13]. Furthermore, waiting for acceptable weather conditions to perform repairs can inflict turbine downtime and lost production will negatively impact the economics of the project. Another challenge facing offshore development is the possibility of shortage of materials, such as the number of vessels available for construction and repair as more projects begin development. Lastly, offshore turbines are exposed to harsher environmental conditions such as wave and current loading, and possible icing and corrosion. Project developers have also cited difficulties in securing construction contracts under which risks are carried by the contractor due to an unwillingness to bear the significant geotechnical and weather risks associated with offshore development [14]. In this case, the developer would have to assume this risk, which could also make project financing more difficult. Dramatic cost reductions have been achieved in the last couple of years. The global average of LCOE for offshore wind according to BNEF has dropped over 67% since 2012, now sitting at $84/MWh. This is expected to continue to drop to $58/MWh by 2025 [1]. The reasons for the significant cost declines include growing investor confidence and the introduction of new GW sized projects.

In addition to monetary disadvantages, there are also environmental concerns that have been raised surrounding offshore development and studies have been commissioned [15]. The predominant concerns include possible negative impacts from noise, lubricant spills, and electromagnetic fields from cables on marine life [16]. Additional potential impacts include disturbance of fish breeding, disturbance of communication between species, and reductions in habitat size due to operational noise emissions [17]. Despite these being raised as possible concerns, studies have demonstrated that species were only affected during the pile-driving operations of construction and that low intensity wind turbine noise during operation posed little possibility of causing hearing impairment of fish [18]. Other works have suggested that there may be beneficial ecological impacts through provision of habitat to marine species as offshore turbines can act as artificial reefs [17]. Environmental concerns can largely be addressed through proper siting and technology and material selection. Design and material innovations aimed at simplifying manufacturing and installation processes are underway and are expected to result in fewer impacts on marine life. Although impacts can be very site specific, in general, offshore developments pose low impacts to the environment especially when compared with other energy generation [17].

Fleet challenges can also have substantial impacts on project timing and costs. In the U.S., the “Jones Act” restricts the “transportation of merchandise by water” between “points in the United States” to qualified U.S. vessels. This act complicates the construction, operation, and maintenance of offshore wind farms in the U.S. as there will be a general requirement for merchandise to be moved between a U.S. port and towers attached to the seabed, or between towers [19]. The purpose-built wind turbine installation vessels used in European developments (and not built in the U.S.) cannot be used in U.S. waters. The offshore U.S. market could eventually support development of multiple purpose-built vessels, with preliminary plans for such underway. In the meantime, developers are relying on resourceful solutions to suit their situation [19]. Even without regulatory restrictions, projects face challenges in accessing a fleet of highly specialized vessels that are required for offshore wind installations.

The most notable barrier to offshore wind development in Canada is the moratorium that is currently in place in Ontario, a province with significant offshore wind potential. In February 2011, Ontario announced a moratorium on all offshore wind development in the province, citing visual impacts amongst the major concerns [20]. Several large projects were affected by this decision including: Superior Array (650 MW), Trillium Power Wind I (480 MW), Trillium Power Wind II (740 MW), Great Lakes Array (1600 MW), Erie Wind Energy (4000 MW), and Wolfe Island Shoals (300 MW). Both Windstream Energy and Trillium Power Wind had wind turbine projects planned for Lake Ontario when the government brought down the moratorium. Again in 2017, the province has signaled that the moratorium will remain in place for some time, despite being hit with a $25 million penalty under the North American Free Trade Agreement for stalling the Windstream project [21]. The province cites the need for more research on noise and environmental issues, despite the five government-commissioned studies that have taken place since 2011. The province also plans to monitor the impacts of the Icebreaker project in the Great Lakes.

Adequate terrestrial space is also a barrier to offshore development. In some countries, space is becoming scarce for onshore wind turbines [5], and therefore, offshore developments provide a suitable option. With terrestrial space still available in Canada, making a business case for offshore development can be challenging. Furthermore, there are technical challenges surrounding installation. Many of the potential offshore sites in North America are located in deeper waters than those installed globally, requiring new technologies for installation. Stronger wind and larger wave and ice loadings would also have to be considered. Especially in the Great Lakes, a major concern is the freshwater icing that occurs. Areas with the greatest water depth are ice free, but the wind and wave conditions may be harsher, and different floating offshore wind technologies would need to be explored. Deep water prototypes have successfully been installed in Norway (220 m depth) and Italy (110 m depth) demonstrating the ability of the technologies to be adapted for North American waters [17].

Furthermore, vessel size is more restricted in the Great Lakes than other areas, as vessels larger than 23.7m cannot enter the St. Lawrence Seaway locks [22]. If specialized vessels are created for the construction and decommissioning of offshore turbines in Canada, they may not be as capable as those present in Europe [22]. The build-out of high voltage transmission has also been identified as a potential challenge to offshore wind development in the Great Lakes.

# Offshore Wind Policies in North America

Different policies exist within North America providing various levels of support for the development of offshore wind.

## Offshore Wind Policies in the United States

Recent policy support for offshore wind in the US will further support this sector. In May 2017 Maryland awarded the Public Service Commission's first offshore wind renewable energy credits (ORECs) to two projects [23]. The ORECs were awarded to Deepwater Wind's 120 MW Skipjack Project, expected to be operational in 2022, and US Wind's 270 MW project, expected to be operational in 2023 [24]. Each of these projects will receive an OREC for US$131.93/MWh for 20 years which will significantly improve the economics and directly allow them to be built [23].

Massachusetts committed their electricity distribution companies to produce 1600 MW of offshore wind energy by June 2027 [25]. Also, in 2017, Massachusetts released the nation's first competitive solicitation for commercial-scale offshore wind [26] which resulted in proposals from three developers. Different funding programs were also created to support research and development and workforce training on offshore wind. Many states have continued their support of offshore wind development. Rhode Island, Massachusetts, and New York have all passed policies to support private investments in offshore wind projects in 2017 [27], and since then have continued to support the industry.

The National Offshore Wind Research and Development Consortium was established in 2018 to collaborate with industry to advance research and development focused on improving technical, supply chain, social, or economic barriers faced by the offshore wind industry in the US[28]. Resulting from a solicitation for R&D projects in 2019 the Consortium awarded $17.3 million in funding. Recently (August 2020), another $9 million of funding was announced to be awarded to projects focused on the current challenge areas of offshore wind in the US. These challenge areas are focused improving the costs of development, barriers to deployment and growth of the offshore wind industry [28]. An non-American company can be awarded this funding, permitting that the proposal is focused on benefiting the US offshore wind industry [28].

## Offshore Policy in Canada

Policy developments in Canada are necessary to shape the future of offshore energy. In February 2018, the Canadian federal government proposed how it plans to regulate offshore renewable energy projects. Part 5 of the Canadian Energy Regulator Act defines how the government will regulate offshore renewable energy projects and includes a commission to regulate activities, an authorization regime, and a process by which proponents can apply for an authorization [29]. The proposed act also specifies impact assessment timelines and liability and financial requirements for these projects.

Canada's Minister of Natural Resources also announced the Emerging Renewable Power Program, which will provide funding intended to reduce risks and associated costs with emerging renewable energy technologies not yet established in Canada. This could include offshore wind [30]. The funds are also intended to help emerging sectors navigate regulatory issues and ultimately provide Canada with a more diverse set of clean energy technologies.

Another encouraging development for offshore wind in Canada came from the announcement that Marine Renewables Canada will officially be including offshore wind energy in their mandate [31]. The organization, previously focused on wave and tidal energy, now recognizes that there are significant overlaps between these technologies and offshore wind when it comes to supply chain, regulatory issues, and operating environment and plans to focus on the roles that each can play in Canada's low-carbon future.

The 2018 State of the Art Sector Report for Marine Renewable Energy in Canada laid out some funding support available within Canada for potential marine renewable energy projects, which could include offshore wind. The Green Infrastructure Fund is focused on clean energy development in remote communities. The Clean Growth in Natural Resources Program can support clean technology research and development in Canada’s natural resource sectors in energy [6].

Comparing policies and incentives generated by the US, Canada is not receiving the same support as the US in the offshore wind industry. This poses a major barrier to offshore developments in Canada.

# Offshore Wind Developments

## Offshore Wind Outside of North America

At the end of 2019, there was 29.1 GW of installed offshore wind around the globe, accounting for 5% of total global wind capacity (see Figure 2-1). Although Europe remains the leader in total offshore wind installations, hosting 75% of total global capacity (Figure 2-2), activity in Asia, specifically China, has been continuously increasing throughout the past few years (Figure 2-1). China has now installed 24% of the world’s offshore wind capacity, the third highest of any country after The UK (with 33% of total global capacity) and Germany (with 26% of total global offshore wind capacity) (Figure 2-3). 2019 was the greatest year in history for the offshore wind industry, as over 6.1 GW of new capacity was installed [1]. China installed the largest capacity of new offshore wind in 2019 at 2.4GW, the UK installed 1.8GW and Germany installed 1.1 GW, followed by Denmark and Belgium (Figure 2-4) [1].

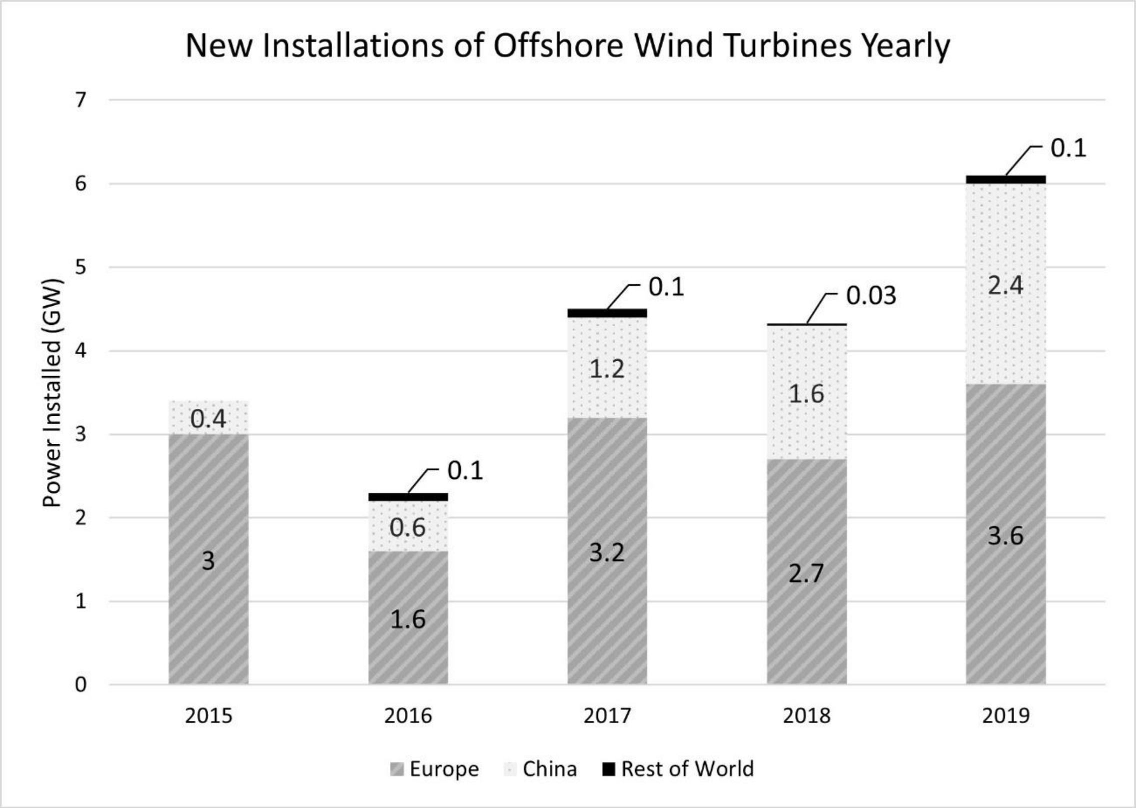

*Figure 2-1- New installations of offshore wind turbines per year from 2015 to 2019 in different countries. Credit: This figure was generated by the author using data from (Lee and Zhao 2020).*

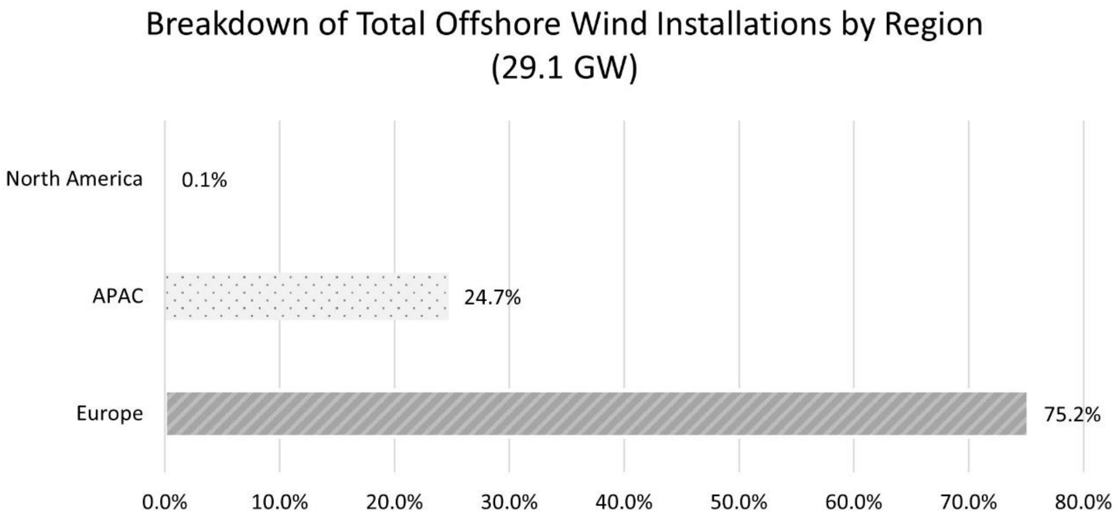

*Figure 2-2- Breakdown of total offshore wind installations in 2019 by percentage installed per region. Credit: This figure was generated by the author using data from (Lee and Zhao 2020).*

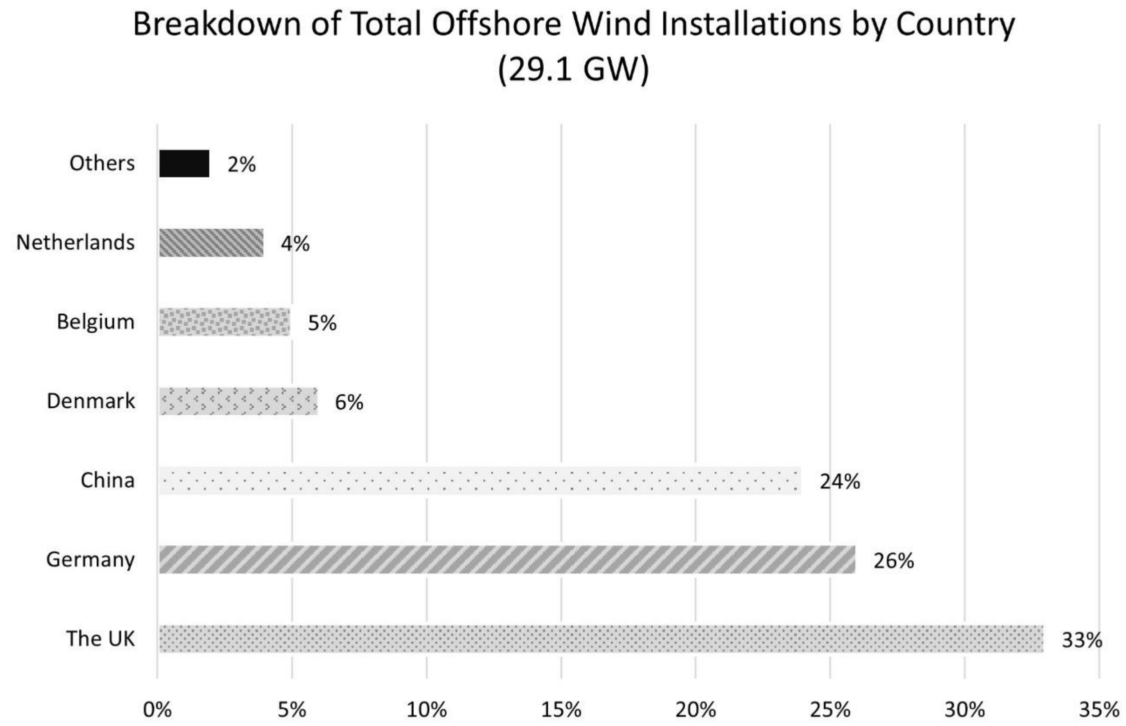

*Figure 2-3- Breakdown of total offshore wind installations in 2019 by percentage installed per country. Credit: This figure was generated by the author using data from (Lee and Zhao 2020).*

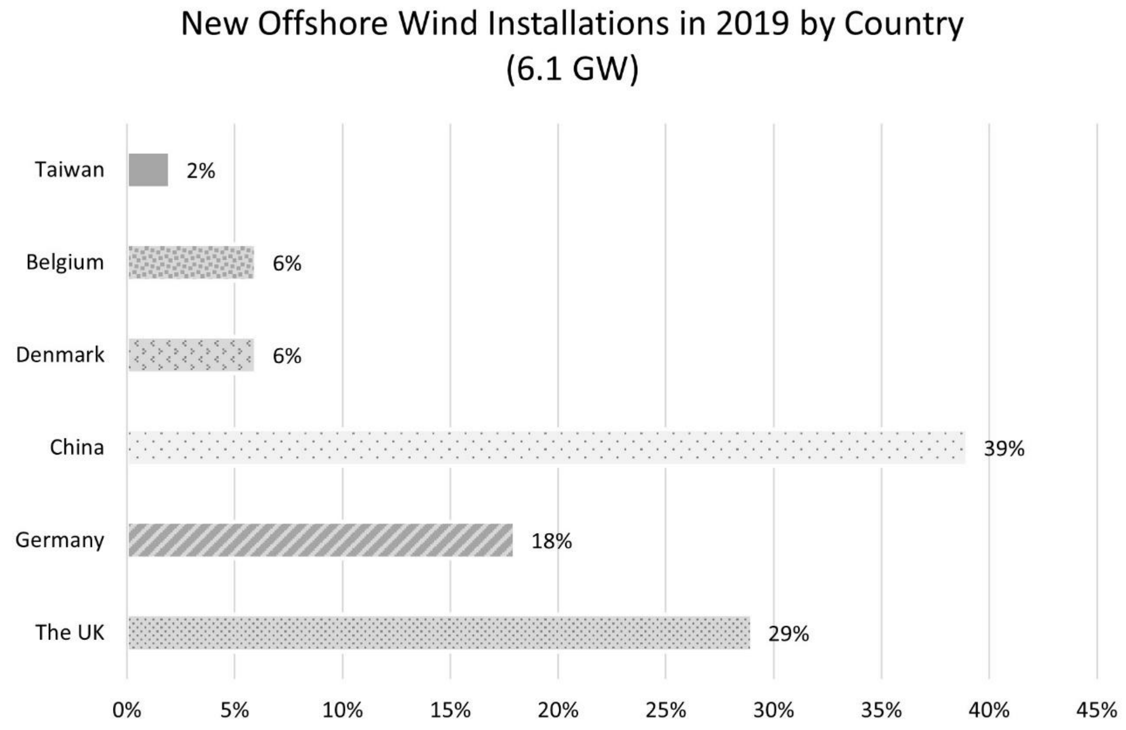

*Figure 2-4- Breakdown of new offshore wind installations in 2019 by percentage installed per country. Credit: This figure was generated by the author using data from (Lee and Zhao 2020).*

## Development of Offshore Wind in the US

The first US offshore wind farm came online in December 2016. The 30 MW, 5 turbine Block Island project installed off the coast of Rhode Island has secured a 20-year PPA to sell its electricity. The project will connect Block Island to the mainland grid for the first time resulting in a 40% reduction in island electricity rates [32]. The Block Island Farm is linked to the New England electricity grid by National Grid's new sea2shore submarine transmission cable system. The project, built on-time and on-schedule and employing hundreds of local workers, was a success story for offshore wind. The successful implementation of offshore turbines in U.S. waters has paved the way for more U.S. offshore developments.

The US has many other projects in the pipeline, the majority of which are proposed to be located in Massachusetts, New Jersey, and North Carolina [33]. The Skipjack wind farm is an example of a planned project in the US [34]. The 120 MW wind farm is located in the Atlantic Ocean, 19.5 miles from its closest point in Maryland. The project plans to come online by 2023 [34].

Plans for the largest combined offshore wind and energy storage project in the world, Revolution Wind off of the coast of Massachusetts, are also underway. The project was approved for a 20 year power purchase agreement for 400 MW of clean energy [35]. The project is predicted to be coming online in 2023 [35]. Support for offshore wind in the US is evident from the US DOE's roadmap for wind power which envisages offshore wind providing 2% of US electricity demand by 2030 and 7% by 2050 [36].

## Offshore Wind in the Great Lakes – Icebreaker Project

The first Great Lakes offshore wind project is currently being developed by the Lake Erie Energy Development Corporation [2]. The demonstration scale Icebreaker project, sponsored by the U.S. Department of Energy, will be the first freshwater offshore wind project in North America and will produce electricity to power over 7000 homes. The 20.7 MW project will be located 13 km off the coast of Cleveland, Ohio in Lake Erie in water 18 m in depth. The distance from shore was selected based on available meteorological tower wind data from the Cleveland Water Intake Crib. Icebreaker Wind will interconnect with the Cleveland Public Power transmission system with secured rights to participate in the PJM market.

Findings from the Environmental Assessment have demonstrated negligible or minor, short-term impacts across resource areas. Preliminary analysis and monitoring shows minor, short-term adverse impacts on fish and avian species as well as lake water quality. Negligible impacts were reported for drinking water supply and quality, insects, and aquatic and terrestrial protected species. The project is also anticipated to create 500 jobs and to result in community, environmental, and health benefits. The project plans to be operational by the end of 2022 [2]. This project is of particular interest to developers considering projects in Canada since it is within Lake Erie, bordering the US and Canada. If successful, this project can settle environmental, economic, and regulatory concerns and catalyse future offshore development in the Great Lakes.

The Great Lakes have approximately 136 GW of technical resource capacity [37]. This number assumes that none of the water above 60 m in depth would be feasible for development due to icing concerns. An NREL study identified the Great Lakes as being relatively low cost due to the high-quality wind resource and general absence of extreme meteorological ocean events such as strong winds and waves [38]. Tides and water currents are negligible in the Great Lakes, and wave heights are much smaller than those in open ocean conditions [22]. Levelized cost of energy values for offshore development in the Great Lakes are estimated to be as low as \$75/MWh by 2027 [38]. The least-cost locations found are in Lake Erie, Lake Michigan, and Saginaw Bay in Lake Huron. These locations have strong wind resources that are close to shore. A wind atlas was recently developed for the Great Lakes to provide a blueprint for offshore wind resource assessment effort [4]. The wind atlas demonstrated that for most of the province, turbines at a height of 90m would be met with speeds greater than 8m/s and achieve a mean energy density of greater than 314 W/m$^2$ [4]. Additionally, Great Lakes shorelines are also peppered with coal plants, offering a low-cost opportunity for grid connection. Developers and regulators will be closely following the impact of the Icebreaker project to gauge the feasibility of future developments in the Great Lakes.

## Development of Offshore Wind in Canada

The offshore wind energy potential in the Atlantic and Pacific Oceans and in the Great Lakes is enormous. Boasting the longest coastlines in the world, offshore wind potential in Canada has been estimated at over 500 TWh/year [3] with British Columbia and Ontario possessing by far the most potential. The Great Lakes hold enough energy potential to power the entire country and the winds of Lake Erie alone could meet over 10% of our electricity needs by 2030 [2]. Barrington-Leigh et al. [3], set out to determine the optimal locations for offshore wind in Canada. The authors defined high potential offshore winds sites as those with large areas of water (> 25 $km^2$) with average depths less than 30 m and average wind speeds (at a height of 80 m above sea level) greater than 8 m/s. Based on those criteria, high potential sites were identified around four main areas: off the coast of British Columbia, the Great Lakes, the Gulf of St. Lawrence, and off the coast of Nova Scotia near the Bay of Fundy [3]. Although the maximum potential of these sites would ultimately be affected by shipping lanes, environmental concerns, and winter freezing over of fresh water (Great Lakes) [3], there is no doubt that significant amounts of clean energy could be supplied by offshore turbines in Canadian waters.

### Planned Projects in Canada

To date, there are no operational offshore wind turbines in Canada. There are, however, several offshore wind projects in the planning stages. In British Columbia the Naikun Wind Energy Group recently sold their offshore wind project to Northland Power Inc [39]. The 396 MW wind project will be located in the Hecate Strait between Gwaii and Prince Rupert, off the coast of British Columbia. This project has faced many setbacks, and is still in the early stages of development [39].

On the East Coast of Canada, Beothuk Energy Inc. has several projects in the pipeline. Beothuk's C$466 million, 180 MW St. Georges Bay offshore wind project is proposed to be located 30 km offshore of Bay St. George, with water depths averaging 40 m [40]**.** The proposed site has some advantages such as being outside of shipping lanes, away from bird migration routes, and near Emera's Maritime Link Transmission line. The company has also proposed a C$4 billion offshore wind farm 20 km from Yarmouth, Nova Scotia [40]. The intention for this project is to sell the energy generated from 120 turbines to New England through a 370 km subsea cable called the Can-Am Link [41]. Progress with this system has been delayed due to developments in other plans belonging to the project partners [42]. Beothuk has additional projects planned for St. Ann's Bay, Nova Scotia, Burgeo Banks, Newfoundland, and Prince Edward Island.

There was also interest in Ontario for implementing wind farms throughout the Great Lakes, however those plans were terminated in 2011 when the Ontario Government put a stop to all projects until more scientific studies are completed [43]. Originally, Ontario became an attractive location for offshore wind farm development due to the combination of the Great Lakes wind conditions, and the "Feed-in-Tariff" program that incentivized renewable power [43]. The government of Ontario stated the reasons for canceling projects for offshore wind farms in the Great Lakes included limited scientific research in fresh water wind turbines, even though there are hundreds of offshore developments in ocean waters throughout the world [43], and a few fresh water farms [43].

## Canadian Companies on the Global Offshore Scene

Canada has a vast experience in offshore and marine industries which makes the nation a strong candidate for offshore wind energy development projects. There are many synergies between offshore oil and gas and the offshore sectors suggesting transferability of knowledge and products between the two, as has already been demonstrated in the UK [44]. Similarities between the offshore oil and gas and wind industries are present at each step of the development process. The project management experience of offshore oil companies is important in the offshore wind industry due to their understanding of the harsh working environments, maintenance needs and coordination of working in offshore waters. Offshore oil and wind projects require similar expertise for the design and supply of equipment including substation structures, foundations, secondary steel, array cables and cable protection. Developers are especially likely to hire expertise from the oil and gas industry for cable installations, as it is considered a high-risk and challenging operation [45]. Many of the foundations considered in the offshore wind industry have been previously deployed in the offshore oil and gas industry, although under different loadings [45]. This understanding of the different foundation types can be transferred to determine the necessary design for a certain project's water depth, seabed, and loading conditions. Companies with experience in the construction and installation of offshore oil and gas platforms are also very well suited to apply their knowledge to offshore wind projects. Much of the equipment and skills required in the handling and installation of components is similar. Both industries have many standards, certifications, and maintenance requirements in common as well [45]. Due to the mentioned synergies above and many more, knowledge and skills obtained from Canada's years of experience in the offshore oil and gas industry can be transferred to applications in the offshore wind industry.

In order to introduce offshore wind to Canadians in the current offshore field, educational and training programs can be redirected for studies relating to offshore wind, and current graduates and employees in the offshore sector of Canada can be trained specifically on development of offshore wind turbines. Canadian companies are recognizing these and capitalizing on global offshore opportunities.

Northland Power, a Canadian company based out of Toronto, Ontario, is 85% owner and 100% operator of the 332 MW Nordsee One offshore wind farm in the German North Sea [46]. The wind farm is expected to produce an annual output of more than 1,300 gigawatt-hours of electrical energy, enough to supply the equivalent of approximately 400,000 German households. Northland also acquired 60% ownership of the 600 MW Gemini offshore wind project, located 85 km off the Netherlands coast. This project was completed ahead of schedule, in April 2017, and under budget. It is expected to generate enough clean and renewable energy to meet the needs of 1.5 million people in the Netherlands, and reduce the country's CO2 emissions by 1.25 million tons per year [46]. Northland also has 100% ownership of the 252 MW DeBu offshore project in Germany, 77 km from the Nordsee One project.

Enbridge, a Canadian energy company is also actively involved in the global offshore scene. In November 2015, Enbridge entered the offshore scene with its acquisition of a 24.9 percent stake in the 400 MW Rampion project developed by E.ON [47]. The project consists of 116 Vestas 3.45 MW turbines located in the English Channel 13 to 20 km south of Brighton [47]. In February 2017, Enbridge also acquired 50 percent ownership (with the remaining 50 percent retained by EnBW) in the 497 MW Hohe Sea Offshore Wind Project located in the North Sea, 98 km off of the German coast [48]. The project will receive a 20-year fixed pricing contract under the German government’s offshore wind incentive structure. Recognizing the vast potential for offshore wind, Enbridge has also partnered with EDF Energy on the development, construction, and operation of three French offshore wind farms which would collectively produce 1428 MW of power [49]. The Saint-Nazaire Offshore Wind Project, 50% owned by Enbridge, is expected to enter service in 2022 [50].

With global offshore estimated to approach 234 GW by 2030 [1] comes exciting business opportunities for companies who can provide expertise and services to this sector. There are many ways in which Canadian companies can capitalize on the approximately CAD$350 billion dollars that will be invested in capital and operational expenditures over this timeframe. Project development, engineering services, software and modelling, research and education, marine vessels, geotechnical and geophysical services, turbine supply, electrical systems, and port facilities are some more of the areas of the offshore supply chain where Canadian companies could play a role [51].

## Current Best Practices for Offshore Wind in Canada

Three scenarios for Canada’s involvement in the offshore wind industry are considered: (1) install in Canadian waters and sell power to Canada or export power, (2) do not install in Canada and instead focus on exporting Canadian expertise and supporting the international supply chain, or (3) it is not yet beneficial for Canada to be involved in the offshore scene in any form.

Canada has a very high potential for the development of offshore wind along its coastlines, however, significant installations are not very likely in the foreseeable future due to a low value proposition of such development. Across the country, terrestrial space is largely available, which makes it difficult to accept the development of more expensive offshore wind rather than continuing to expand onshore wind energy. The Canadian federal and provincial governments have not provided many policies, funding, or support for offshore wind, which is a large barrier in its development across the country. In the US, government support, especially at the state levels, has been key in the development of necessary research, testing and project plans. Additionally, Canada already has a relatively clean energy grid, with many options for other clean energy sources that can be integrated further. Also, there has not been enough research completed on the effects of offshore wind in freshwater environments, which rules out any opportunities for development in the Canadian waters of the Great Lakes for the foreseeable future.

Offshore wind could provide many benefits for Canadian communities, especially for remote and coastal communities currently dependent on diesel-resources for energy, or with compromised energy infrastructure. The west coast and remote communities could be potential suiters of offshore wind use in Canada. However, challenges are expected in these areas due to the deep waters requiring floating technology and the potential icing which has not been largely tested in offshore installations. Floating wind turbines have been previously installed in global projects; however, the technology is newer, more expensive and has higher risk during extreme winds and waves. Without funding or support programs and further understanding of the challenges facing floating offshore wind technologies, installing offshore wind along the Canadian west coast or in remote communities is not recommended at this time. This is due to the uncertainties and lack of research in these water types. However, if supported as a research project, installations in these areas are important to further the understanding of challenges being faced by this technology.

Along the Eastern coast of Canada, there are very long shorelines; however, the population density along them are not very high. Considering the low population density along the Eastern shoreline of Canada, building up extremely large offshore wind farms may not be economical or necessary to meet energy needs. Due to this, installations of offshore turbines in Eastern Canada to only provide energy to Canadian populations is not recommended at this time. However, if the Canadian government provided more support, funding and research findings, developments in Canadian waters could become viable. Additionally, following the results of US offshore wind projects could provide valuable insight to optimizing projects in similar waters within Canada. The US has many projects in their pipeline for installations in waters along the Eastern Coastline, and an overwhelming interest as well as high targets for integration of offshore wind energy.

By following the successes of the upcoming US projects, especially those in similar waters, Canadian developers can use the lessons learned from the US to confidently implement infrastructure along the Canadian Eastern Coastline. Although the Canadian population density in this area may not be large enough for the full potential of offshore wind production, these developments could sell their power to bordering US states, where population densities are high [52]. This would allow Atlantic Canada to become a provider of offshore wind energy to Eastern US states looking to improve their green economy [53]. With the US actively building up its offshore wind capacity along their bordering shorelines with Canada, economics will play a large role in the ability for Canada to sell power generated by future offshore wind farms on its coast to the US. Even with the head start in offshore wind development and support within the US, this may be possible, as the US has developed restrictions on the use of foreign wind towers [54], [55] and vessels within their developments. These restrictions in infrastructure use will increase the costs of energy projects within the US [56]. With support from the Canadian Federal government an energy contract could be generated between the US and Canada, allowing the sale of Canadian generated offshore wind energy at a competitive price to bordering US locations. This could help in creating an economical plan for offshore wind project installations in Canada. However, further developments in both the US and Canada are necessary before development in Canadian waters to export energy sales becomes a practical next step for Canadian offshore wind developers.

In the current state, installation of offshore wind in Canadian waters for energy sales to Canada is not a feasible option for Canadian developers. Following the development of government support and further understanding of floating wind in waters similar to Canadian waters, installing offshore wind in Canadian waters for the sale of energy to bordering US states is recommended. In the present, Canada should contribute and benefit from global offshore wind developments by exporting expertise to projects elsewhere. This is the recommended best course of action for Canadian involvement in the offshore wind industry currently. Canadian expertise of the offshore oil and gas industry can be valuable when transferred over to offshore wind, as there are many synergies between the two industries. This has been proven by the many successful partnerships of international offshore wind projects with Canadian developers to date.

Future work should focus on the development of a supply chain database for offshore wind in Canada (similar to that provided by Marine Renewables Canada for other marine technologies) to identify expertise and capabilities within the country and match these to global project needs.

## Conclusions

The future for offshore wind energy in Canada is very promising. Global and North American capacity will continue to increase over the next decade, spurred by climate targets, decreasing costs, and resource quality. This will require massive investments in the offshore sector but will also generate many great benefits. Canada has abundant resources, experience, and interested developers to support offshore wind development. There are several advantages that offshore wind boasts over its onshore counterpart, including stronger and more predictable winds, larger turbine capacity, and aesthetic appeal of installations far from shore and their suitability for powering remote communities. These advantages rationalize why offshore wind energy is an important consideration for Canadian waters and companies alike. However, the barriers to installation of offshore turbines make the decision for involvement in offshore installations difficult. Offshore turbines are much more costly than their onshore counterpart, and although they save on terrestrial space, Canada has expansive land available currently. These findings are in parallel with [57] who also found that due to the abundance of land and alternative lower-cost energy sources, it is unlikely for offshore wind to take off in Canada. However, this statement did not consider the potential for sales of energy generated by offshore wind to the US. Additionally, in European waters, where offshore wind is the most popular, turbines are developed for much more shallow waters than there are in Canada, and do not face as high weather concerns including icing, and therefore uncertainties in the necessary technologies are present. It was also found that the lack of government support and related policies is a major obstacle for the growth of offshore installations in Canada. Studying past offshore wind developments and areas advanced in this industry, it is clear that support is necessary for initial integration to be feasible.

Although Canada is not currently poised to launch significant offshore developments, with the global growth of the industry projected to drastically increase, and Canadian businesses should be seeking out new opportunities in this sector. Providing expertise on international offshore wind projects is the recommended first step for Canada's involvement in the offshore scene. Immediate contribution to international projects can ensure leadership in the offshore wind supply chain internationally, and especially in North America, which is important due to the rapid growth of the industry. Recently, this has been stressed by [52] as US offshore wind projects advance, seeking international expertise. Canadian developers should also consider involvement in manufacturing offshore wind turbine parts, a potential that [58] considers Canada to be currently missing out on.

Following Canada's entry to the offshore wind supply chain, it is recommended that the next step would be to explore the potential of implementing offshore wind in Canadian waters to export power to the US. This second recommendation could be implemented after closely following the outcomes of US offshore wind developments. Eventually, with more support, funding, and declining technology costs, offshore wind energy may become a feasible option to meet the energy needs of Canada as well.

Canada is in a great position to benefit from lessons learned from the US, global experiences, and from the improvement and maturation of technology and growing investor confidence. The Icebreaker Wind Project in Lake Erie will provide a valuable case to evaluate North American specific impacts and gauge feasibility of future projects. In relation to Canadian policies regarding offshore wind, while the moratorium remains in place in Ontario, development will be limited. At the federal level, stable, coordinated policy is needed to offset high initial costs and drive development.

Finally, it is recommended that future work should develop a supply chain database to identify expertise in the offshore industry in Canada and match it to the needs of global offshore wind projects. The literature review and descriptions of projects to follow should be continuously updated as the industry grows, and installations advance.

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# Chapter 3 : Experimental Investigation of the Movement of an Offshore Floating Platform in Straight Wind, Tornadic Wind, and Downburst Conditions

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## Chapter Summary

There is growing interest in multi-purpose offshore floating platforms that: harvest energy from the sun, wind, water, and waves; desalinize water; host agriculture and aquaculture; and house residents. While there are some basic commonalities with well established, oil and gas platforms, lighter variants are functionally different with little wind research coverage. Here we investigate a floating, multi-purpose, light duty platform under 1:150 scaled straight atmospheric boundary layer wind (ABL), tornado like vortices (TLV), and downburst (DB) conditions. The experiments examined the movement of a 1:150 geometrically scaled platform with six degrees of freedom and two mooring Configurations. Four Configurations are studied, (1) Loosely moored platform, (2) Tightly moored platform, (3) Platform with ballast, and (4) Platform with ballast and weight on the deck. DB winds produced the greatest movement, followed by the TLV winds. Little movement was seen under the ABL winds. Loosely moored platforms moved more than tightly moored.

## Introduction

The number of applications for offshore floating platforms has expanded far beyond oil and gas floating production systems, or floating wind turbines [1]. Floating platforms are now being considered for multi-purposed uses, which could include offshore greenhouses or food production [2], solar farms [3], [4], residential real estate [5], floating airports [6], or entertainment facilities [7]. They can also be considered for holding compressors necessary for underwater compressed air energy storage. For some, these multi-purposed floating platforms are necessary to enable island living, while in other cases, they have been relied upon to improve reliability and resiliency of energy generation and to provide energy storage and clean water [8].

Offshore energy applications are experiencing increasing interest owing to growing energy demand, climate change, and the desire for clean energy sources. The 2019 International Energy Outlook report predicted that worldwide energy consumption will increase by nearly 50 percent between 2018 and 2050 [9]. The IEA proposed that renewable energy will be the fastest growing source of electricity generation enhanced by technological improvements and government incentives [9], [10]. Although many uncertainties remain regarding the effects of the Covid-19 pandemic on the future of energy innovations, it was still predicted that the only energy source expected to grow this year is renewables, as they are to take the "center stage" in the future of energy [10]. Momentum is building, particularly with new pressures reshaped by pandemic stimulus spending [10]. Increasingly, countries understand that new infrastructure spending should support clean tech projects that bolster national economies and benefit the environment.

Due to the embryonic state of these newly developed multi-purposed floating platforms, few studies have considered the dynamics of such systems. The US Federal National Offshore Wind Strategy states that a gap remains in the understanding and development of design practices for extreme weather conditions at offshore sites in the US [11]. As climate change continues and the weather becomes less predictable, extreme weather conditions will become more frequent and more powerful [12]. More research must focus on the necessary design standards for offshore floating structures under extreme weather conditions [11].

Vulnerabilities of offshore renewable energy infrastructure have already been exposed. One example of an offshore wind turbine failure due to a lack of improved design standards is the Sway turbine [13]. The 1:6 scaled model wind turbine manufactured by Sway sunk on the Norwegian coast in 2011. The test was modeled to withstand wave heights up to 4 m, but failed after waves 6.3 m high filled the tower with water [13]. At full scale, the turbine would have faced waves 40 m high. A hundred-year wave does not exceed 30 m, so the Sway turbine experienced very unlikely conditions [14]. Further testing and understanding of these unlikely, extreme events are necessary to avoid these failures in the future.

Simulations and experimental tests have been completed on offshore structures [15 – 17]; however, the majority take place in a wave tank or basin and are therefore only able to investigate wave loads. More recently, it has been recognized that it is necessary to consider both wave and wind loads, so recent testing has focused on both parameters. This has been accomplished by performing tests in a wave basin and adding a Configuration of fans to generate a straight-line wind load on the experimental area. While not entirely realistic, the method provides initial insight into the effects of simple winds on offshore structures. The Maritime Research Institute Netherlands (MARIN) Offshore Basin created a 1:50 scaled straight-line only wind generation set-up for model tests concerning wind and wave loading simultaneously [15]. The DeepCwind concept was developed and tested in many stages, and modifications of it were also examined [16]–[19]. These experiments involved testing non-optimized floating structure designs to compare the reactions of different generic floating Configurations to wind and wave loads. Here the spar buoy provided insight to the effect of lowered center of mass far from the center of buoyancy, while the Tension Leg Platform (TLP) based model showed reactions of a taut mooring stabilized system and the semi-submersible structure represented a system with a low center of mass and large water plane area. The study found that the order of systems with maximum surge was the semi-submersible, closely followed by TLP, while the spar experienced the smallest surge. As for pitch rotation, the spar saw significantly higher rotations, followed by the semi-submersible, while the TLP experienced very small rotations. The winds generated in these tests were added into the testing chamber using a make-shift array of 35 fans generating straight-line winds [19].

Further, a numerical study was completed to test the Configuration of the floating structure with various numbers of columns [17]. Experimental tests [20] were conducted at the wind-wave-current tank at Newcastle University to test the effect of a stabilizer on the motions of an offshore wind turbine. Tests with simulated waves, current and straight-line winds only were completed [20]. Other experiments focus on the effects the dynamics of the structure have on wind energy production. One study involved the testing of scaled wind turbine models first only in a controlled wave simulator tank and then with an industrial fan placed in front of the model to produce straight on winds [14]. The models were ballasted tension leg platform and spar buoy types. Findings showed that surge acceleration dominated over heave acceleration, and pitch rotations were minimal for each test [14].

Our review of the literature has not revealed any experimental studies similar to that described herein, which considers the effects of extreme weather events on the motions of a multi-purpose light-duty floating platform with multiple mooring line variations. Platforms were subjected to harsh wind conditions characteristic of those found in tornadoes, extreme thunderstorms, downbursts, and other strong windstorms. Introductory insights into these dynamics may serve as a starting point for additional studies and improved perspectives on stability, safety, energy efficiency, and suitable applications for these platforms.

# Methodology

All experiments in this study were performed in the Wind Engineering, Energy and Environment (WindEEE) Dome at Western University. This facility is a three-dimensional large-scale wind simulator designed to produce various types of flows, including the atmospheric boundary layer (ABL) winds, tornadoes, and downbursts [21], [22]. The testing chamber of this simulator is 25 m in inner and 40 m in outer diameter with a height of approximately 3.8 m. The simulator has 100 fans installed along six peripheral walls of the test chamber. Out of these, 60 fans are installed on one of the walls (i.e., the 60-fan wall) and used for the generation of different types of ABL and shear flows; [21], [23] (Figure 3-1).

*Figure 3-1:WindEEE Dome chamber showing the 60-fan wall and bell mouth (Hangan et al., 2017)*

## Wind Profiles

Within this experiment, the floating structures are subjected to three different wind profiles, an open water ABL straight-line wind test, Tornado-Like Vortices (TLVs), and downburst-like (DB) outflows. The set-up for experiments with each wind profile can be seen in Figure 3-2.

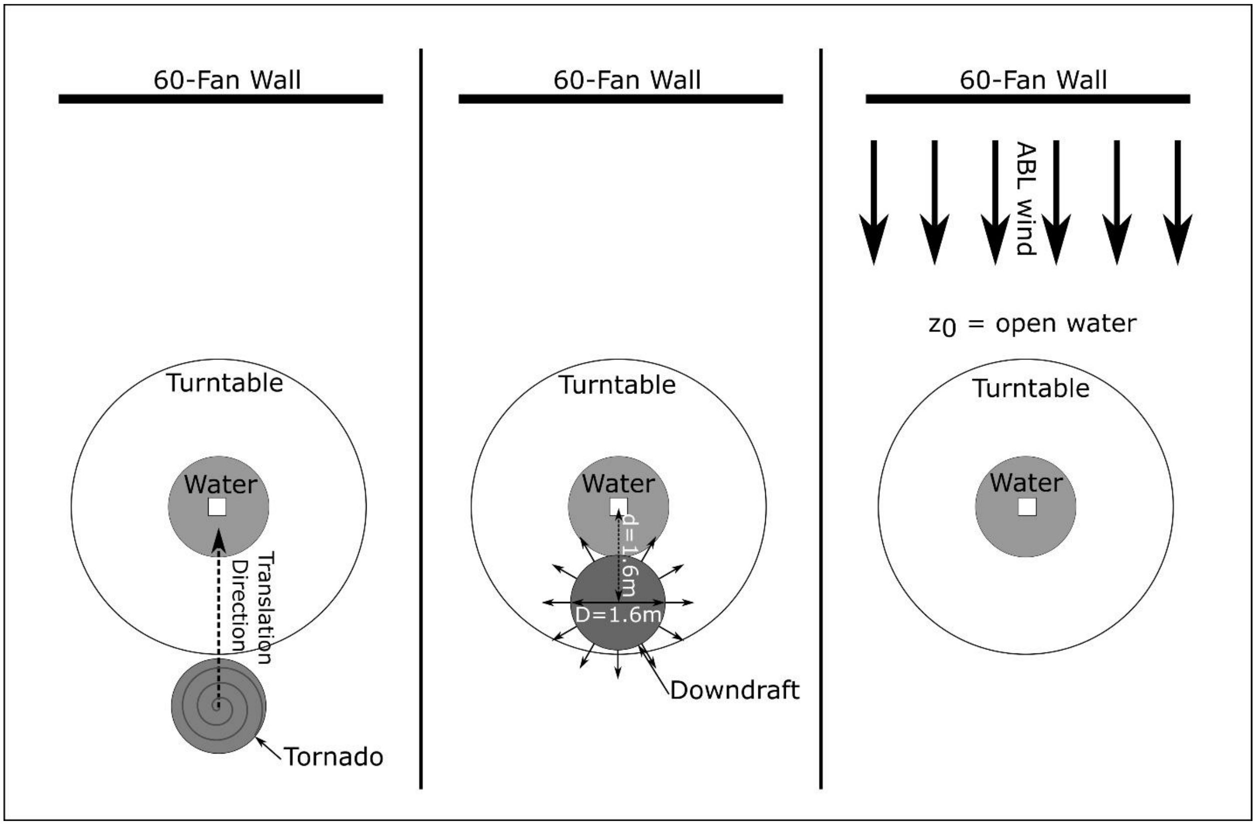


*Figure 3-2: Experimental set up for (a) TLVs (b) DB outflows (c) ABL winds*

An open water ABL wind profile (roughness length, $z_0$, of 0.003 m) at the geometric scale 1:150 was used for the straight-line wind tests in this study [24]. In this Configuration (Figure 3-2c), the roughness elements in front of the model were raised at 25% of their nominal height. No spires, flow contraction devices or trips were used in the generation of ABL winds. The fans in each of the four rows of the 60-fan (Figure 3-1) wall were operated at 70% (bottom row), 75%, 70% and 70% (top row) of their nominal revolution per minute (rpm). The matching of the generated velocity profile against the ESDU (Engineering Sciences Data Unit) profiles for large expansion of water was reported in [21].

The tornado-like vortices (TLVs) in the WindEEE Dome are produced by employing 6 large fans situated in the upper plenum to generate updraft and the system of peripheral louver vanes to create swirl in the inflow [25], [26] (Figure 3-2a). The upper plenum and the test chamber are connected through a bell mouth with a diameter of 4.5 m. The depth of the inflow that enters the testing chamber through the louver vanes is 0.8 m. The angle of louvers was set at 15°. The geometric scale of the produced TLVs in this study is ~1:150 [26]. The TLVs were translated over the model at the velocity of 0.5 m $s^{-1}$ using the guillotine system that moves the bell mouth over a 5 m distance (Figure 3-2a). In addition, the generated TLV corresponded to an EF1-rated [27] real tornado in the atmosphere (e.g., validated against the Goshen County, Wyoming, tornado in [26]). This TLV is a two-cell vortex with the swirl ratio between 0.5 and 0.8 [28]. The swirl ratio represents the relationship between the circulation the updraft intensity. Lastly, these TLVs are characterized by a maximum tangential velocity of 11.6 m $s^{-1}$ at 20 cm above the floor and 45 cm radially away from the center of the vortex [26]. No roughness elements or peripheral fans were used for these tornado tests.

The WindEEE Dome produces various downburst-like outflows by using an impinging jet approach. The event is initiated with the bell mouth louvers closed while the upper 6 fans are used to pressurize the upper plenum (i.e., reversed mode from the one used in TLV generation). Once the pressure difference between the upper plenum and the test chamber reach the target value, the bell mouth louvers are instantly opened and a downdraft impinges onto the testing chamber floor (Figure 3-2b) [29], [30]. Junayed et al. [29] and Romanic et al. [30] reported that the downburst-like outflows in the WindEEE Dome are characterized by geometric scales that vary between 1:100 and 1:200. Here a scale of ~1:150 was chosen as it was demonstrated by Burlando et al. [31] to be characteristically representative of downbursts that have been observed recently in the Mediterranean Sea [31]–[33] – home to several experimental multipurpose platforms. The centerline downdraft velocity was 8.8 m $s^{-1}$ [30]. The downbursts impinged on the bare floor without any roughness elements. The results shown within this paper were conducted at a radial location of $r/D = 1$, where r is the radial distance from the center and D is the diameter of the downburst jet. Accordingly, the radial distance from the center is 1.6 m, as the diameter of the downburst is 1.6 m. At $r/D = 1$ the flow reaches a maximum velocity [34], and maximum lateral spread [35].

# Experimental Set-Up

## The Water Tank

The tank was made of Expanded Polystyrene (EPS) Foam – Type II chosen for it's easy formability and light weight. The type II EPS foam was tested for water absorption and was able to withstand absorbing a significant amount of water for over 24 hours – longer than the length of this test. Therefore, Type II or Type III EPS foam were both suitable choices for the tank material. The foam was cut in multiple layers using a water jet machine and assembled within a silicone sealant adhesive. A 3D CAD model of the tank, displaying the different layers and final assembly, can be seen in Figure 3-3. A chemical water-proofing material was also added to the tank on all surfaces which the water would be touching. This guaranteed leak-proof seals on all seams. This was important as water damage is an obvious concern when bringing water into a wind chamber testing environment for the first time.

The tank was designed to have a water testing area of 1 m in diameter and 0.4 m deep This translates to a full-scale (considering a scale of 1:150) water depth of 60m, which could be considered "deep-water" in different offshore applications [36]. The water tank also included a slanted edge along the full diameter of the tank to encourage the dampening of wave reflections. This slanted slope allowed the waves to travel up the edge as it steepened and then break, reducing reflection back into the testing environment. This beach stretched 1.7 meters in diameter, and is at a slope of approximately 9.5 degrees, or ratio 1:6. This slope was tested both with and without an absorbent layer added on top of the slope. The final experiment did not include an absorbent layer as the minimal wave reflections were considered adequate without it.

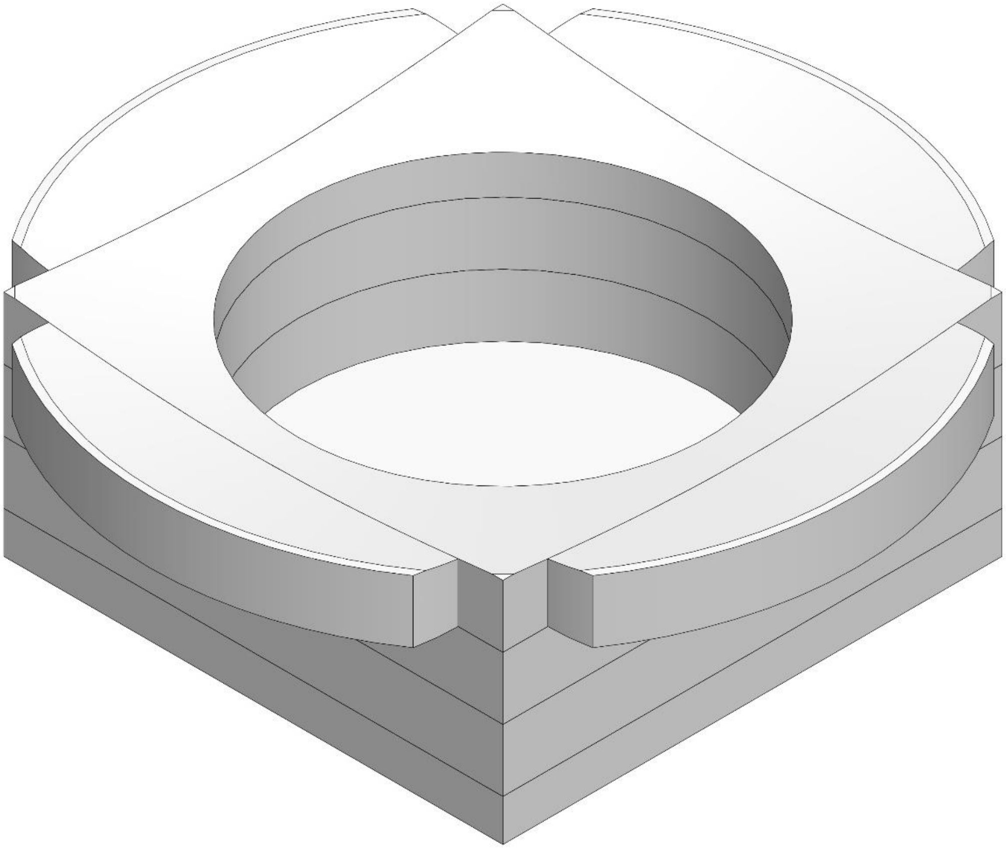


*Figure 3-3: CAD model of water tank assembly. The lines represent the adhered and chemically sealed layers of expanded polystyrene foam*

The wind chamber at WindEEE hosts a round testing platform, the turntable, which can rise and drop to allow objects being tested to be flush with the chamber floor for accurate projection of the wind profiles. Placing the water tank within the boundaries of this moveable turntable to be flush with the chamber floor, as shown in Figure 3-4, was the most cost-effective option to obtain accurate wind profile simulations and results from these tests. The turntable had strict weight and space limitations, which were the constraining factors for the design of the water tank testing environment in this experiment.

*Figure 3-4: Water tank installed flush with chamber floor in WindEEE testing dome*

## Floating Platform Design

The base platform was designed to be a simple, generic floating platform. The design of this model was initially inspired by the DeepCwind tested prototype designs [16], [17], then modified to suit materials, test components, and facility size. The geometry represents a simple light duty, multi-purposed platform, which could host many different offshore applications. The base platform, shown in Figure 3-5 (a), is a 0.3m x 0.3m multi-column stabilized platform, where the platform legs provide buoyancy and stability. The 4 main column legs located at each corner of the base, can be filled with water to assess ballasting effects on the platform movement in different configurations. At the center of the platform, there is a smaller column that provides further stability and buoyancy.

### Froude Scaling

Froude Scaling is used to determine the relationship between factors of the model within this study and its full-scale counterpart. A scaling factor of 1:150 was used here, denoting λ=150.

Since: $\lambda = \frac{L_{FS}}{L_M}$

FS = Full Scale
M = Model

It is important to consider scale factors to determine which characteristics will change by how much when converted from the model to the full-scale system. Commonly considered scale factors for Froude scaling is shown below in Table 3-1:

*Table 3-1: Scaling conversion factors for common variables using Froude scaling*

| Variable | Dimensions | Units | Scale Ratio | Full-Scale Multiplier |
|---|---|---|---|---|
| Length | L | m | $\lambda$ | 150 |
| Acceleration | $L/T^2$ | $m/s^2$ | 1 | 1 |
| Mass | M | kg | $\lambda^3$ | $150^3$ |
| Angle | | Deg | 1 | 1 |
| Wave Height | L | M | $\lambda$ | 150 |
| Wave Period | T | s | $\sqrt{\lambda}$ | $\sqrt{150}$ |
| Time | T | S | $\sqrt{\lambda}$ | $\sqrt{150}$ |

When Froude scaling is applied, it should be noted that Reynolds number scaling is not guaranteed. Within this study, the discussions consider the scale model only and focus mainly on the acceleration and rotational movements the platforms are subjected to.

## Parts and Assembly

The platform was designed to be made from easily accessible, machinable, and affordable parts for easy replicability. McMaster-Carr was the main supplier for most components, however many of them can be purchased at a hardware store. The EPS foam was from a local supplier. Table 3-2 contains descriptions of the parts used.

*Table 3-2: Bill of Materials for the floating platform design*

| Part No. | Part Number | Description | Size | Supplier | Quantity |
|---|---|---|---|---|---|
| 1 | 48855K23 | Thick-Wall Dark Gray PVC Pipe for Water, Unthreaded, 1 Pipe Size, 5 Feet Long | Pipe Size 1 | McMaster | 1 X 5” |
| 2 | 4880K780 | Standard-Wall PVC Pipe Fitting for Water, Straight Connector, White, 4 Socket-Connect Female | Pipe Size 4 | McMaster | 1 |
| 3 | 9283K320 | Polyethylene Plastic Snap-in Round Plugs, 0.99" to 1.08" ID | 1-1/4” Dia. | McMaster | 1 |
| 4 | 1608T107 | Drain, Waste and Vent ABS Pipe Fitting for Chemicals, Reducer, 3 x 1-1/2 Socket Female | Pipe Size 3 x 1-1/2 | McMaster | 4 |
| 5 | 1608T501 | Drain, Waste and Vent ABS Pipe, Size 1-1/2, 5 Feet Long | Pipe Size 1-1/2 | McMaster | 4 X 2.625” |
| 6 | 9750K440 | Panel Plugs, Polyethylene, Snap-in, for 3-1/2" ID | 3-7/8” Dia. | McMaster | 4 |
| 7 | 1608T102 | Drain, Waste and Vent ABS Pipe Fitting for Chemicals, Connector, 1-1/2 Socket-Connect Female | Pipe Size 1-1/2 | McMaster | 4 |
| 8 | 8505K741 | Cast Acrylic Sheet | 12” x 12” x 1/8” | McMaster | 1 |
| 9 | | Expanded Polystyrene (EPS) | 12” x 12” x 2” | | 1 |
| 10 | | Thick Pine Wood | 12” x 12” x 0.5” | | 1 |
| 11 | 74605A14 | Pipe Cement for PVC Plastic for 6" Maximum Diameter | | McMaster | 1 |
| 12 | 7425A5 | Silicone Sealant, Dow Corning 700, 10.1 oz. Cartridge | | McMaster | 1 |

To assemble the floating platform, the follow steps were followed. First, the PVC tubing was cut to the necessary length and smoothed around the edges. Four pieces of 1.5” diameter and 2.625” length ABS pipe (Part No. 5) was used for the legs at the four corners of the platform. The straight fitting connectors (Part No. 2 & 7) were glued onto the Acrylic Sheet (Part No. 8) to act as mounts for the legs to connect to. Next, each leg the 1 ½” tube was bottomed out in the reducer (Part No. 4) and adhered to it using the pipe contact cement (Part No. 11). Silicon sealant (Part No. 12) was used to seal around the seam of the pipe and reducer. Next, the snap-in round plug (Part No. 3) and panel plugs (Part No. 6) were sealed with silicone into the PVC pipe (Part No. 1) and reducers (Part No. 4), respectively. Sealant was smoothed around the edge of the pipes and plugs. The EPS foam block was cut in the middle to fit a waterproof hardware box for the IMU and microcontroller boards discussed in the instrumentation section. The acrylic sheet was then adhered to the EPS foam with silicon sealant, creating the platform “deck” and all edges were sealed. The legs can be fit to the mounts on the bottom of the “deck”. This should be a very tight fit. These legs should not be sealed with silicone as they must be removable to add water to the legs of the platform to monitor ballasting effects during the experiment. During set up at the facility the waterproof hardware box was added to the center of the platform and adhered to it. The cedar wood was assembled to the top of the “deck” for configurations requiring the additional top-heavy weight added on top.

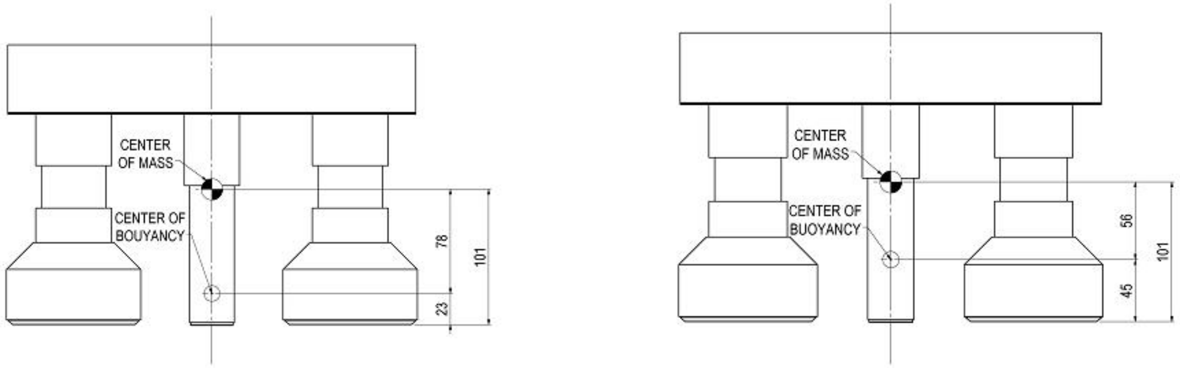
## Platform Configurations

Four Configurations (Figure 3-5) of the floating platform (Figure 3-6) were tested to evaluate the effects of extreme weather conditions on floating structures in different conditions of stability. The four platform Configurations were: (1) Base platform with loose mooring, (2) Base platform with taut mooring, (3) The base platform with ballast added into the legs, and (4) The base platform with ballast added to the legs and weight added to the deck. ABL, tornado and downburst wind profiles were tested for each experiment.

Each type of mooring line is attached at the bottom of the system’s four main column legs. Adjusting the tension within the mooring lines restricted how freely the structure could move. The loose mooring lines in Configurations 2, 3 and 4 hung loosely in a catenary shape and laid on the floor of the water tank allowing the platform to move relatively freely. The tight mooring lines were attached to a spring and pulled the system into the water to generate a draft of 100 mm. This restricted the movement of the platform and increased the center of buoyancy of the system in Configuration 2. Configuration 3 was the base platform with the addition of 140 grams of water ballast into each of the four corner legs of the platform. This lowered the center of mass and raised the center of buoyancy. The addition of weight to the platform deck in Configuration 4 increased the center of mass more than Configuration 3, and increased the center of buoyancy as the platform was lowered further into the water. A summary of the locations of the center of mass and buoyancy along the centerline of the structure for each of the four Configurations is found in Table 3-3.

a) Configuration 1

b) Configuration 2



c) Configuration 3

d) Configuration 4

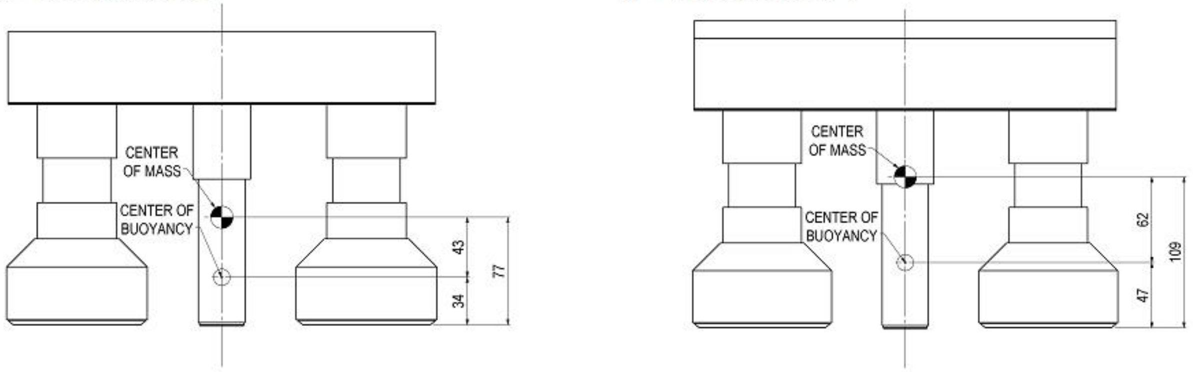


*Figure 3-5: 2D schematic of each Configuration of the floating platform model showing the location of the center of mass and center of buoyancy measured from the line of reference at the bottom of the structure legs (a) Configuration 1 (b) Configuration 2 (c) Configuration 3 (d) Configuration 4*

*Table 3-3 Comparing the Center of Mass and Center of Buoyancy of each Configurations. All measurements are taken from the bottom of the platform legs.*

| Platform Configuration | Center of Mass (mm) | Center of Buoyancy (mm) | $D$ [Center of Mass – Center of Buoyancy] (mm) |
|---|---|---|---|
| 1 | 101 | 23 | 78 |
| 2 | 101 | 45 | 56 |
| 3 | 76 | 34 | 43 |
| 4 | 109 | 47 | 62 |

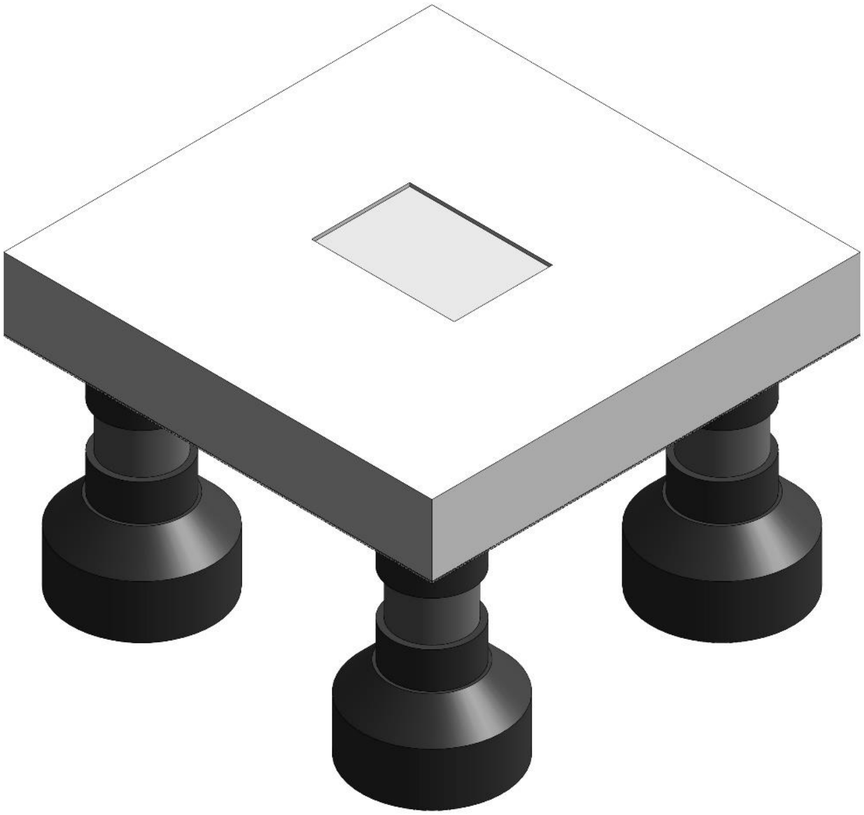


*Figure 3-6: CAD model of the "base" Configuration of the floating platform*

## Instrumentation

Experimental data were obtained using various instrumentation to record the six degrees of freedom of the floating platform, as well as the wind profile characteristics for each test. The set-up of this instrumentation can be seen in Figure 3-7. The sampling interval for ABL winds was 180 s, while the duration of TLV and downburst flows was 90 s and 120 s, respectively.

### Accelerometer

An accelerometer was placed on the top center of the platform. The accelerometer tracked the acceleration of the platform in the $X$, $Y$, and $Z$ directions at a sampling rate of 1250 Hz.

### Wave Probe

A resistance wire wave probe (labelled as 2 in Figure 3-7) was placed near the platform location to measure the wave heights at a single location. This wave probe can provide insight into the reaction of the water within the tank to the wind, tornadoes, and down burst of different profiles. This wave height data is synced up with the two accelerometers which were placed on the platform in the middle and back right corner to create an easy analysis of the platform acceleration vs. wave height at a single spot for any instant during each test.

### Inertia Measurement Unit Device

An IMU device [37] was connected through a breadboard to an Adafruit Feather microcontroller board with LoRra radio transmission. This assembly was place in a waterproof box and assembled to the hole cut out in the center of the platform deck, labelled as instrumentation number 3 in Figure 3-7. The IMU device recorded the actual orientation of the platform using the built-in accelerometers and gyroscopes and output the rotation of the structure in degrees. From this data the pitch, roll and yaw are determined. This microcontroller with LoRa transmission was able to wirelessly transmit the data across long distances, of up to 20km. This device had a lower sampling rate of approximately 6 Hz, but still provided a usable representation of the movement of the structure.

The weight of each of these instrumentation devices (Table 3-4) was considered when calculating the overall weight of the platform, and corresponding balancing factors, such as center of mass and center of buoyancy.

*Table 3-4: Model weights of instrumentation devices placed on the platform*

| Hardware | Model Weight (g) |
|---|---|
| IMU | 3 |
| Feather Microcontroller | 5.7 |
| Battery | 4.7 |
| Breadboard | 38.9 |
| Waterproof Hardware Box | 121 |

### Cobra probes

Four-hole Cobra probes developed by Turbulent Flow Instrumentation Pty Ltd. were used for all wind velocity measurements in this study. The applicability of the Cobras to measure highly turbulent flows—with the turbulence intensity reaching 35%—was demonstrated in [38]. In comparison to hot-wires, the Cobras are robust, insensitive to temperature variations inside the wind simulator, capable of measuring flows that are seeded with particles, and easy to use. The probes can measure the incoming flow with the yaw and pitch angles up to 45°. The manufacturer's reported accuracy of the Cobra probes is within ±0.5 m $s^{-1}$ and ±1° of pitch and yaw angles for turbulence intensity below 30%. The Cobra probes were also used in [25], [28] for measuring flows in TLVs, and in [29], [30], [33], [39] to measure downburst-like outflows in the WindEEE Dome. Their studies have demonstrated the applicability of these pressure-based probes in tornadic and downburst flows.

A total of 8 Cobra probes were installed on a vertical mast with the steel base. The probes were mounted at 3, 7, 10, 15, 20, 30, 50 and 70 cm above the floor. The Cobra probe mast is labelled as number 2 in Figure 3-7. The Cobras sampling frequency was set at 1250 Hz in all experiments to match the acquisition frequency of the accelerometer installed on the platform.

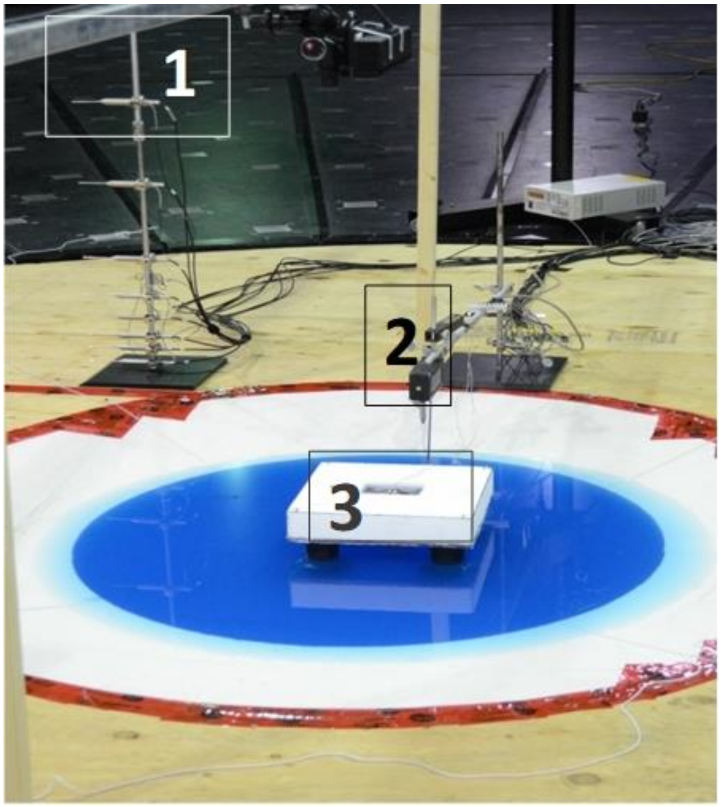


*Figure 3-7: Instrumentation Set-up: (1) Cobra Probes, (2) Resistance wire wave probe (3) Floating platform with the IMU and accelerometers. The ABL wind is coming from left.*

# Results

Here we examine the motions affecting the stability of the platform by studying the surge, heave, and pitch. Given the square profile of the structure and even weight distribution, rotations about the x and y-axes are easily related, so only the pitch is compared in the data shown. Similarly, the accelerations in the x and y-directions were comparative to one another, so again, only the surge is shown in the results, in part b) of Figures 3-8, 3-9, 3-10 and 3-11. The heave and surge accelerations, as well as pitch rotations, are depicted for each of the platform Configurations. Each acceleration and rotational data set is depicted separately and compared. Within each of the graphs, the movements of the platforms driven by the different wind conditions - ABL, TLV and DB – are graphed together. Each of the DB and TLV flow tests were conducted three times to ensure consistency between multiple runs. The ABL tests were conducted for a long period to ensure the reactions of the platform were relatively consistent for a long duration of wind subjection.

Each of the DB and TLV tests were run multiple times, and the ABL test was conducted for an extended period to ensure the reactions of the platform were similar in each repeated test. The different DB runs can be seen within the graphs in Figures 3-8, 3-9, 3-10 and 3-11 and are clearly similar in magnitude between each run. As for the TLV profile runs, only one of each test is shown below. The largest difference in the means of surge, heave, and for pitch for all tornado runs was 0.27 m $s^{-2}$, 0.02 m $s^{-2}$, and 0.75°, respectively. Comparing the results of each repeated test, it was observed that the shapes of the graphs were similar between runs. This suggested that the reactions to the wind profiles were similar between the repeated experiments.

Within this study we are examining the differences in movement between identical floating platforms with different Configurations. Firstly, we examine a basic floating platform loosely moored, and then tightly moored. Following this, we examine the effect of adding ballast to the legs of the loosely moored platform to lower the center of mass of the structure, and then adding weight to the top to generate a top-heavy Configuration.

To improve understanding while discussing the findings in this paper, the magnitudes of the motions examined have been defined as follows: Within this paper the surge acceleration is considered small when the peak-to-peak amplitude is less than 0.6 m $s^{-2}$, medium when the peak-to-peak amplitude is between 0.6 m $s^{-2}$– 1.2 m $s^{-2}$, and large when the peak-to-peak amplitude is above 1.2 m $s^{-2}$. The heave acceleration is considered small when the peak-to-peak amplitude is less than 1 m $s^{-2}$, medium if the peak-to-peak amplitude is between 1 m $s^{-2}$– 2 m $s^{-2}$, and large if the peak-to-peak amplitude is greater than 2 m $s^{-2}$.The motions of the platform were significantly smaller in all degrees of freedom (DOF) when the structure was subjected to the ABL flow, in comparison to the TLV or DB flows for Configurations 1 and 2.

While the floating structure was loosely moored with only the base platform (Configuration 1), the maximum values of platform movement based on wind profiles was ordered: TLV > DB >> ABL for all motion directions (Figure 3-8 a,b,c). When the tornado passed over the structure, it caused similar responses in both the heav (Figure 3-8a) and surge (Figure 3-8b). The suction (i.e., negative pressure) within the TLV lifted the platform from the water, and consequently, the platform experienced a large positive surge and heave acceleration. It was then proceeded by a negative acceleration as the tornado passed over and into the surrounding water. The movements of the platform influence one another and since the loosely moored platform is free to move in many directions, the surge and heave movements have similar profiles. The drop in surge acceleration was of similar magnitude to the initial large rise. While the drop in heave acceleration was larger than its initial peak, as the tornado was able to push the platform down into the water as it passed over top. Following the drop in acceleration, both the heave and surge accelerations experienced small and then medium oscillations before completely settling at a new equilibrium of -1 m $s^{-2}$.

The surge and heave motion responses of the platform during the DB test on the loosely moored base platform system does not show similar patterns. However, the maximum and minimum acceleration values do occur at the same time. Just before the downburst hits the platform, there is a positive acceleration followed by a quick drop as the structure is forced down by the wind flow. The surge acceleration consists of large, high frequency vibrations of the platform back and forth between the starting position throughout the duration of the experiment. The heave acceleration experiences medium amplitude and high frequency oscillations around a temporary zero of approximately -3 m/$s^2$ before quickly accelerating upwards as the downburst concludes and then settling at the initial state.

The TLV flow caused significantly larger magnitudes of acceleration, which ultimately generated a larger force on the mooring system and platform components. This subjection to large forces on improperly designed, weak, or damaged systems could result in a yielding failure due to the large stress subjected to the structure. The repeated fluctuations caused by the DB flow are more likely to result in fatigue failure due to the recurring stress subjected to the system throughout the wind flow.

Figure 3-8c) shows the pitch rotations subjected to the loosely moored base platform system during each of the three wind types. When subjected to the DB flow, the system experienced a large pitch rotation of 19.8° when the flow hit and then remained at an angle, rotating slightly about this position for approximately four seconds before returning to equilibrium as the downburst was completed. During the tornado flow test, the structure experienced a large rotation of 13° in the negative direction, followed by a larger positive rotation of over 28°. For the loosely moored system, it appears that both TLV and DB flows could cause significant rotations to a possibly dangerous degree.

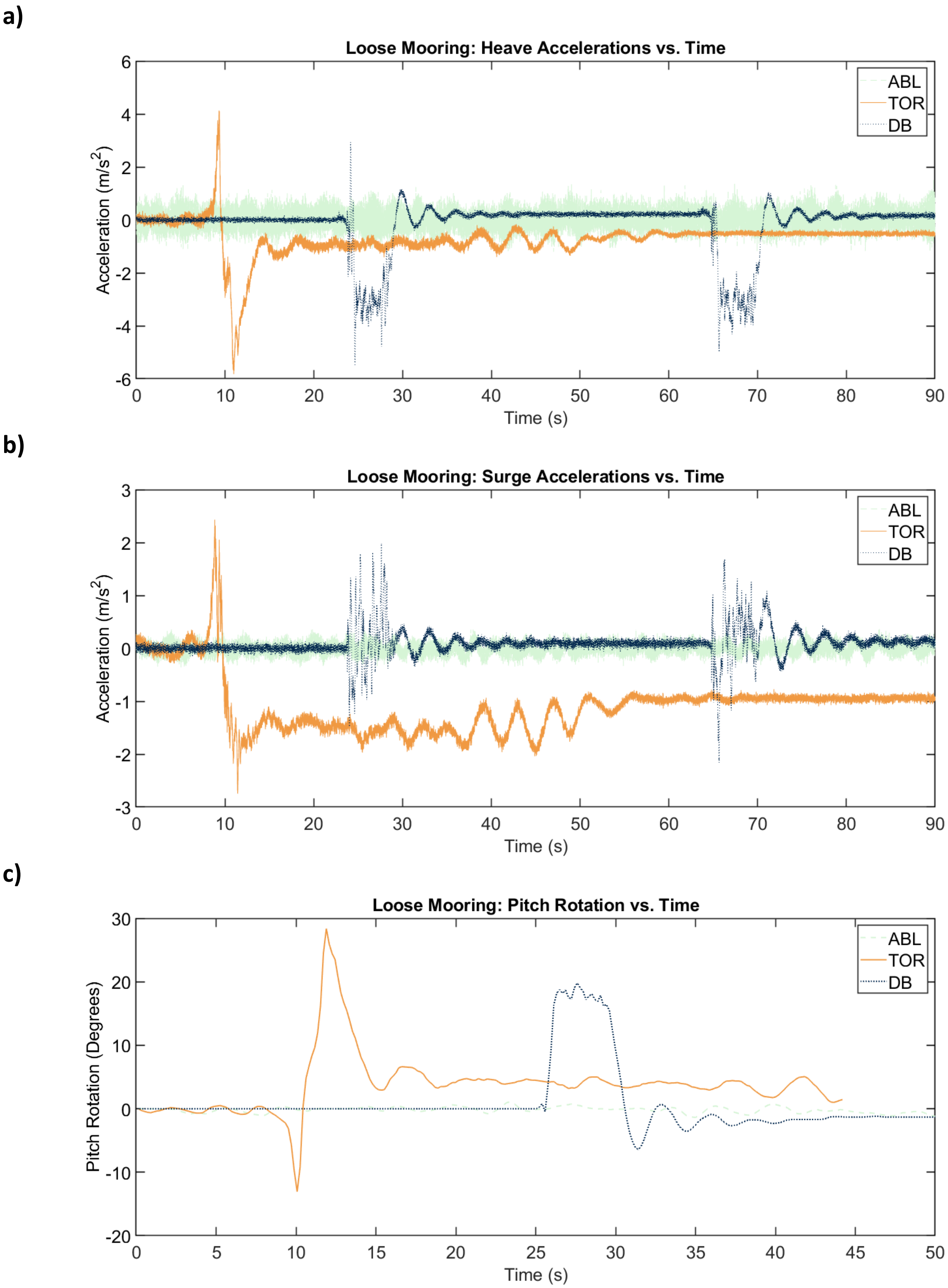


*Figure 3-8: (a) Heave acceleration, (b) Surge acceleration, and (c) Pitch rotation of Configuration 1 - Loosely moored base platform*

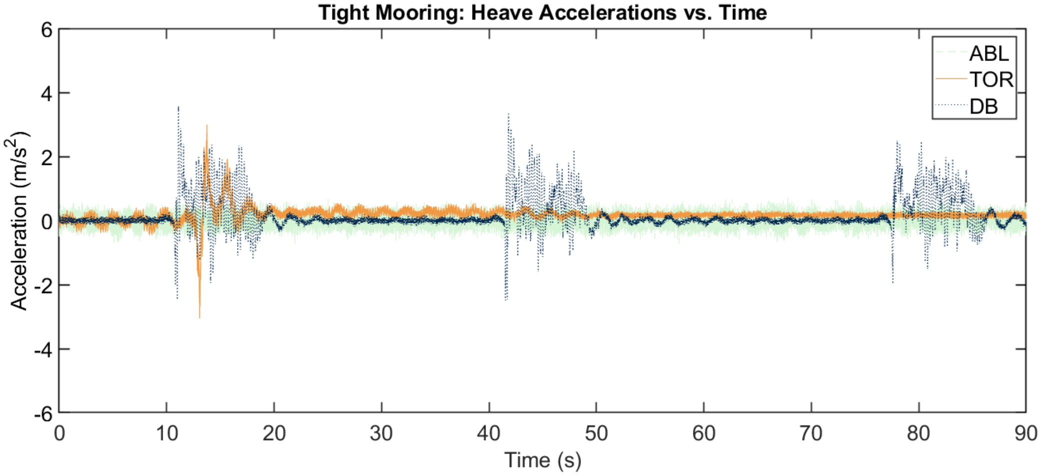
For the tightly moored system, the maximum values of surge acceleration (Figure 3-9b) and pitch rotation (Figure 3-9c) were ordered: TLV > DB >> ABL. However, the maximum heave acceleration for the tightly moored system (Figure 3-9a) was caused by the downburst, followed by the tornado and then was much smaller during the ABL wind profile (DB > TLV >> ABL). As expected, the tension in the mooring lines produced restriction in the structure's dynamics, causing the absolute maximum of any motion to be lower than that of the loosely moored system of the same design (base platform, no ballast as in Configuration 1). The ABL wind profile generated movements resulting in extremely small oscillations around the equilibrium position compared to the DB or TLV flows. Therefore, the dynamic responses to the TLV and DB flows are studied in more detail.

The tightly moored system generated similar magnitudes of acceleration during the downburst and tornado flows because the tight mooring lines helped to restrain the motion. While tightly moored, the TLV flow, again, caused a similar response to that of the other Configurations in surge and heave accelerations beginning with a large spike in surge acceleration. The heave acceleration of the tightly moored system (Figure 3-9a) during the TLV flow began with a negative acceleration, significantly lower in magnitude to the loose system of Configuration 1 (Figure 3-8a). The lack of initial positive spike in surge and heave acceleration was due to the restrictions of the tight mooring lines, preventing the platform from being pulled upwards out of the water due to the tornado. Following the initial negative spike in surge and heave acceleration, the platform experienced a few additional large oscillations which afterwards clearly dampened to medium and then small oscillation before ending in the equilibrium state. The dampening of the tightly moored platform is much more controlled than the loosely moored system of Configuration 1, due to the tight mooring lines pulling the platform back to the equilibrium position. The lower magnitudes of acceleration may reduce the likelihood of ultimate strength failure in the platform's components.

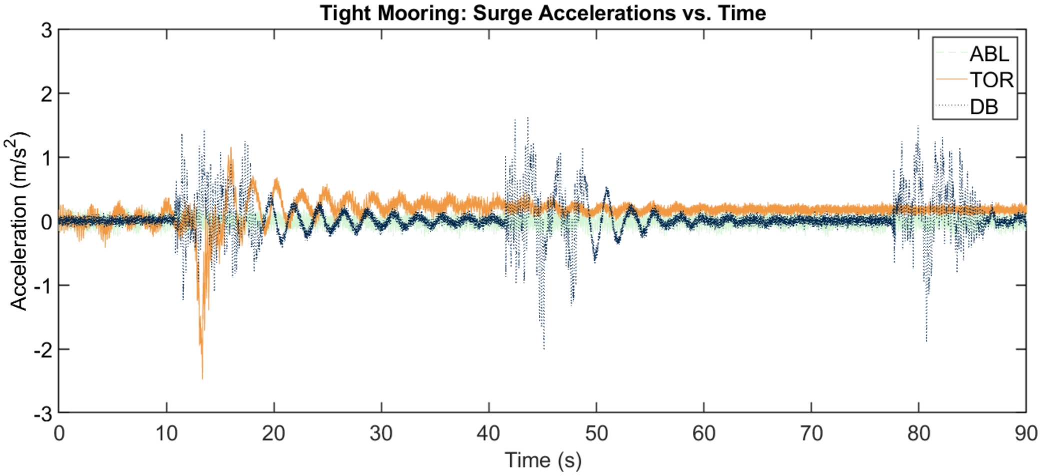
During the tightly moored experiment the magnitudes of rotation were similar for the DB and TLV flows, while the profiles of the rotations were not. The downburst caused a small negative rotation of 5.8° which climbed back up into the positive direction very slightly before settling down to the equilibrium level. The tight mooring lines kept the rotation during the TLV test between +3° and -6°, with only 3 large rotations followed by settling of the system. Compared to all other Configurations studied, the rotations during both the TLV and DB tests were significantly reduced with the use of tight mooring lines. These results are comparable to [19]. The comparable study tested three different types of platforms which were different in design, but the characteristics chosen for comparison were similar to the Configurations compared in this present study. In [19] the TLP was comparable to Configuration 2, as both consider the effects of taut mooring lines on the stability of the system, the semi-submersible platform is comparable to Configuration 3 as they both were chosen for their lowered center of mass, and the spar buoy is comparable to Configuration 4, as they both consider the effects of low center of mass and larger differences between the center of mass and center of buoyancy. Their study also found that the

TLP with tight mooring lines experienced significantly lower pitch values in comparison to the spar and semi-submersible studied.

**a)**



**b)**



**c)**

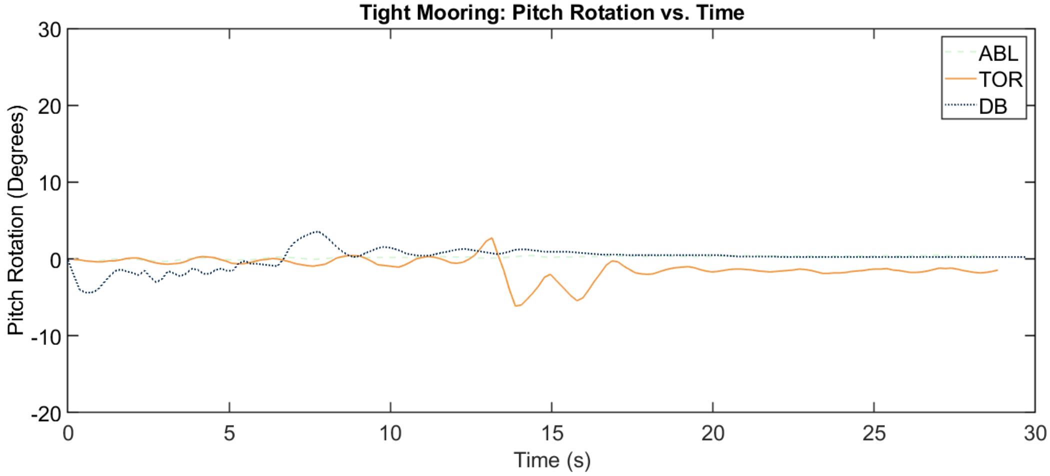


*Figure 3-9: (a) Heave acceleration, (b) Surge acceleration, and (c) Pitch rotation of Configuration 2 - Tightly moored base platform*

Next the effects of adding water ballast to the legs of the floating platform (Configuration 3), and then further, generating a top-heavy deck (Configuration 4) with loose mooring lines, are examined. Since floating offshore multi-purposed platforms can be considered for implementation in deep waters, it is important to consider possibilities of implementing these systems in areas where taut mooring lines may not be possible.

The dynamics of Configuration 3; the floating system with ballast added to the legs of the platform with loose mooring lines, are displayed in Figure 3-10a,b,c. The absolute maximum values for the platform movements of this system were ordered: TLV > DB > ABL, for both the heave acceleration (Figure 3-10a) and pitch rotations (Figure 3-10c). For the surge acceleration (Figure 3-10b) it was ordered: ABL > TLV > DB.

Configuration 3, similarly to the other Configurations, experienced a large initial spike when the downburst and tornado first hit the platform. Following this initial spike, the heave accelerations were greatly reduced in comparison to Configurations 1 and 2, however, the surge accelerations were not. During all three wind profiles, Configuration 3 experienced many large, high-frequency surge accelerations.

During the TLV wind profile, the response in acceleration generates a graph with a similar shape to the results generated from Configuration 1 (base platform, loosely moored), however, at different magnitudes. The system experienced a spike in acceleration and then experienced negative acceleration as the tornado moved across and passed over the platform. Following these initial peaks, the platform experienced one more large surge positive acceleration and then experienced a negative acceleration. This was likely caused by the sloshing effects of the water ballast within the system's legs. A small rise and fall can be seen in the heave acceleration corresponding to this reaction since the heave and surge accelerations are correlated. Subsequently, both the heave and surge accelerations continued at relatively low-frequency and medium-sized oscillations before settling back to a stable position.

The downburst generated a large negative acceleration of the system in the surge direction upon its execution, followed by many more large and high-frequency oscillations for around 15 s, which would be 184 s at full scale (for all subsequent instances of presenting times analyzed throughout these experiments the full-scale values will be presented in brackets following the experimental values). This Configuration took the greatest amount of time to settle from the large surge oscillations compared to all other Configurations.

The pitch rotation experienced by Configuration 3 when subjected to the TLV flow also generate graphs similar in shape to those of the pitch motions seen in Configuration 1, however, at different magnitudes. Configuration 1 had a maximum rotation of 28.38°, which decreased to a maximum of 10.5° in Configuration 3, an almost three-fold difference. A peak in negative rotation and then positive rotation was experienced, followed by additional medium-sized rotations before settling to the equilibrium position. The downburst caused two large rotations back and forth as the wind profile hit the platform, followed by many high-frequency medium-sized rotations for a period of approximately 30 seconds. This result is different from Configuration 1, where the platform was held on an angle during the downburst flow. In Configuration 3, it can rotate back from the initial response of the downburst hitting the platform, but consequently experiences more sharp, higher frequency rotations than seen before. Again, the absolute maximum rotation caused by the downburst was significantly reduced by the addition of the ballast. The ABL flow caused small, relatively controlled rotations with a maximum value of 1.38°.

For the test conducted in Configuration 3 the wave heights would correspond to full scale peak-to-peak wave heights of 0–7.5 m. Within [14] by Naqvi et al., the corresponding full scale wave heights were 0–7 m, which is comparable to the Configuration 3 in ABL wind test conducted in this study. In the Naqvi study the motion response of a ballasted tension leg platform and spar buoy in controlled wave and wind conditions was examined. It was found that the surge accelerations dominated the heave accelerations, which was also discovered for both ballasted systems (Configuration 3 and 4) tested in the present study. The surge acceleration generally resonated between ±0.1 g, with the maximum surge being approximately 0.98 m $s^{-2}$. The pitch rotations generated from this test were between approximately -0.75 to 1.75 degrees. Examining the graph of the Configuration 3 motion response to the ABL wind, it can be seen that most of the surge responses were within ±1 m $s^{-2}$, although the maximum values are higher at some periods within the test. The major difference between these two experiments is that within Naqvi's study the system is a tension leg platform while Configuration 3 is a loosely moored system. However, due to the comparable wave generations and subjection to straight wind flows it seems helpful to compare the two findings and to consider the cause of any differences. It is likely that the spikes in surge acceleration within Configuration 3 could have been avoided with more taught mooring lines, as used in [14]. The pitch rotations of Configuration 3 subjected to the ABL flow were between -0.56° and 1.34°, which again is comparable to the findings in Naqvi's study [14].

The findings for Configuration 3 in this study are similar to the findings of the semi-submersible in [19], due to both of these studies being compared for their lowered center of mass. In this compared study it was found that the semi-submersible platform experienced the highest surge response out of all three types studied [19]. In the present study, the surge motions of Configuration 3 were the greatest in both magnitude and frequency, compared to that of the other Configurations compared here as well.

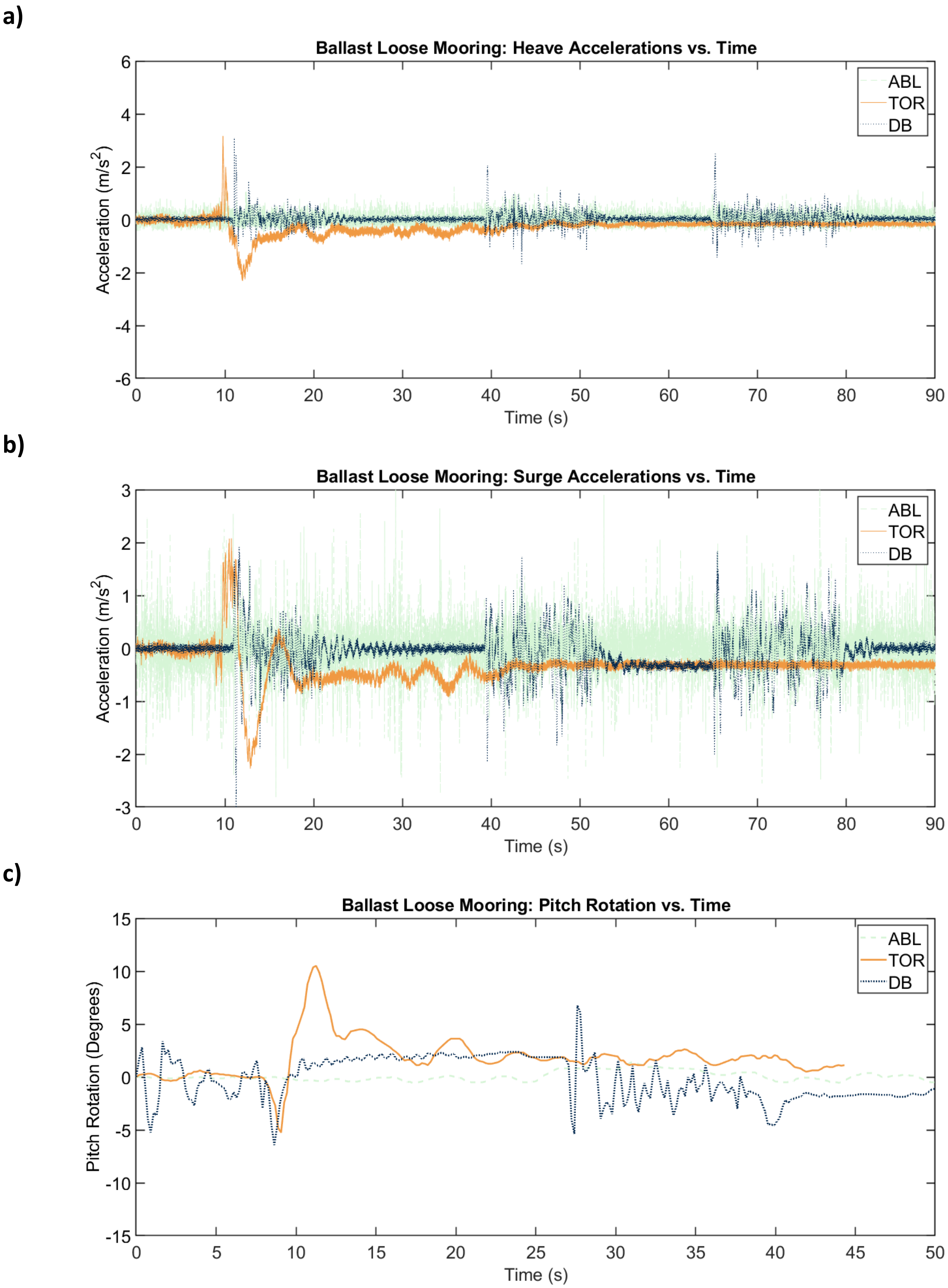


*Figure 3-10: (a) Heave acceleration, (b) Surge acceleration, and (c) Pitch rotation of Configuration 3 Loosely moored ballasted platform*

For the platform with additional top-heavy weight added to the system deck (Configuration 4), the order of maximum values of heave acceleration (Figure 3-11a) and pitch rotation (Figure 3-11c) were: DB > TOR >> ABL. The maximum values of the surge acceleration (Figure 3-11b) were of the order: TOR > DB >> ABL.

During the TLV flow, Configuration 4 experienced an increase in both heave and surge acceleration, as the tornado slightly lifted the platform and then passed into the surrounding water. This was followed by small oscillations which very quickly settled to the equilibrium position. When this top-heavy platform was subjected to the DB flow a sharp change in acceleration was generated as the downburst hit the platform. This was followed by small heave accelerations and medium sized surge accelerations for approximately 10 s (123 s at full scale) before the system steadied out to the equilibrium position. The oscillations following the initial peaks generated from the DB and TLV, but before the system settled to the equilibrium position, were significantly smaller in magnitude than those of Configurations 1 and 2 for the heave acceleration, and Configurations 1, 2 and 3 for the surge acceleration. Configuration 4 has the most obvious stability in the heave direction compared to any of the other Configurations.

The period it takes for the motion to settle back to its equilibrium position following the downburst or tornado hitting the platform is shortest in Configuration 4. The reduction in time needed to return to equilibrium for Configuration 4 is most significantly reduced, by 30–50 s (367-612 s) during the TLV wind profile compared to Configurations 1, 2 and 3. The ABL flow caused extremely small accelerations in both the heave and surge directions.

Comparing the pitch rotations of each Configuration, the tightly moored platform of Configuration 2 experienced, by far, the lowest and most controlled rotations. For the loosely moored systems, the addition of ballast in the legs of the platform significantly reduced the maximum pitch rotations of the platform, however it caused more sharp back and forth rotations during the settling of the platform after the downburst and tornado was completed. Further, the addition of a top-heavy deck on the floating platform in Configuration 4 increased the absolute maximum rotation during the DB from 8.88° to 9.44°. The TLV absolute rotation decreased from 10.5° to 6.88°. A study completed by Yang. et al found that with increasing water depth, the pitch rotation decreases [40]. In deeper waters taut mooring lines become less realistic, and platforms will likely be freer to move such as the ones in the present paper represented by the loose catenary mooring. The stability of the pitch rotation for configurations 3 and 4 could be dampened further in a deep-water application, generating a more stable platform.

Comparing these results to the findings of [19], the spar system is comparable to Configuration 4, due to the characteristics of both systems being a low center of mass and large difference between the center of mass and center of buoyancy. The results of [19] found that the surge of this Configuration was lowest in comparison to the other configurations in the study. In the study presented here, Configuration 4 did still experience large spikes in acceleration when the wind profiles first hit the platform, however, the motions following those peaks were the lowest of all other configurations.

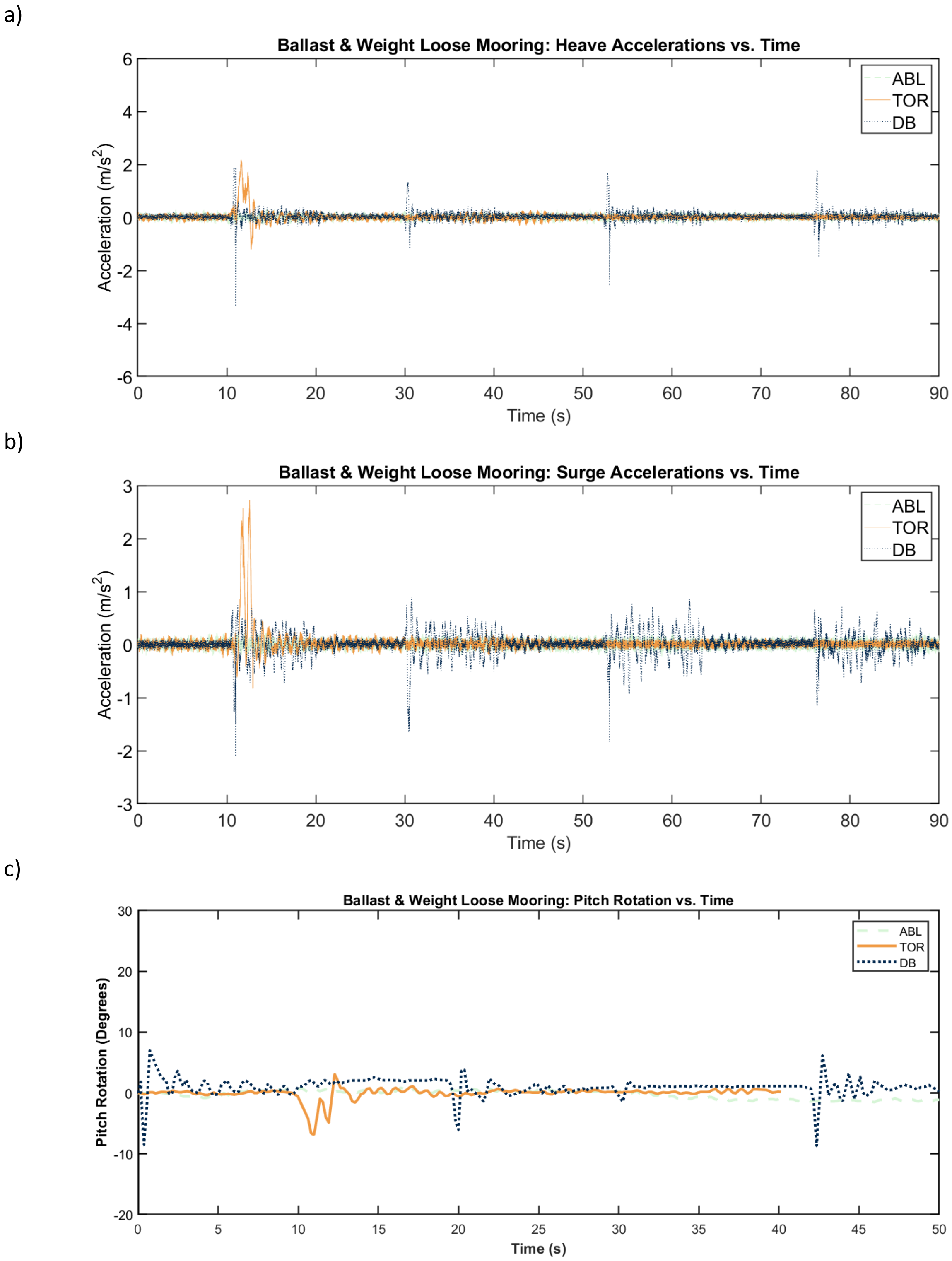


*Figure 3-11: (a) Heave acceleration, (b) Surge acceleration, and (c) Pitch rotation of Configuration 4 - Loosely moored ballasted platform with added top-heavy weight*

# Conclusions

Four Configurations of scaled models of a floating offshore multi-purpose platform were developed and experimentally tested with two types of mooring lines to examine the dynamic responses and stability when subjected to 1:150 scaled Atmospheric Boundary Layer (ABL), Tornado-Like Vortices (TLV) and Downburst (DB) wind flow. The experiments conducted within this study repeatedly resulted in large peaks and sharp movements caused by the TLV wind profile, followed by smaller but significant oscillations before the motions were able to return to equilibrium. The DB profile generated repeated high-frequency accelerations throughout its duration. The ABL wind profile produced very small accelerations and rotations for all tests except the surge acceleration of Configuration 3 (loosely moored and ballasted platform).

The tightly moored system in Configuration 2 experienced reduced motions compared to the loosely moored base platform of Configuration 1. The tight system absolute maximum values of acceleration were lower than the loose system, and the rotations were the lowest of all Configurations studied. Considering only the rotational response of the systems, the tightly moored system has by far the greatest stability.

Configurations 3 (ballast addition) and 4 (ballast and top-weight addition) did still experience large peaks when the tornado and downburst first hit the structure. Configuration 4 provided insight to the effect of raising the center of buoyancy of the system, with the loosely moored, ballasted, and top-heavy system. This system experienced very low accelerations following these peaks in comparison to the other loosely moored systems (Configurations 1 and 3) and even the tightly moored system (Configuration 2). The heave of Configuration 4 is significantly dampened, even at the peaks, resulting in Configuration 4 experiencing the greatest heave stability of all the tests. However, the peaks of the surge acceleration were high for this system. The ballasted system without top-heavy weight in Configuration 3 experienced even greater peaks for the surge acceleration, resulting in the highest absolute surge maximum of all the systems.

Additionally, the platform was forced on an angle for the entire duration of the downburst wind flow when loosely moored with no ballast. The addition of ballast in Configurations 3 and 4 generated lower maximum rotations compared to Configuration 1. However, the ballasted systems experience a higher frequency of sharp back and forth rotations during the downburst test and following the TLV.

Overall, the downburst caused higher frequencies and large magnitudes of oscillations of the floating system that lasted the entire duration of the downburst. This caused repeated stress on the structure's components that over time may result in higher fatigue loading of the system. The tornado generated very large platform movements with less significant oscillation, and thus likely producing a greater tendency to experience higher yield stress or potentially ultimate strength failure of system components. The long period of rotation subjected on the platform by the DB flow could also be detrimental to the platform and systems on top of it.

The loose mooring line systems are freer to move in any direction, which caused them to move more sporadically. This was especially obvious comparing the pitch rotations of Configurations 2, 3, and 4 to Configuration 1 with the tight mooring lines. The tight mooring line system was able to oscillate more closely and cleanly around the equilibrium point due to the forces from the mooring lines and the added buoyancy force from the platform displacing more water. The tightly moored system faced lower magnitudes of motion in all tests compared to the loosely moored system with no ballast. The tightly moored system did, however, experience a longer period of high-frequency oscillations of acceleration during the DB flow subjection, compared to that of Configuration 2.

The results of these experiments show that the stability of floating structures is much more varied under TLV and DB flows than it us under ABL winds, and the dynamic motions are much larger. Clearly, further studies of light-duty floating platforms under extreme winds and environmental conditions should be considered to advance design efficiencies and overarching safety concerns in this nascent segment of the offshore sector.

## Critiques and Recommendations for Future Research

Upon completion of this chapter and this work, some critiques and recommendations for future studies are presented below. Time, budgetary and resource limitations constrained some aspects of the experimental tests conducted at the WindEEE Wind Dome at Western University. Some of these limitations and corresponding recommendations for future testing are:

- The water tank was placed on top of the turntable device within the wind chamber, which has a maximum weight limit. If additional weight is necessary, supports would need to be added to the chamber turntable and possibly the chamber floor, or a deck would need to be built to fully support the tank on its own with the turn table fully lowered.
- The need for transportation of the water tank limited the size of the tank significantly. The water tank could be assembled at the WindEEE wind chamber to resolve transportation constraints. It is important to consider the time necessary to waterproof the tank after the assembly as well, especially if using a chemical sealant as in this study.
- There were concerns related to the uncertainties regarding the reaction of the water to the wind profiles, as well as the safety of the instrumentation since these experiments marked the first time that water was ever brought into the WindEEE wind chamber for testing. There was a very small amount of spillover of water from the water tank onto the wooden deck surrounding the tank during the experiments conducted in this study. To avoid the loss of water level due to a spill over, there should be an external chamber surrounding the water tank to collect the water spilled over during the experiment for protection of the wind chamber and instrumentation. A basic concept design for this improved water tank can be seen in Figure 3-12.

- Due to the weight limitations, and to ensure the water level is consistent throughout tests, this water should be collected and then redistributed to the tank immediately using a pump and check valve system at the bottom of the chamber collecting the water spill over. The purpose of the pump is to keep the water level in the tank consistent during the experiments. The pump pushes the reserve water into the tank from the bottom. Any extra water that fills the tank up will spill over back into the “water reserve” area of the tank. This includes extra water from the pump, or waves and other water that splashes out of the main water area. The check valve is used to prevent the higher water pressure in the main water area, from coming into the lower pressure area of the water reserve, when the pump is turned off.

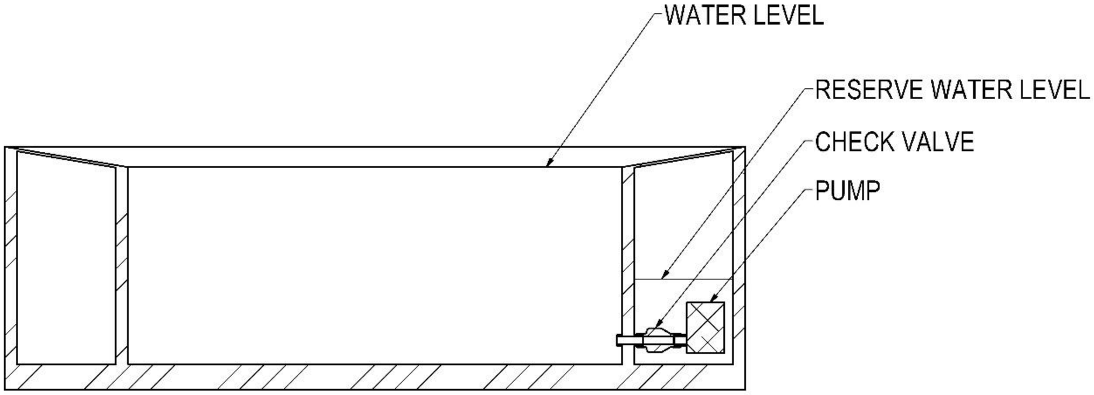


*Figure 3-12: Concept design for water tank with water collection reservoir, for use in future experimental studies in the WindEEE wind chamber*

- Timelines of availability of the wind chamber restricted the number of and lengths of the tests conducted. These experiments took a total of three days of set-up, two days of testing and one day of tear-down. A longer-term reservation may be necessary when testing the effects of all three (TLV, DB and ABL) wind types, as was completed in these experiments.
- To simplify the data analysis following the experiments, the instrumentation used for data collection should be synchronized.
- For further insight to the effects of different wind conditions on offshore systems, the tension in the mooring lines should be measured.
- Detailed designs should be created for scaled models of offshore structures either already installed in prototype or full scale, or with plans to install in prototype or full scale. The scaled experimental results should be compared to full-scale or larger-scaled structures.

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# Chapter 4 : Financial Model of a Carbon-Neutral Microgrid at an Ontario High School

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## Chapter Summary

Microgrids are systems of distributed energy resources and loads that can operate autonomously or synchronously with a traditional electricity grid. This work focuses on the business case for implementing a microgrid at an Ontario high school to meet their energy needs and net-zero carbon emissions. A 30-year financial model was developed to support project decision making and future investments at similar facilities. It considers several factors, including capital expenses, electricity and natural gas cost projections, CO2 emission credits, declining technology costs, savings from efficiency measures, and demand charge mitigation. It considers case-specific factors and non-monetary microgrid benefits, including increased reliability, environmental impact, carbon savings and education. Ontario-specific policies and incentives for technologies commonly used in microgrids are discussed. This project provides base-case scenario evaluation and sensitivity analysis of factors that could sway the economic feasibility of similar projects. Multiple scenarios are compared to determine the requirements for financially feasible microgrids.

## Introduction

Microgrids, along with their components of distributed and decentralized power sources, are growing in popularity as they change the way energy is being produced, transferred, and managed. A microgrid is a small energy network with a local source of inter-connected distributed energy resources (DERs), storage and loads. These units can be tethered to the main electricity grid or be independent of it while in an “island mode”. Islanding allows the system to provide a high level of security in the case of power loss on the main grid. A microgrid is strategically controlled and monitored to increase reliability for the facility and main electricity grid. Microgrids can feed energy back into the main electrical grid in times of excess demand to reduce major voltage increases and decreases, and can act as reserve energy in emergencies when demand is high [1]. Many microgrids take advantage of renewable energy technologies. Commonly referred distributed energy resources (DERs) are renewable generation, conventional generators, storage devices, electric vehicles and demand response. These technologies are experiencing declining costs and rapidly increased uptake [2]. Some major benefits microgrids offer to consumers is improvement of their sustainability profile, reduction in central-grid dependence and increased reliability of their electricity.

A study [3] conducted by Utility Dive highlighted concerns about the future of North American utilities. These include aging infrastructure and replacement costs, the growing demand for clean energy by utility customers, and the reliability of bulk energy distribution. Replacing aged electrical infrastructure with microgrid energy technologies can provide improved resiliency, reliability, and potentially reduced energy costs [4,5]. The shift towards electric vehicles is another concern for the current central grid energy providers. The projected increases in energy demand related to EV charging will be challenging to meet with many current electricity grids [6]. It is important that the necessary amount of EV charging stations be implemented across Canada to support the transition to electric vehicles. This comes at the risk of overloading the main power grid, unless this is done with smart charging, peak shaving or vehicle-to-grid bidirectional charging [7,8]. The utilities will be expected to supply the necessary power for these new technologies, which would ordinarily require additional power plants and transmission and distribution infrastructure [8]. Microgrids serve as a solution to the increasing energy demands, the pressure to reduce carbon emissions, and with regard to ageing central grid infrastructure [9], which should be moving towards a smart grids set-up. These systems provide a modular-type integration of new energy production and transmission resources, allowing progress on updating the main power grid or alleviating part of the electrical demand from it. This can result in significant cost savings for the main power grid and more support for the growing EV industry.

Microgrids have many applications [5, 8–10], including residential homes [11], communities [12–17], commercial or industrial facilities, military and remote locations [18–21], and universities or school campuses [6,22–25]. Campuses and institutions have typically installed microgrids due to social demand for renewably generated energy, remote communities implement them because of the economic infeasibility of developing large transmission lines and military bases to ensure energy security for crucial assets.

The University of California, San Diego (UCSD) campus is one example of a successful university-based and grid-connected North American microgrid that demonstrates a beneficial partnership with its local utility. This microgrid displays the highest standard of energy efficient buildings, which are strategically controlled to assist in reaching the campus' goal of net zero gas emissions by 2025. The microgrid collaborates with its utility as the greatest demand responder, lowering their loads when requested to do so and providing additional backup power to the main grid in emergency events [22,25–26].

The smart microgrid at the British Columbia Institute of Technology's (BCIT) Burnaby campus is an ongoing project being developed to provide insight to the future possibilities of an Intelligent Grid. This system is designed to manage all resources and loads within the smart grid. An intense number of technologies are placed at some buildings of major interest, such as smart metering and communication modules. This allows the campus to manage their energy uses and distribution strictly, exploring methods for reduced energy consumption, power losses and waste, and reduced demand peaks. BCIT is collaborating with utility companies and researchers to develop a plan for the requirements necessary to implement such smart-grid infrastructure and to develop an understanding of these advanced technologies [24].

The University of Genoa, Savona Campus, implemented a smart polygeneration microgrid as a demonstration of the abilities of these technologies. The microgrid, consisting of multiple generation, storage, and control units, has the overall goals of managing the energy produced and consumed within the campus in an efficient and economic manner. The system can forecast generation trends based on weather conditions but also adjusts its generation, distribution, and storage charging schedules according to real-time data. This data is logged and used for further research [27,28].

This work focuses on a microgrid pilot project that is being implemented at a secondary school in London, Ontario. The objective of the project partners was to design and size a system that would allow the school to meet their energy demand while achieving nearly net-zero carbon emissions by means of energy efficiency measures and the microgrid implementation. This project will demonstrate the capabilities of an Ontario education facility generating and storing its own energy and utilizing it at the most beneficial times, considering the finances and resiliency of the system.

This microgrid is to be owned, operated, and maintained by the project partners while the energy will be provided to the secondary school facility, the microgrid hosts, as a service. This is the energy-as-a-service methodology which is becoming popular in microgrid projects [23,29–30]. This model allows the school to implement these technologies without the burden of the high upfront costs as the microgrid owners will be paying the capital costs with the help of grants and incentives. It also reduces the costs of maintaining and managing the energy generation as it saves the school the costs of acquiring outside help with the necessary skills to accomplish these needs. The microgrid owners are professionals in this field, with the abilities to operate this microgrid themselves. Overall, this results in a low financial risk for microgrid hosts [30].

Specific technologies were chosen by the project partners to allow the school to generate a large amount of its own energy, store it, and use it to meet the electrical and thermal load demands of the building and in emergency situations for increased reliability. The design involves a rooftop photovoltaic (PV) system array, solar covered parking lot carports, electric vehicle (EV) car and bus charging stations, a microgrid controller, battery storage units and a geothermal heat source system. The system is meant to provide resiliency for both the facility itself and to the main electrical grid.

The focus of this work is evaluating the business case for this microgrid. As a pilot project, it is accepted that the technologies used within this system and integrating them together may not be fully optimized. Capital costs of such technologies are currently high, resulting in a large overall project cost. The cost of these systems is predicted to greatly decrease soon, which could render the microgrid costs to a more positive case. The costs of these technologies have already significantly decreased. Since 2010, the cost of large solar systems, similar in size to this project, has dropped from $4.2 per watt to $2.3 per watt [12], which is approximately a 45% cost reduction. It is projected that the cost of large solar systems will drop about another 45% by the year 2035, going down to $1.2 per watt [12].

From 2010 to 2015, the cost of lithium-ion battery storage systems decreased at an average of 23% per year. These costs are predicted to continue to fall [12,31]. Large scale battery storage systems have decreased by 50% since 2010, from $1300 per kWh to $740 per kWh in 2016 and continue to decline in cost. By 2035, it is predicted that the cost of these systems will be around $230 per kWh, resulting in approximately a 70% price reduction from the year 2016 [12].

The purpose of this financial model is to evaluate different scenarios to better understand the factors that will impact the economic feasibility of this, and similar projects. Microgrid economic assessments have been completed in the past, but many do not provide the level of detail needed to fully understand the current position of microgrid implementation costs and benefits. Some assessments of these systems only consider small microgrids which only are able to support a fraction of the full energy demand of a facility or area [6], while others focus on only one commonly understood area of energy consumption such as the lighting demand [6]. Some existing microgrid technical and feasibility models are produced using a modelling software [11,19,32], which commonly does not provide full details of the inputs and assumptions. Others discuss only one aspect of economics such as the overall levelized cost of energy (LCOE) [10] or complete basic calculations as a portion of multi-criteria assessment [18]. The model discussed in this paper states the inputs and assumptions made, providing an understanding of the parameters of the microgrid. These inputs and assumptions can be modified to model a different scenario, allowing a feasibility study to be completed on a different microgrid using the same process discussed here.

This financial analysis considers the full electrical demand for the secondary school, along with the current state of the facility and different possibilities for the future energy consumption. A common first step when considering a microgrid at an existing building is to consider energy retrofits to achieve maximum energy savings. Various energy savings initiatives were provided by the project partners and were separated into multiple scenarios for financial consideration. The implementation costs, maintenance costs and corresponding electrical, financial, and environmental savings are considered for each scenario within this model.

The business case for microgrids is not solely based on the financial benefit, as these systems have many attributes which cannot easily be measured but must be considered. This research looked at other benefits of the system, such as the environmental impact, carbon savings and educational benefits, which may not always be directed towards the microgrid owners or hosts but contribute to the project considerations [33].

The remainder of this paper is structured as follows: The next section will provide an overview of the project, the project partners and microgrid owners. This is followed by a description of the model development, including a look at the facility, its surrounding area, the building's current demand profile and its technologies. The third section gives a description of the chosen microgrid technologies. Information on the type of units, their impacts and costs were provided for use within this financial model and could not be altered or reconsidered within this model. This section is followed by a listing of the model inputs and parameters. The results of the model are then presented, followed by a discussion and an evaluative conclusion of the financial assessment.

# Model Development

## Facility Description

The secondary school being studied is in London, Ontario. The school and its affiliated school board is committed to investing in their facilities towards their objective of contributing to a carbon-free future. This facility is a 12 558 $m^2$ two-story building. The main months of operation within the building are from September to June, with part-time summer activities taking place in the remaining months.

The general schedule of use within the school is shown below. This follows a standard occupancy schedule for a secondary school in Ontario.

- Custodial staff arrive beginning at 06:00
- Teaching and Office staff arrive beginning at 06:30
- Students arrive beginning at 08:00
- Most students leave by 16:00
- Most staff leave by 18:00
- Custodial staff leave by 23:00

From approximately 18:00 to 06:30 the occupancy of the building is at less than fifteen percent and consists mainly of cleaning and maintenance staff. During this time heating, cooling, ventilation, and lighting demands are low. The rest of the day occupancy is much higher. From 06:30-08:00 the teachers and office staff arrive at the school. Students arrive around 08:00 and classes are run until 14:30. During class hours the occupancy of the school is above 90% and the building demands are much higher. As is common in London, Ontario, most students are transported to and from the school by bus. These buses are parked off-site when not picking up or dropping off the students. All teaching and maintenance staff at this facility arrive by their personal vehicles and park in the west lot. Currently there are no electric vehicle owners at the school. The facility includes two parking lots, one on the east, and one on the west side of the building. The west parking lot has 34 spaces while the east lot has 139 spaces. This schedule of occupancy is standard for secondary schools in Ontario.

A building automation system (BAS) controls the facility's main heating, ventilation, and air conditioning system (HVAC). Within this BAS program details on the building's HVAC system schedules of use are provided.

Both the occupancy schedule and the current BAS schedules were considered for energy reduction suggestions described in the energy audit and discussed below.

## Demand and Load Data

The historical load data for the school was analysed to determine the energy demand and carbon footprint of the facility. Future energy demands were predicted with the addition of various energy efficiency changes considered. Electric vehicle charging stations will be implemented for both cars and buses. Initially, only two EV chargers are to be integrated to this system, but for similar projects with more EV chargers, these additions have the potential to cause very large peak demands if many cars are charging at the same time. This system will use smart charging protocols to explore the abilities of levelling out the building's demand curve with EV chargers [7,34]. Additional generation requirements requested from the IESO controlled grid were also estimated and considered in the demand requirements for the microgrid system designed.

### Facility Hourly Electrical Demand

The breakdown of the past hourly electrical usage throughout the year is shown in Figure 4-1. This is based on the actual electrical demand data for the facility being studied throughout the year 2017.

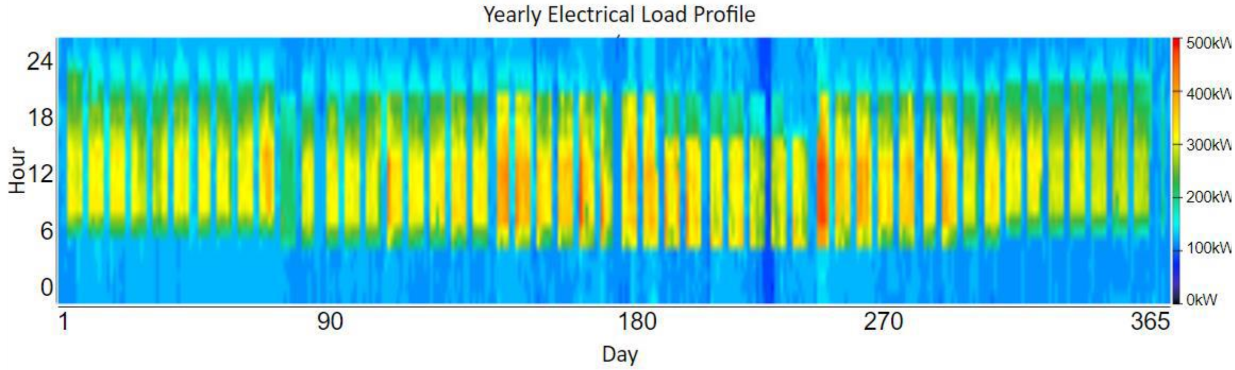


*Figure 4-1: The facility's hourly electrical load profile for 2017*

The electrical demand of the building generally follows the occupancy schedule of the school. The peak demand occurs during the school day from approximately 08:00 to 16:00, as shown in Figure 4-2.

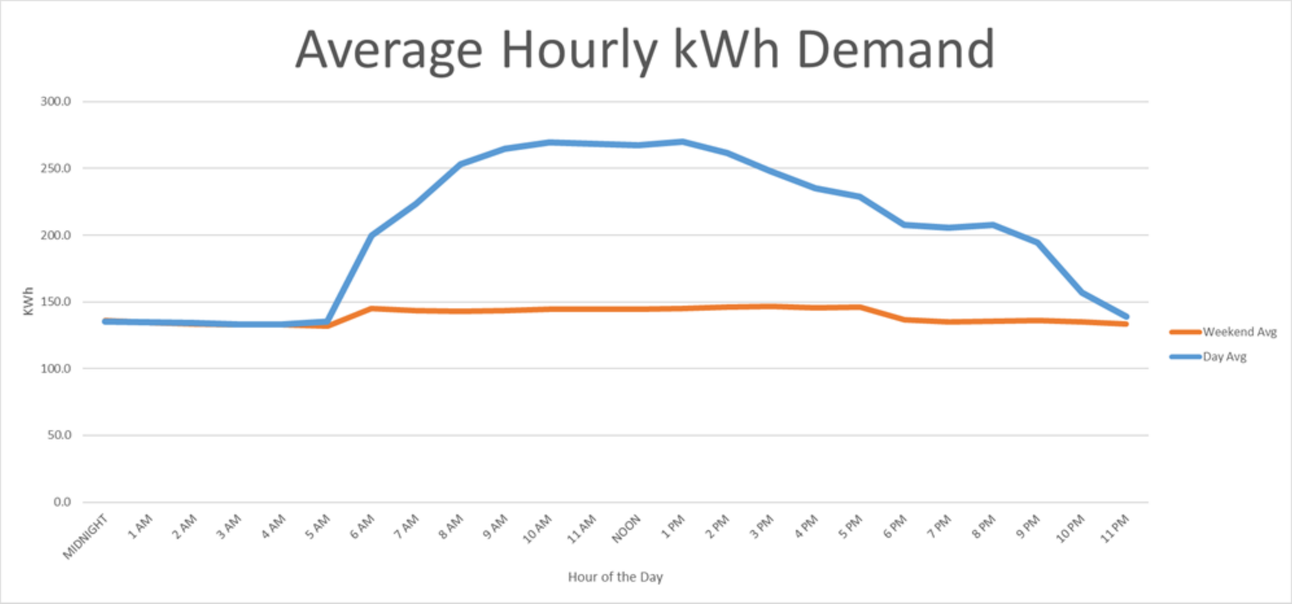
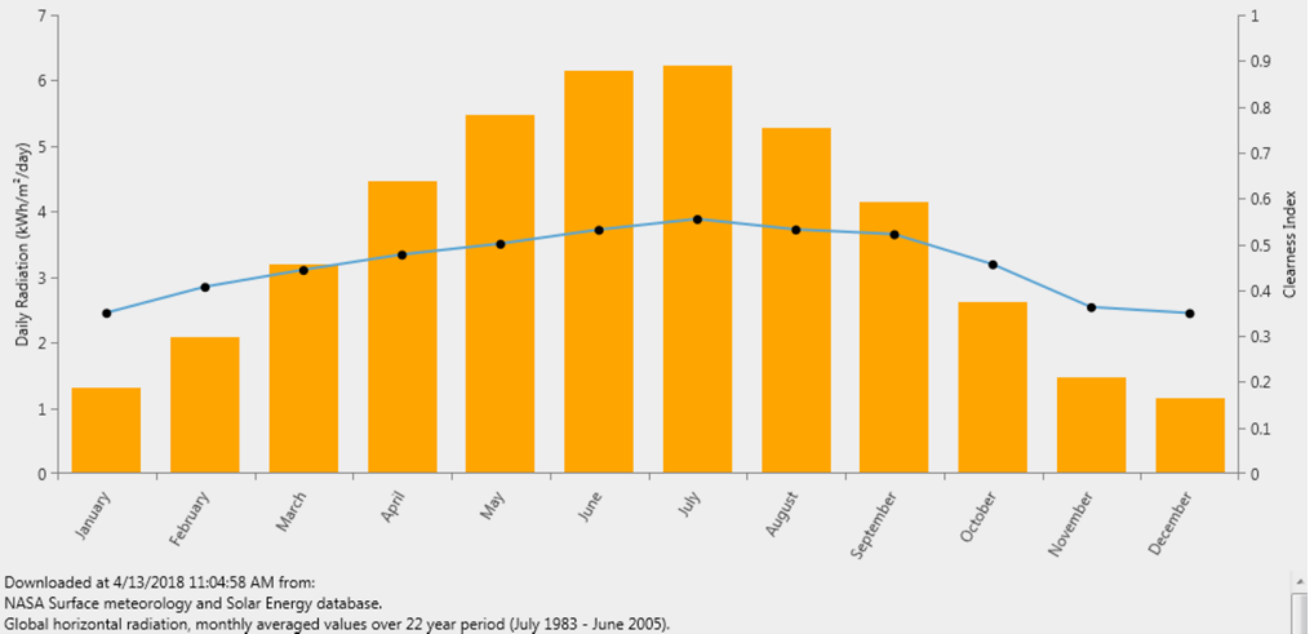


*Figure 4-2: Average Hourly Electrical Demand for One Day*

The demand data shows that there is low electrical use throughout the night with an increase around 06:00, when the first staff arrives. The electricity usage increases again around 08:00 when students arrive, then drops slightly around 16:00, at the end of the school day. The electrical demand decreases when the building shuts down for the night. The base load of the building during the night sits around 150 kW per hour. This load profile shows that most of the demand exists between 7:00am and 7:00pm with the peak usages occurring between 10:00am and 2:00pm. This coincides well with the optimal sunlit hours of the day, being the hours just before and after midday, meaning a solar array would be most efficient around the times of peak demand due to the intensity of the solar radiation available. The average daily radiation each month for the location being studied is shown in Figure 4-3, defining times of greater solar generation for the facility.



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NASA Surface meteorology and Solar Energy database.
Global horizontal radiation, monthly averaged values over 22 year period (July 1983 - June 2005).

*Figure 4-3: Average daily solar radiation in London, Ontario*

## Selected Microgrid Technologies

The project partners provided the microgrid design based on their analysis and optimization of the available technologies. The associated costs and impact on the system from these chosen technologies were also provided. Design characteristics were included as inputs to the model.

Based on the available area at the facility, the proposed microgrid suggested implementing an 805 kW photovoltaic system located on the school's roof and parking lot carports. Since the land surrounding the facility is limited, the roof and parking lot carports allow the implementation of large solar arrays without purchasing or destroying new land, conserving the overall environmental footprint of the project. The limit on available area to implement the solar array was the driving factor for the maximum size of the solar generation system. The roof has capacity for 1307 modules. These units are 350W solar panels, resulting in a total roof array of 457.45kW. A total of 128 parking spaces are to be covered by the carports, which includes the entire west parking lot and all south or north facing spots in the east lot. In total, 993 modules will be implemented on top of carport structures. This results in a 347.55kW system on the carport structures. These panels are spaced according to common panel shading calculations, considering a tilt angle of 10 degrees and -20 degree azimuth angle.

The design included a 2MWh battery energy storage system and 1100kW inverter, allowing a storage capacity of one full day of autonomy. This project will be used to develop an understanding of the costs, technical capabilities, benefits, and reliability of providing different services to the grid which it is connected to including energy reduction, regulation, ramping and operating reserve. This research will demonstrate how storage can be used to provide ancillary services to the main grid. A $500,000 grant from the IESO Grid Innovation Fund, discussed further below, was provided to the project to complete the research in this area.

A geothermal system is also included in the microgrid system, sized to enable the facility to minimize natural gas dependency. The only on-site natural gas usage will be from the kitchen facilities, which is very low.

To further encourage development and use of new clean technologies, the system also includes two electric vehicle (EV) chargers, despite the current lack in any EV drivers within the facility. These are incorporated with anticipation of the growing EV market and to encourage their use by employees and students at this school. The cost to use the EV chargers will be only the cost of electricity needed for the charge. Therefore, no revenue will be generated by these units.

Additional costs found in the financial model include the microgrid controller and switchgears (including SCADA and interface), circuit metering and peak power software analytics. Operating cost estimates of the PV and battery technologies were provided by the project partners.

## Photo Voltaic System

The PV system used for this microgrid allows for a self-generation of approximately 942,618 kWh. Based on the 2017 usage, this would require a net annual energy purchase from the grid of 580,378 kWh. In Ontario, this is charged by volume of energy, time of purchase, and peak hourly power demand, or global adjustment charges. With the microgrid, the energy purchase from the central grid at any hour by the facility can be controlled. In times of known high demand across Ontario, the facility can use their self-generated energy or stored energy from the battery to meet their needs. This can then eliminate high global adjustment charges as well as the reduce purchases during times of peak cost. Based on policies available in the area of this school, the excess generation at any time can be sent back to the central grid via Net Metering, receiving full credit in return. The graph in Figure 4-4 displays the schedule for energy purchases and sales from the central grid. The grid purchases largely occur during peak occupancy hours for the facility. Grid sales occur mainly during times of high PV production, and lower facility occupancy.

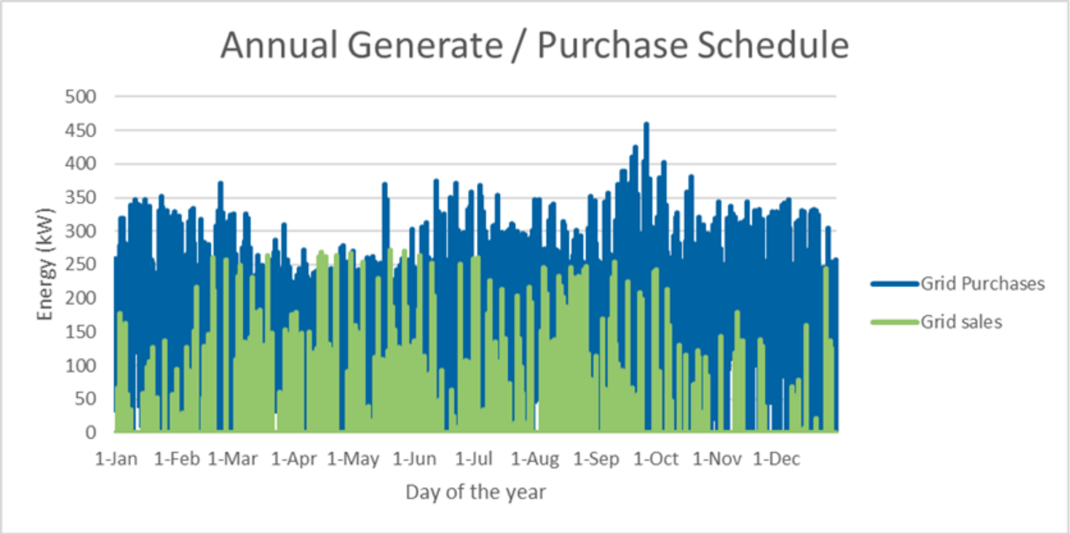
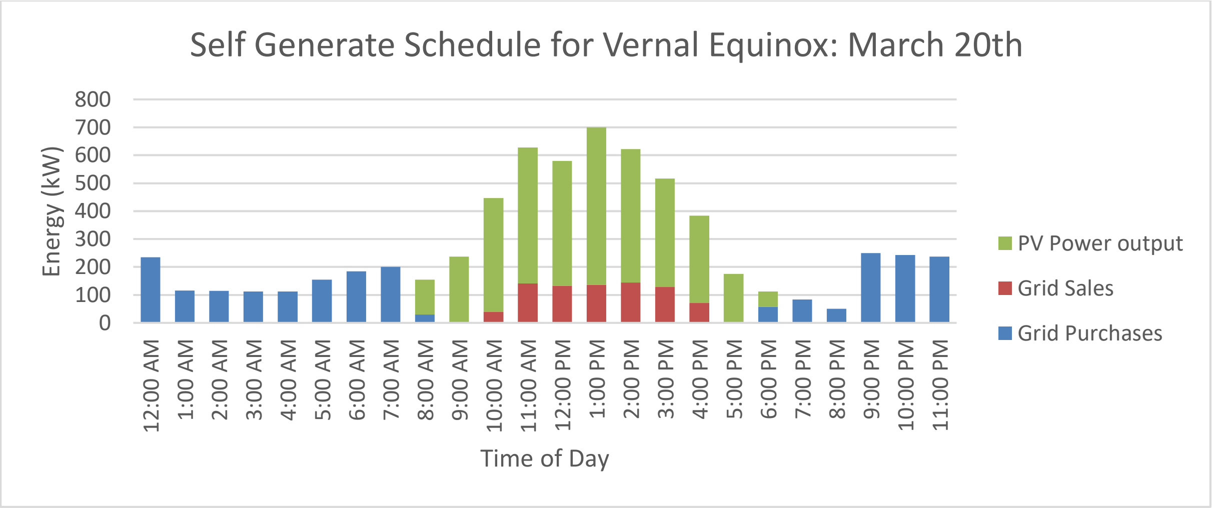


*Figure 4-4: Grid sales and purchase schedule*

Predicted self-generate schedules for the microgrid are provided for each season of the year in Figures 4-5a, b, c, d. The PV system is observed during the Spring and Autumnal equinoxes, and Summer and Winter solstice. Earth's axis is oriented perpendicular to the Sun's rays during the Spring and Autumnal equinoxes. This allows for even day and night times within these days. Summer Solstice, occurring on or about June 21, is the day which the Northern Hemisphere is tipped closest to the sun. The Winter Solstice, occurring about December 21$^{st}$ or 22$^{nd}$, is the day which the Northern Hemisphere is tilted furthest away from the sun. During winter solstice the area hosting this microgrid will experience the least amount of sunlight hours in one day.

a)



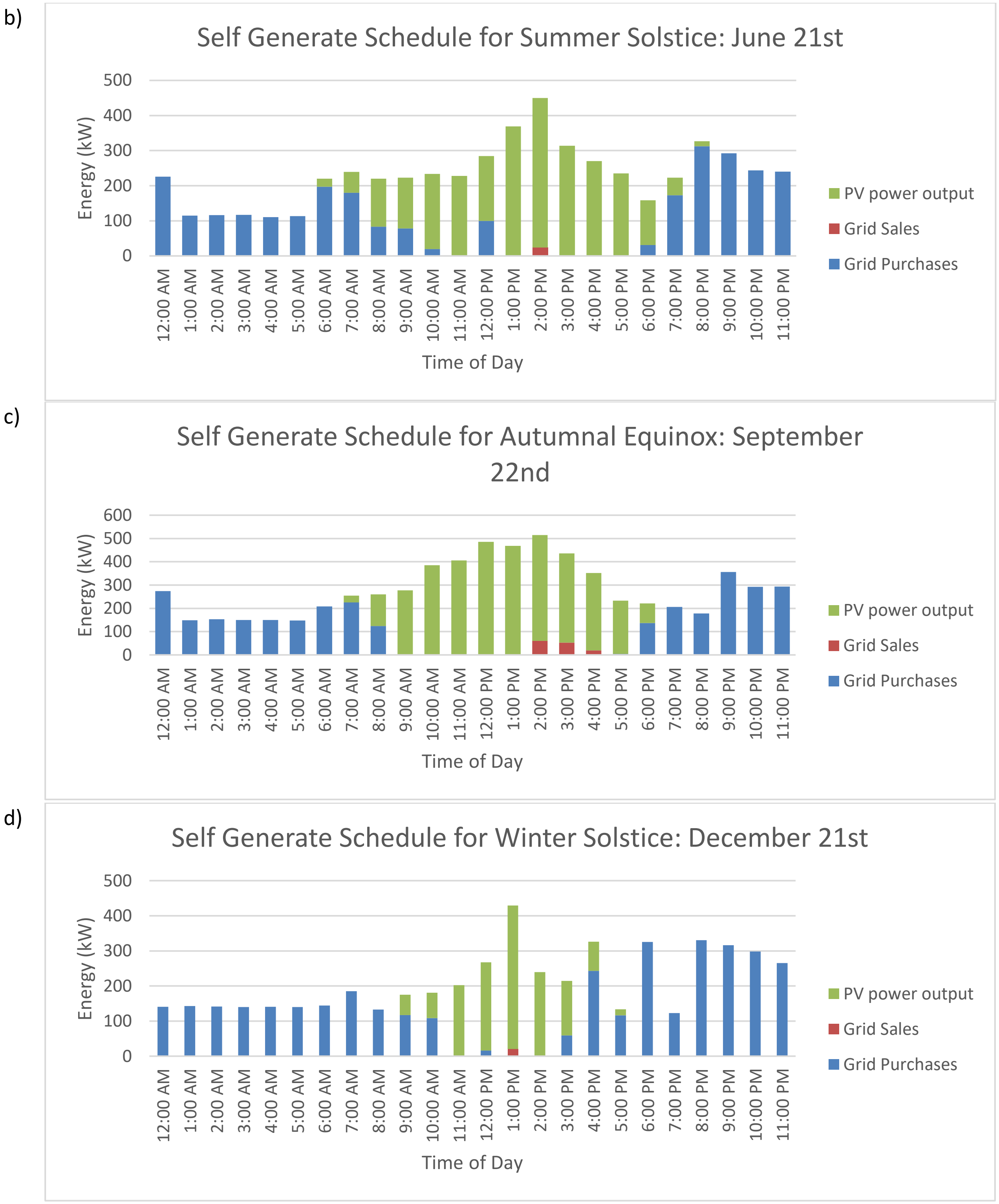


*Figure 4-5: Self Generate Schedules for the facility during (a) Vernal Equinox; March 20th, 2017, (b) Summer Solstice; June 21st, 2017, (c) Autumnal Equinox; September 22nd, 2017, and (d) Winter Solstice; December 21st, 2017*

For this study the solar panels are placed at a fixed angle throughout the year. They are placed based on the angle to produce optimum generation during Winter Solstice.

In Ontario, previous case studies [35] have found that if panels have an azimuth approximately due south and tilt angle less than the area latitude, the revenue generated does not change significantly by placing the panels at the absolute ideal orientation. This would only provide a 0.7-1.7% increase in overall revenue [35]. It was considered not financially feasible to include a PV tracking system or moving panels for this system.

## Model Inputs and Assumptions

### Facility Energy Audit

A facility energy audit was completed at the school to identify and prioritize ways to reduce energy consumption, decreasing the size and cost of the potential microgrid generation and storage units. The analysis considered the energy breakdown for facilities of similar use, such as other schools and offices, to determine where the focus for energy conservation changes should be placed. Figure 4-6 shows the general breakdown of energy requirements in educational spaces. Space heating, cooling, lighting, and use of office equipment can be seen to be the highest energy consumers. The effect of implementing different combinations of these energy savings suggestions on the financial case for the project was calculated in this model.

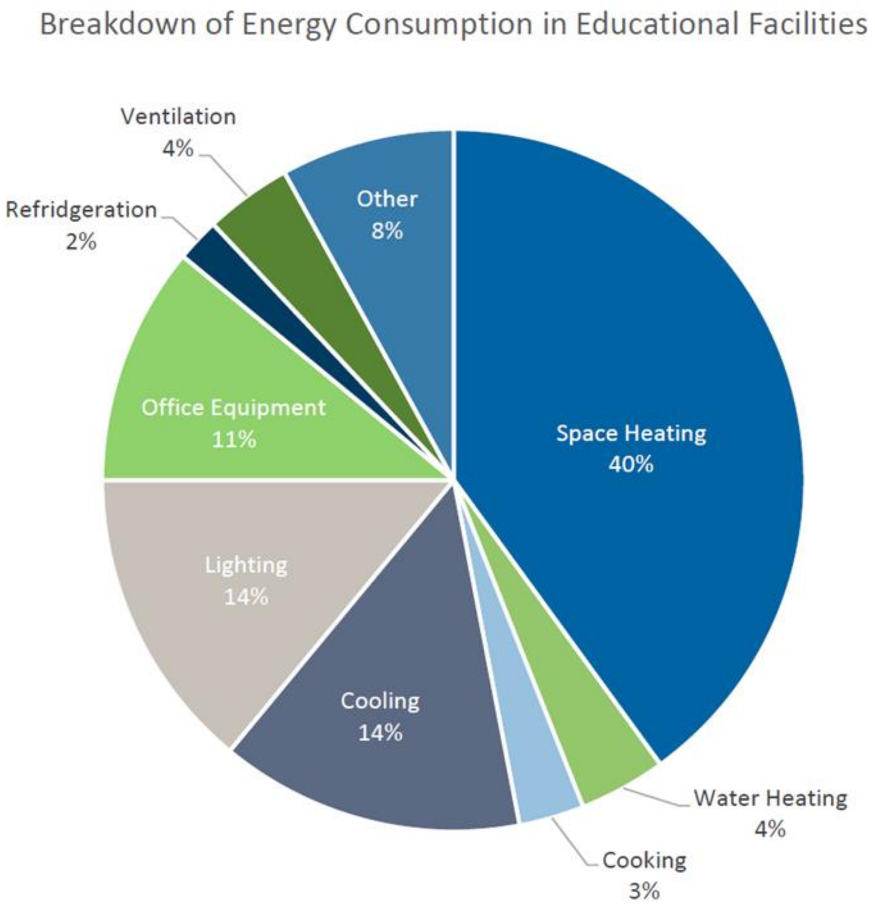


*Figure 4-6: Breakdown of energy consumption, including electricity and natural gas, in educational facilities*

Currently, the school is fully air conditioned, and uses heat pumps as well as natural gas-fired hot water boilers to meet its energy demands. Electricity is used for many applications, including lighting, cooling, ventilation equipment, supplemental heating, and office equipment. Natural gas is used within the building for space heating, domestic hot water, and cooking. Analysing both types of energy requirements, a breakdown of the school's areas of consumption was generated, as shown in Figure 4-7. It is obvious that space heating accounts for a large part of the facility's energy usage since the systems required for it are very large and energy-intensive, running throughout most of the year. Cooling the building only accounts for about 5% of the facility's annual energy consumption.

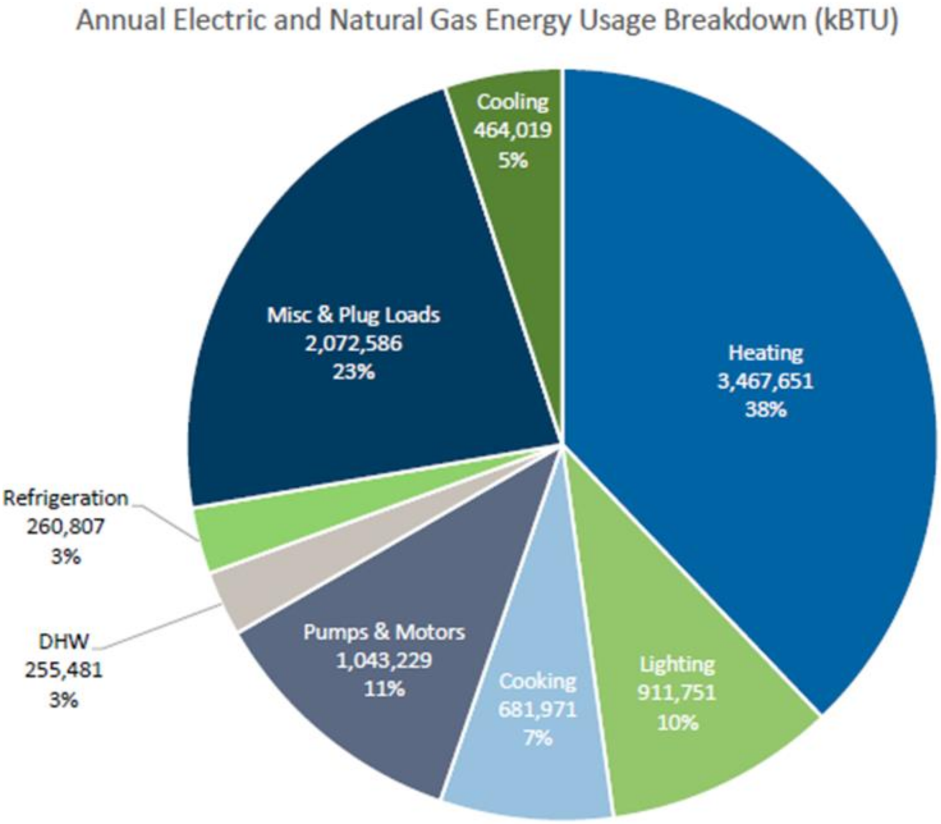


*Figure 4-7: Breakdown of annual energy usage for the facility being studied*

## Energy Audit Results: Scenarios for Consideration

Based on the findings of the facility energy audit, three system modification scenarios were generated, shown in Table 4-1. Outlook 1 considers implementation of all projects resulting in a payback period of less than three years, Outlook 2 considers all projects with a payback period of less than seven years, and Outlook 3 includes all projects suggested in the energy audit.

*Table 4-1: Energy efficiency outlooks based on audit findings.*

| **Outlook 1** | | | | | | |
|---|---|---|---|---|---|---|
| Project | Savings (kWh/year) | Gas Savings ($m^3$/year) | GHG Reduction (kg $CO_{2e}$/year) | Estimated Cost ($) | Estimated Grant Incentive ($) | Estimated Cost without Grant ($) |
| Heat pump loop main pump VFD | 53558 | | 2678 | 18630 | 5356 | 13274 |
| Fresh air unit fan VFD | 37131 | | 1857 | 16200 | 3713 | 12487 |
| Timed lockout of kitchen exhaust fan | 11895 | | 590 | 3000 | 1181 | 1819 |
| Occupancy sensor on two lamp LED T8 fixture | 158 | | 8 | 45 | 15 | 30 |
| Totals | 102742 | | 5133 | 37875 | 10264 | 27611 |
| **Outlook 2** | | | | | | |
| Project | Savings (kWh/year) | Gas Savings ($m^3$/year) | GHG Reduction (kg $CO_{2e}$/year) | Estimated Cost ($) | Estimated Grant Incentive ($) | Estimated Cost without Grant ($) |
| Recommission BAS | 21241 | 8825 | 17820 | 240000 | 2124 | 21876 |
| Fluid cooler fans VFD | 28257 | | 1413 | 18630 | 2826 | 15804 |
| Totals | 49498 | 8825 | 19233 | 258630 | 4950 | 37680 |
| **Total Outlook 1 + Outlook 2** | 152240 | 8825 | 24366 | 296505 | 15214 | 65291 |
| **Outlook 3** | | | | | | |
| Project | Savings (kWh/year) | Gas Savings ($m^3$/year) | GHG Reduction (kg $CO_{2e}$/year) | Estimated Cost ($) | Estimated Grant Incentive ($) | Estimated Cost without Grant ($) |
| CHP | 432881 | -83463 | -136852 | 408830 | | 408830 |
| **Total Outlook 1 + Outlook 2 + Outlook 3** | 585120 | -74638 | -112486 | 705335 | 15214 | 474121 |

Outlooks 1, 2, and 3, would result in energy savings of 6%, 9%, and 34% respectively.

The addition of Variable Speed Pumping (VFD) to the two primary heat pumps, to control the pressure and flow rate, as well as other smaller pumps and motors could generate large energy and cost savings. The cost of VFD devices has significantly decreased in the past decades [36,37], causing them to be affordable options for many energy retrofit and energy savings projects. VFD devices can improve the operating efficiency, robustness and lifetime of devices by controlling them to improve their energy use efficiency [36]. For this facility, it would result in an energy savings of 53,557.50 kWh per year, which is a 21% per dollar savings.

At the facility, the kitchen exhaust fan can be manually switch on or off, allowing control to the kitchen staff to use the fan as needed. However, the fan is often left on after-hours, causing it to run throughout unoccupied times. It is suggested that a timed lockout be added to ensure that the fan is turned off from 3pm-6am, when the kitchen is not in use. This allows for a potential energy savings of 11,805 kWh per year, resulting in $1820 of savings each year.

Internal lights are mainly controlled by occupancy sensors, excluding the janitor’s closets, mechanical rooms and similar spaces. It is suggested to add occupancy sensors to these spaces in order to ensure all lights will be switched off when the rooms are not in use.

Building automation systems (BAS) can determine what makes up the facility electrical demand, it can control the use of equipment based on occupancy schedules or comfort limits and track any faults that may occur such as heating and cooling a room simultaneously. These simple uses of building automation can greatly improve energy efficiency, which can be further adjusted by more complex automation approaches [38]. Over time, the effectiveness of a BAS system will decrease due to changes in use and occupancy, wear and tear, and other factors. Because of this, it is suggested that the BAS system be recommissioned every five years, and especially at the launch of this project. This is expected to yield high energy savings as well as improve the quality of comfort within the facility.

Installation of a combined heat and power (CHP) system was recommended. This process would burn natural gas to generate electricity and use a portion of the inevitable “waste heat” to provide hydronic hot water. This has a large initial cost but will generate major cost and energy savings for the facility over its lifetime.

## Carbon Pricing

The Ontario Energy Board, along with ICF Consulting, released a Long-Term Carbon Price Forecast (LTCPF) document for Ontario [39]. Projections were made for three scenarios from 2018 through to 2028, shown in Table 4-2.

*Table 4-2: Ontario carbon price forecast scenario results expressed in real 2017 CAD $/m3 of natural gas [39].*

| **LTCPT** | **2018** | **2019** | **2020** | **2021** | **2022** | **2023** | **2024** | **2025** | **2026** | **2027** | **2028** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Mid-Range** | 0.032 | 0.034 | 0.034 | 0.036 | 0.037 | 0.039 | 0.058 | 0.067 | 0.081 | 0.09 | 0.11 |
| **Minimum** | 0.032 | 0.034 | 0.034 | 0.036 | 0.037 | 0.039 | 0.041 | 0.043 | 0.045 | 0.047 | 0.051 |
| **Maximum** | 0.13 | 0.13 | 0.14 | 0.14 | 0.15 | 0.16 | 0.17 | 0.18 | 0.18 | 0.19 | 0.20 |

The mid-range LTCPF values were used to determine approximate values of carbon emission abatement over the 30-year analysis period. For the years beyond 2028, a linear relationship was assumed to estimate LCTPFs, shown in Figure 4-8.

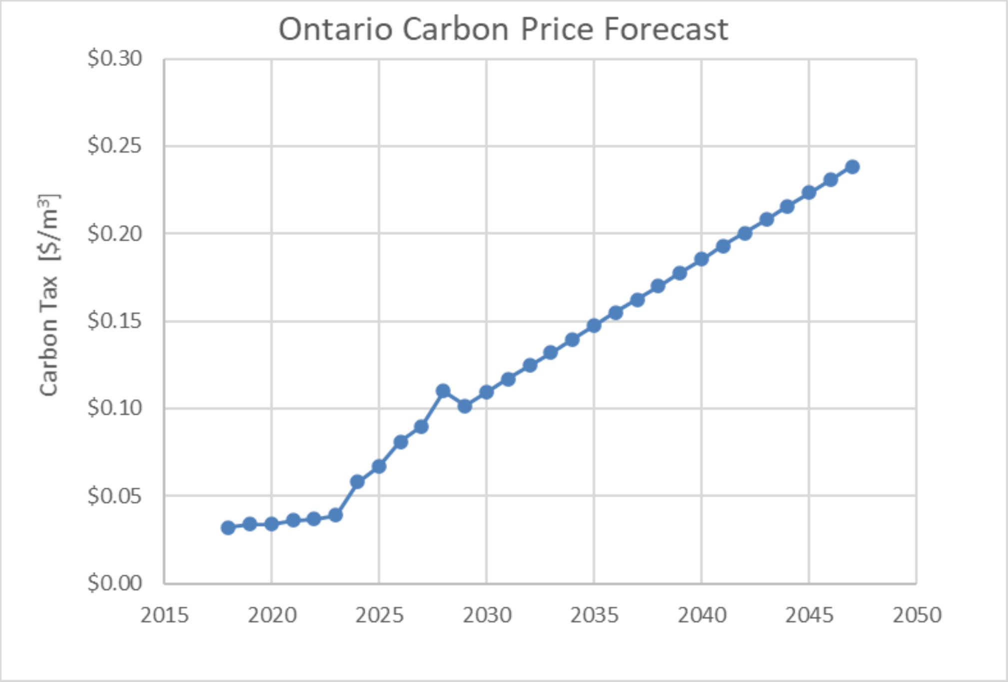


*Figure 4-8: Ontario Carbon Price Forecast linear relationship estimate in 2017 CAD $/m3 of natural gas.*

### Electricity Cost Projections

Electricity costs were projected based on available AMPCO projection resources for Ontario [40] shown in the graph in Figure 4-9. Throughout this analysis an annual electricity price increase of 3% was used as a conservative value.

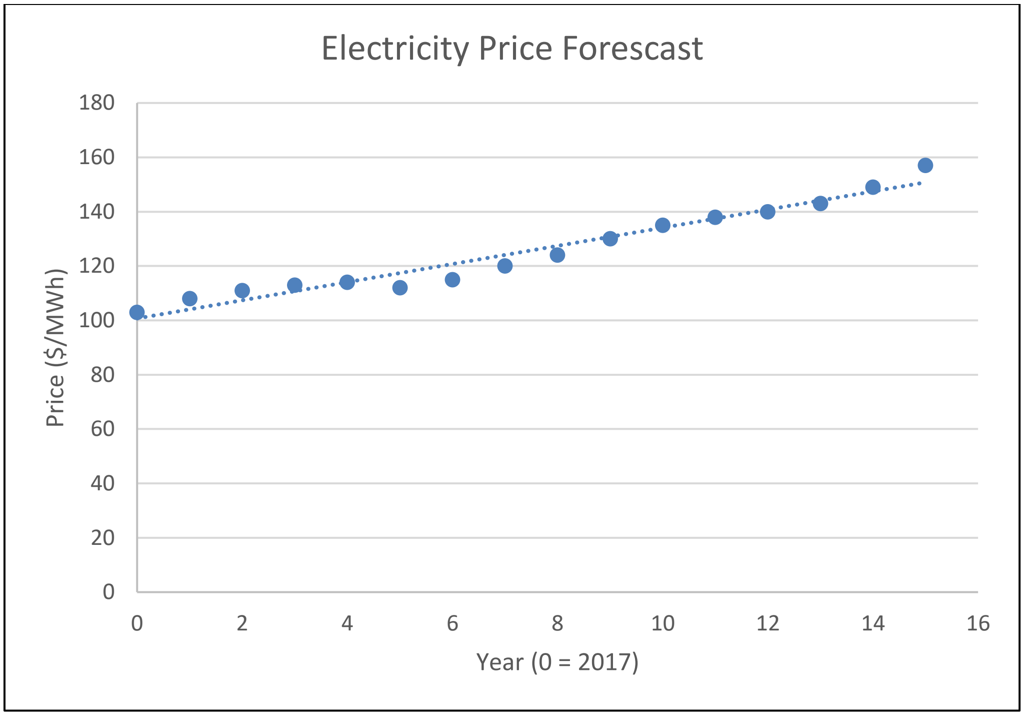


*Figure 4-9: Electricity Price Forecast based on AMPCO projections for Ontario [32].*

## Rebates and Incentives

Funding programs, rebates, and incentives are important considerations for developing the business case of microgrids. They assist in providing positive financial cases for microgrids, helping to overcome barriers such as high capital costs, operation and maintenance needs, and complex installations.

Rebates and incentives for implementing renewable energy generation and storage units are often changing which causes difficulties when producing a financial model and business case for these systems. Some rebates or incentives are offered for a short amount of time and can be taken advantage of only if the project is being designed or implemented during the program duration. Initial consultations of this microgrid design began when previous rebate programs were existent, which have now been cancelled. Incentives which could be representative of past programs are still considered in one case of this microgrid business model. Another case considers only the rebates and incentives which were actually applied to this microgrid. Considering all possible funding opportunities for DERs and microgrids is necessary to understand the vast number of programs that have been or still are available to support these systems. Due to a microgrid's range in system components, uses, and their novel development in many locations, numerous types of funding programs can be explored for supporting such projects. These could include programs supporting research and development efforts, renewable energy, energy retrofits, energy savings or emissions reductions. Programs available during initial planning stages of a microgrid system may not be available at a later design stage, however, new programs are created often to continue supporting these projects. Since it is impossible to know what programs will be available in the future, considering grants or incentives from the past, or those available at the start of a project, can assist in generating realistic cases of possible business outcomes for a system.

### ***Incentives Applied to This Project***

At the time of designing this microgrid system the gap between the cost of the system and continuing to purchase energy from the grid was significant. This project was granted large incentives by the Canadian Government to assist in generating a feasible pilot project. The largest contribution was from the Energy Innovation Program (EIP) from Natural Resources Canada (NRCan). This program is meant to support the nation's transition to a low-carbon economy by assisting in making research, development, and demonstration of clean energy projects affordable and sustainable [41]. This project was rewarded a total of $4,538,000 from the NRCan EIP Program.

Funding was also provided for this microgrid to demonstrate the abilities of these technologies to provide services to the electrical grid it is connected to. Demonstrations of the system providing ancillary services to the electrical grid, including energy regulation, ramping, operating reserve, and demand response, will be presented. This research will also consider the project's ability to participate in the Independent Energy Systems Operator (IESO) future capacity market. In Ontario, this will be the first non-carbon-based energy system able to provide resiliency and ancillary services to both a large load and the central electrical grid. This can assist the IESO in understanding the needs for cost and connections of similar systems, as well as prove the benefits of the energy-as-a-service methodology. The project was awarded $500,000 from the Grid Innovation Fund.

Net metering is a program to help renewable energy owners export their excess electricity generation back to the main utility grid, receiving credits equivalent to the cost of purchasing electricity in return [42]. These credits will then offset the cost of purchasing electricity, as the customer will only pay for the difference between electricity purchased from the grid and net metered back to it. The credits must be used within one year, so excess energy generated by solar in the summer can offset grid purchases in the winter.

### ***Additional Programs Supporting Microgrid Implementation***

The Save on Energy Retrofit program provided by the IESO [43] encourages businesses and institutions to make changes to improve energy savings and renewable generation or storage. It includes incentives for quick-changes on the "prescriptive track"- providing cost savings on a per-unit basis if the total project will cost over $500. For larger projects, the retrofit program includes the "custom track" which will provide up to 50% of the project costs in order to reduce upfront costs of large project implementation. For the custom track the project must cost a minimum of 1500 dollars [44].

Ontario does not have any current rebate programs for Geothermal system installations. Past incentives and rebates have improved the popularity of Geothermal in Ontario and helped with covering the capital costs of implementing these systems. The geothermal industry took off when the Ontario government offered a program for promoting geothermal in the province [45]. This was the ecoEnergy program, offering one cent per kilowatt hour of production by renewable energy sources over a ten-year period, up to $80 million for each project [46]. This program was cancelled in 2010. Future programs may be implemented which can benefit the geothermal industry and provide support for the implementation of such systems.

One program which existed in the past and can be explored for design and financial prediction purposes of future microgrid projects is The GreenOn Solar rebate [47]. The rebate offset capital costs by providing the facility with 75 cents per watt for all PV and energy storage systems used. The rebate was to a maximum of 500kW, providing a rebate of up to $375 000 [47]. This program was cancelled June 19th, 2018.

Currently, the MicroFIT program is in place to assist in the cost of integrating small renewable generation projects, of 10kW or less [48].

### *Tax Incentives*

Tax incentives should also be considered for projects and must be specific to the situation studied. Tax incentives will be different depending on the location of and reasoning for a project, as well as the type of system designed, and units used within it. In Canada, The Scientific Research and Development (SR & ED) Program provides tax incentives to encourage businesses to complete research and development projects in many different sectors. This is to promote innovation, generate technological advancements and to discover new methods of ideas to benefit economic growth. Using this program, companies can earn an investment tax credit on qualified SR&ED expenditures, or they can pool their SR&ED expenditures to be deducted from their income in the current year or a future year [49]. Canadian projects with investments in clean energy generation or energy conservation equipment can consider the following federal tax measures for Clean Energy Equipment.as The Canadian Government may provide an accelerated capital cost allowance (CCA) and a first year enhanced CCA allowing full deduction of the capital cost of such systems in the first year they are available for use [50]. Deductions for the Canadian Renewable and Conservation Expense (CRCE) are also available, where expenses for the development of qualifying projects, such as start-up expenses like feasibility studies, may be fully deducted in the year they were incurred, or carried to future years [50,51]. Additionally, projects investments in some qualifying sectors within the Atlantic region of Canada can claim 10% of the cost of prescribed energy generation and conservation properties [50,52].

It is likely that new incentives or programs will be developed, as well as policies to encourage the use of geothermal, solar, wind and other renewable storage and generation technologies. The Ontario government stated that they are looking to shift policies, programs and incentives from supporting fossil fuels to supporting “sustainable development and clean energy technologies and energy” [53], and have created an action plan to represent the foundation of these changes [54].

## Results

A model was developed in excel to calculate the future price of a microgrid system to be implemented at the secondary school. It considers the net present value of each technology, retrofit and service mentioned in the microgrid design sections above, which was provided by the project partners. The model takes into consideration the exact location of the system and corresponding electricity and gas prices, demand related charges, incentive possibilities and location specific parameters.

In Ontario, the demand related charges are considered the Global Adjustment (GA) charge. The global adjustment is meant to support the province in implementing new electricity infrastructure and conservation programs to ensure adequate electricity can be supplied long term. This is a very important factor to consider, although often overlooked in financial models, as the flexibility in central-grid purchase times results in considerable cost savings by lowered GA charges for the facility.

The overall net present value of the capital cost for the project is estimated to be $9,076,000. Three cases were constructed to demonstrate different future scenarios. These are described in Table 4-3. In each case an interest rate of 5% and an O&M cost escalation of 5% are assumed. The comparisons are based on the Net Present Value (NPV) of the total system costs.

*Table 4-3: Case descriptions and summary of NPV analysis.*

| Case | Description | NPV Microgrid Solution | NPV Central Grid Solution | Incentive | LCOE |
|---|---|---|---|---|---|
| 1 | BASE CASE<br>Microgrid costs as provided by project partners. Annual interest rate = 5%. Electricity & natural gas rates escalate @ 3%/year. | $9,999,429 | $6,227,762 | None | $0.33/kWh |
| 2 | INCENTIVE CASE A: Built from base case but with 12.5% NG increase, 30% solar cost reduction, 50% battery cost reduction, and 20% geothermal residual after 30 years. | $7,573,928 | $8,128,267 | 30% Solar CAPEx & OpEx, 50% Battery CAPEx & OpEx, and 20% Geothermal residual at year 30. | $0.25/kWh |
| 3 | INCENTIVE CASE B: Built from base case but with actual incentives provided for this project distributed evenly across microgrid CAPEx. | $4,971,593 | $6,227,762 | $5,038,000 | $0.16/kWh |

For each case, the levelized cost of energy (LCOE), a commonly used metric to compare the costs of energy projects, for the microgrid system is provided to inform power purchase agreements discussions.  Furthermore, for each case the value of the battery storage system is captured through reduced supplementary grid electricity prices by subtracting the cost of global adjustment that would otherwise be paid if no storage system were in place. The battery replacement cost was considered in these calculations, with replacement after year fifteen.

$$LCOE = \frac{(Fixed\ charge\ rate\ x\ Capital\ Costs) + (Annual\ O\&M\ Costs)}{Net\ Annual\ Energy\ Production}$$

$$LCOE = \frac{(RR[\%] x\ Capex[\$]) + \left(Opex\left[\frac{\$}{year}\right]\right)}{AEP[\frac{MWh}{year}]}$$

Using Net Present Values, the levelized cost of energy equation can be simplified as shown below:

$$LCOE = \frac{NPV\ Capital\ Cost\ [\$\ NPV] + Present\ Value\ Annual\ O\&M\ Cost\ [\$\ NPV]}{Net\ Annual\ Energy\ Production\ [MWh]}$$

Where the net annual energy production and operation and maintenance (OPEX) costs are measured over the entire project lifetime. The 30 year net present value cost comparissons between each microgrid case is shown in Figure 4-10.

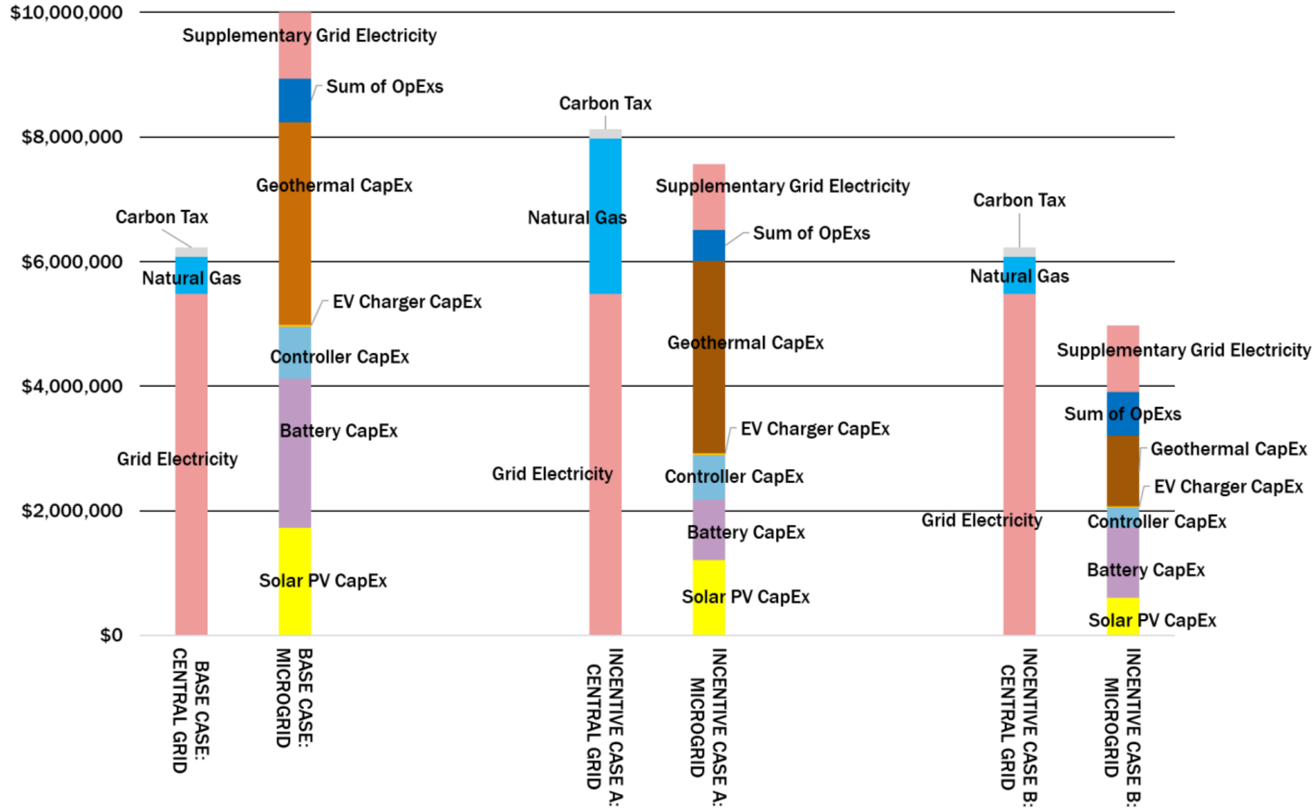


*Figure 4-10: 30 Year Net Present Value Total Cost Comparison between Current Central Grid Energy Solution and Potential Microgrid Design*. Interest Rate = 5%, Grid Electricity Price Escalation = 3%/yr, OpEx Price Escalation = 5%/yr. *NV Potential Microgrid Solution: 40% Total Electricity Demand from Central Grid, 0% Natural Gas from Central Grid. For the Base Case: Natural Gas Price Escalation = 3%/yr, all capital and operation costs of microgrid components as project partners provided them. For Incentive Case A: Natural Gas Price Escalation = 12.5%/yr, Solar CAPEx & OpEx reduced by 30%, Battery CapEX and OpEx reduced by 50%, and Geothermal residual value of 20% provided at year 30. For Incentive Case B: Natural Gas Price Escalation = 3%/yr, ~$5M incentive was evenly distributed across all CAPEx values, as provided in the actual case studied.*

Case 1 represents the Base Case or Business-As-Usual (BAU) scenario. This involves Grid Electricity & Natural Gas to be purchased as it has always been based on historical usage. The microgrid costs are taken exactly as provided by the contributing project partners with conservative escalation rates of 3% per year assumed for electricity and natural gas prices and a 5% per year increase for OpEx costs. Carbon tax projections were taken as per OEB projections for all cases [39]. The Levelized Cost of Energy for the Base Case is estimated to be $0.33/kWh.

Incentive Case A represents a scenario where incentives are applied to reduce the solar, battery and geothermal system capital and operation costs. This case was built from the original base case, but with some changes. This case includes Natural Gas escalation of 12.5% per year, as predicted by Deloitte's natural gas price projections [55]. Solar capital and operating expenses were reduced by 30%, battery CapEX and OpEx by 50%, and geothermal had a residual value of 20% of the capital expense cost at the year 30. The Levelized Cost of Energy for Incentive Case A is estimated to be $0.25/kWh.

Incentive Case B includes the same central grid case as the base case, with conservative natural gas and electricity price increases of only 3%. The microgrid in this case was provided with the grants and incentives actually awarded for the project being studied. This included the NRCan EIP grant of $4,538,000 and IESO Grid Innovation Fund of $500,000 totalling to $5,038,000. These were evenly distributed among the system's capital costs. The Levelized Cost of Energy for Incentive Case B is estimated to be $0.16/kWh.

Figure 4-11, Figure 4-12, and Figure 4-13 break out the overall costs for each case shown in Figure 4-10 by component. These figures provide absolute values for comparison between the cases and to determine incentive levels required for each case. Figure 4-11, which is based on present day cost estimates, shows significantly higher NPVs for the microgrid system than for the central grid solution. This case provides proof that the implementation of these technologies in the present day is not financially feasible without further price reductions, incentives or grants. Figure 4-12 and Figure 4-13 demonstrate the incentive scenarios to reduce microgrid costs, providing positive cases for the microgrid design.

The Base Case, defined in the figure below, contains a very high microgrid total cost in comparison to the central grid total. This is due mainly to the high capital cost of the renewable generation and storage units modeled within this microgrid.

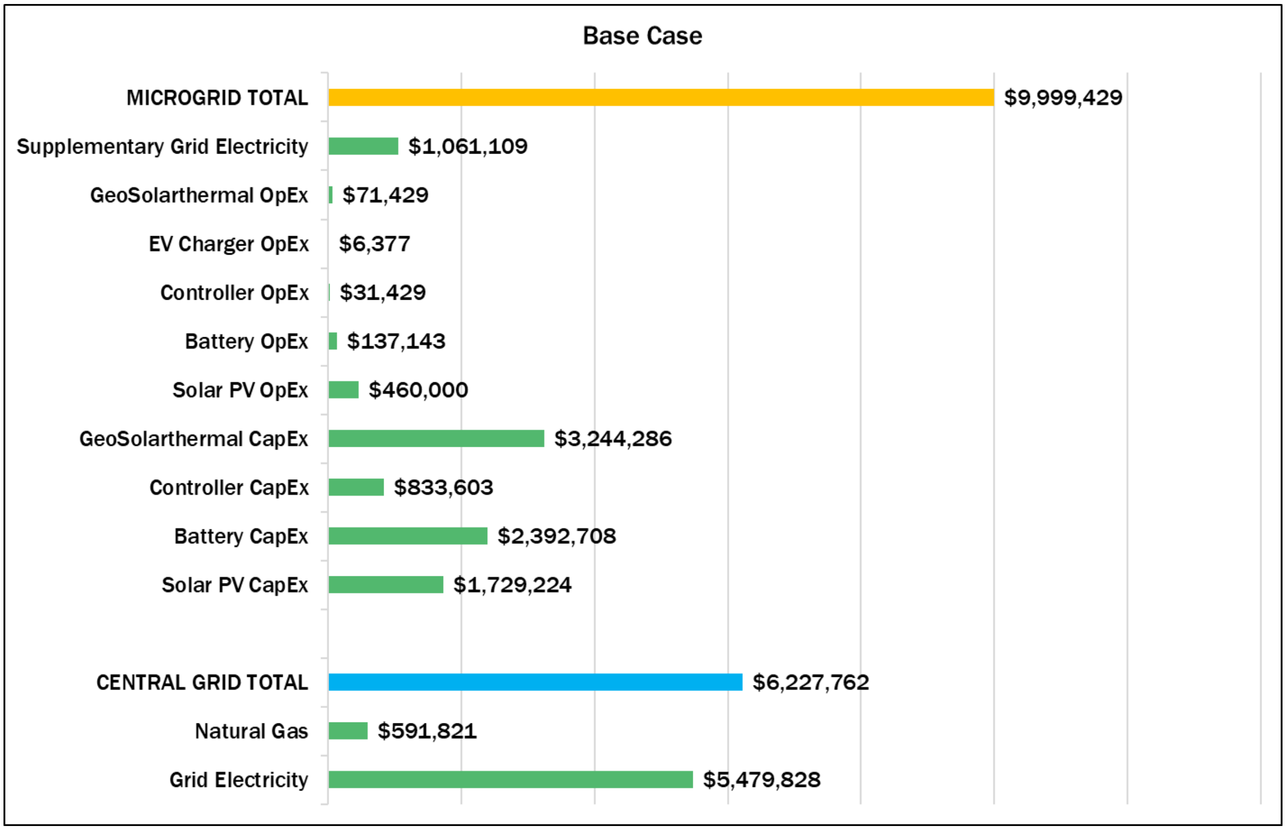


*Figure 4-11: Cost breakdown by component for the Base Case.*

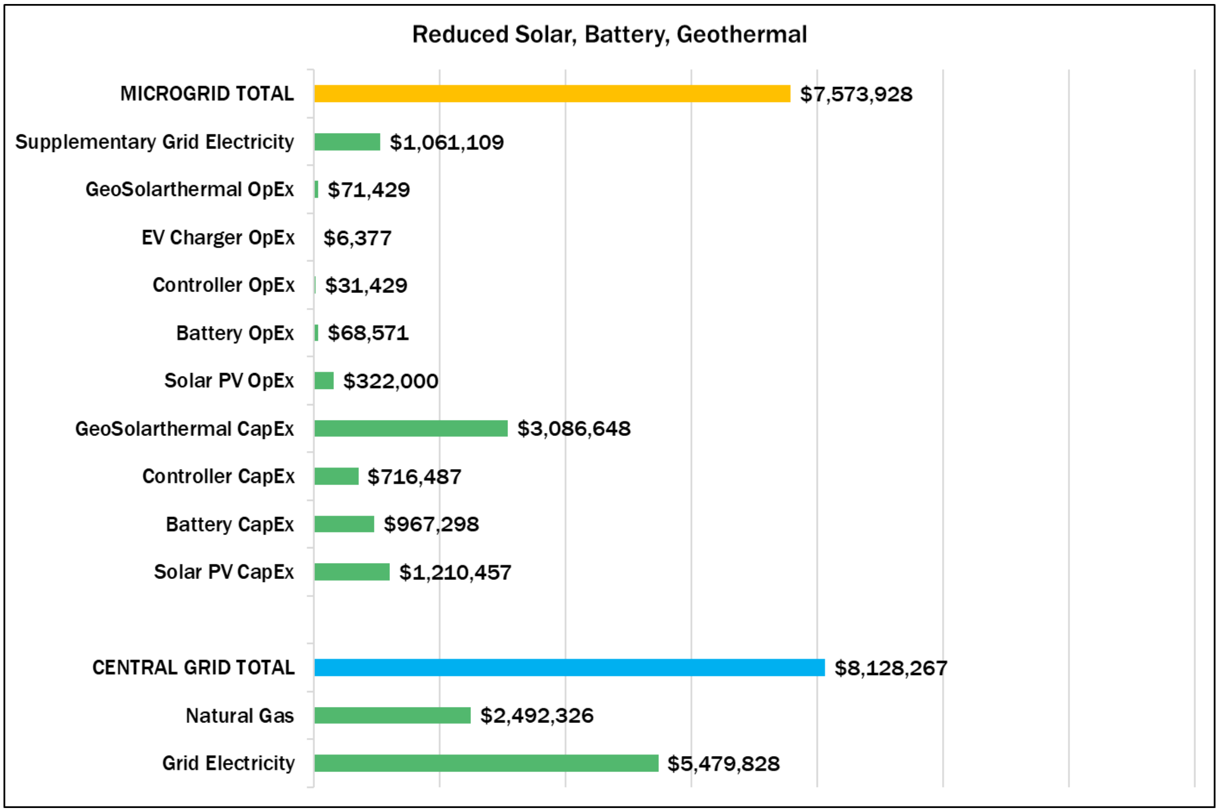


*Figure 4-12: Cost breakdown by component for Incentive Case A: 12.5% NG escalation, Solar CAPEx & OPEx reduced by 30%, Battery CapEX and OpEx reduced by 50%, and Geothermal given a residual value of 20% of the capital expense cost at year 30.*

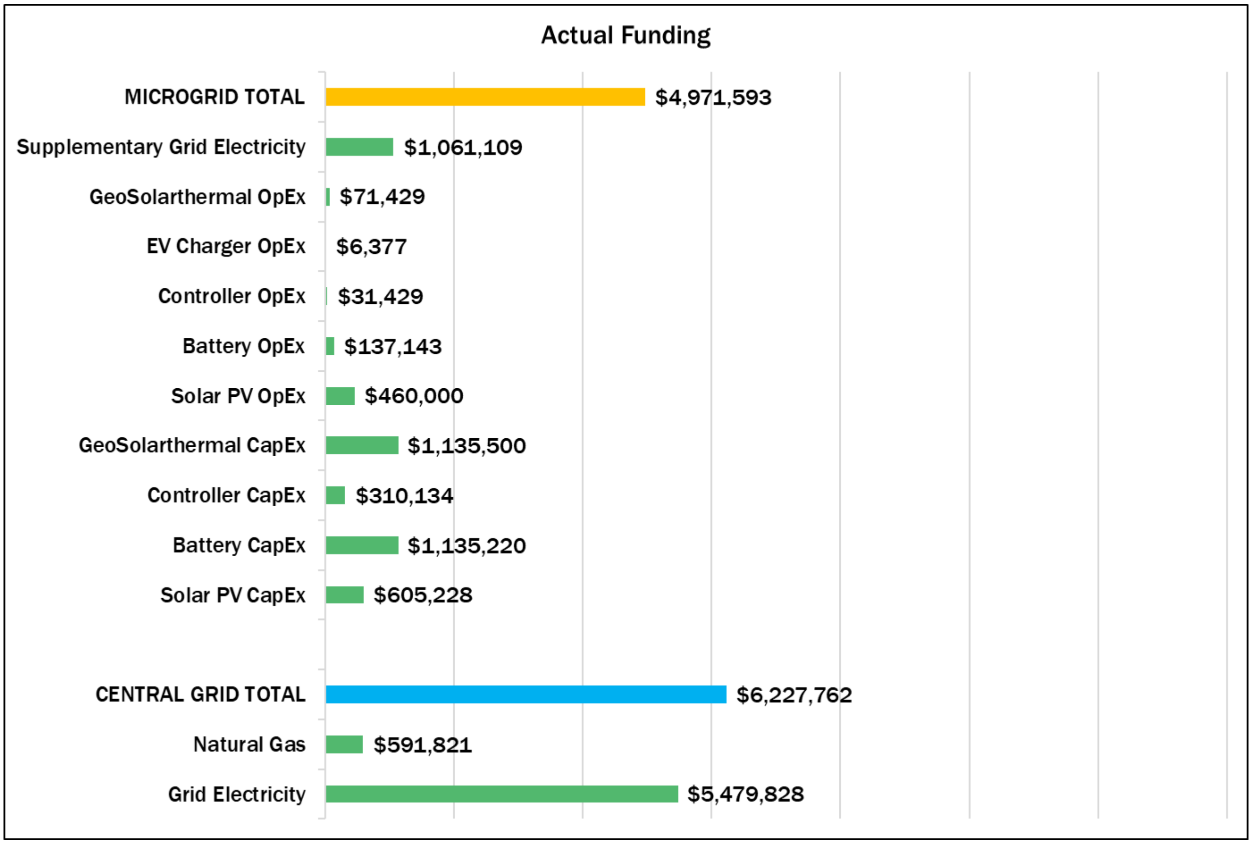


*Figure 4-13: Cost breakdown by component for Incentive Case B: NRCan EIP and IESO Grid Innovation Fund grants distributed evenly across microgrid capital costs.*

Figure 4-14 provides a breakdown of the capital and operating costs of the major microgrid components. The Geothermal system contributes 36% of the capital cost, followed by the battery storage (27%), solar PV system (19%), microgrid controller (9%), OPEX (8%), an EV charger (1%).

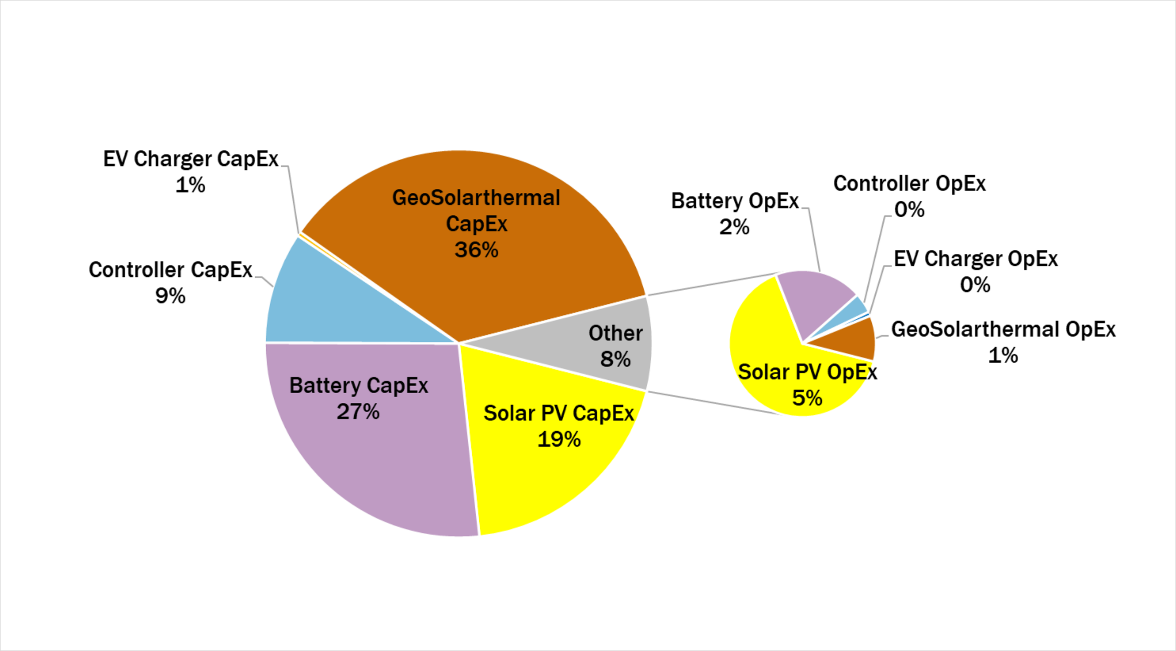


*Figure 4-14: 30 Year Net Present Value Total Cost Comparison among Major Microgrid Components. Interest Rate = 5%, OPEX Price Escalation = 5% per year.*

# Conclusions

Based on this microgrid financial analysis there are many factors which greatly affect the feasibility of similar projects. Each scenario considered here produced varying results. 4. The second case considered, which includes an incentive and more likely escalation estimates, was considered economically feasible. The third case, Incentive Case B, shows application of the incentives actually given to this project. This case, demonstrating significant financial contributions by government funding, rendered a positive case for the microgrid economics. These results conclude that at the time in question (2017 and the time of writing) a microgrid system such as this one being studied requires incentives to close the price gap for the scenarios in which the net present value of the microgrid systems exceeds that of the central grid solution. However, the costs of renewable energy generation and storage devices used in microgrid designs are rapidly declining. Policies are being implemented to encourage investment in these technologies. The increased popularity of these systems will further improve the corresponding capital costs and allow for greater use in microgrid projects. Declining technology costs and policy implementation will support the financial feasibility of microgrid projects soon.

The microgrid business case is not solely reliant on the cost of implementation, net revenues and savings generated. It is also dependant on other benefits, not all of which are purely financial, that microgrids offer, which will provide a positive experience for the facility in the future. This microgrid will allow insight to a test case for the possibility of microgrids at similar facilities throughout Ontario and comparable locations. It will assist in exploring the energy as a service partnership between microgrid owners and hosts. The microgrid will serve as a research method, to understand the opportunities and challenges which may arise by implementing such systems. This project will provide an understanding of the impact of microgrids on the main electric grid, including its ability to become reliant on a microgrid for reduced consumption or to help with energy demand at times of need. A major benefit of the microgrid is the ability for the facility to control how their energy is being produced, reducing their carbon footprint and emissions. More uniquely, the classrooms will use the building retrofits as a learning tool, to educate their staff and students on being aware of energy consumption and the effect of reduced carbon emissions. The case for this microgrid becomes much more desirable if these non-monetary benefits are also considered [1], as well as the benefits for customers and research interests outside of the microgrid facility. Incentives and investments have been made for this project to close the financial gap and move forward with the system.

## Critiques and Recommendations for Future Research

The financial model presented in this chapter is limited by the project and location specific details as described below:

- The following inputs for this financial model were location, site, and project specific:
  - Incentives and government support programs were based off those provided by the municipal, provincial, and federal governments pertaining to London, Ontario. As well, the electricity, natural gas and carbon pricing was based on those set by the Ontario government.
  - The space available for integration of DER units such as: Terrestrial land, carport parking spots, available rooftop were based on the school's building and land ownership.
    - Location specific guides and safety regulations must be taken into consideration for space availability, such as the necessary distance for placement of wind turbine towers from land lines, or the structural limits of rooftop solar.
  - The solar radiation availability, and optimal placement of solar arrays was designed for the site longitude and latitude.
  - The technology and types of distributed energy resources were chosen by the project partners and could not be altered for this case study. Different microgrid designs can be examined within this model to determine the combination of energy generation, storage and controls units pertaining to the highest balance of economic, social, and environmental benefit.
  - The project goals will ultimately determine the outcome of the microgrid design. For example, the research and educational opportunities that could be developed by the integration of a geothermal system generated it a required technology for this project.

    - Additionally, the project also has a goal of near net-zero carbon emissions, therefore the business and microgrid model was required to meet this goal as closely as possible regardless of the economic sacrifice.
    - Electricity, natural gas, and carbon tax prices
- Incentives and government supports are continuously changing regardless of the location of the project. For future studies, the available incentives, programs, rebates, and government supports must be updated.
- As technologies become more widely used and designs are optimized, their capital costs will drop. For future analyses, this model should be kept up to date with current capital costs, as this will be a major player in closing the gap between the feasibility of purchasing energy from the central grid or integrating a microgrid system.
- Forecasting for the electricity, natural gas and carbon pricing were based on historical data or projections for Ontario. As new projections are made, or annual data is provided, these projections should be updated in the model. As well, for a system in a different location, projects should be made based off historical data for the location of the project.

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# Chapter 5 : Conclusions and Future Research

The traditional energy systems consist of a top-down approach of supplying energy involving the use of large, centralized generation plants, transmission lines, and multi-level distribution systems. This approach to energy supply is changing in many aspects due to the rapid increases in energy demand, the desire for cleaner energy sources, and the aging infrastructure that is currently being used. These concerns can be addressed with the use of distributed energy resources (DERs) in energy systems. DERs can be integrated with the current energy supply mix to support the growing demand and eliminate the requirement for new large infrastructure for transmission and distribution. Given the modular abilities to integrate DERs to a system, they provide endless possibilities for innovative improvements to the current energy supply, and new systems. There are many innovative applications for DERs today, including offshore wind turbines, floating multi-purposed platform with generation and storage devices for use in island-life or integration with other energy systems, and microgrid or smart grid systems. However, like any new technology, the concepts and applications of DERs are not completely understood, and extensive research is needed to provide confidence in the benefits of these technologies. In order for DERs to become a viable solution to the concerns of the energy future, it is necessary to gain a greater understanding of the concerns involving innovations in this field.

This thesis provides a significant research contribution to the understanding and analysis of some major barriers to further developments and penetrations of distributed energy resources in energy systems around the globe. It presents three different studies that analyze various barriers to DERs. Together, these studies provide insight into the developments which are necessary to allow the use of distributed energy resources and important innovations in this field within the energy supply mix both within Canada, and globally.

Chapter II describes the importance of Canadian developers and governments becoming involved in the offshore wind energy scene. This chapter examined both drivers and barriers to offshore wind, with a focus on Canada, and presented suggestions for the best methods of Canadian involvement in the offshore wind market. It was determined that the implementation of offshore wind into Canadian waters is not the best option for Canada to become involved in the offshore wind scene at this time. Canadian companies should first export their expertise in offshore wind projects globally. Projects in waters like the Canadian coasts and Great Lakes should be monitored, and lessons learned should be applied to provide insight for future consideration. Canada's ability to integrate pre-developed offshore wind infrastructure could provide for lower costs than US developments. After entering the supply chain, Canada can explore the option of implementing offshore wind in Canadian waters to sell energy to densely populated US locations. Canada's federal government should develop policies and incentives to support entry to the offshore wind supply chain.

Chapter III examined the results of experimental tests of four configurations of scaled models of a floating offshore multi-purpose platform to examine the dynamic responses of each when subjected to 1:150 scaled ABL, TVL and DB wind flows. It was found that the dynamics caused by each of the three wind profiles varied significantly. The stability of the floating platform when subjected to the TVL and DB winds was much more varied than the ABL profile. Additionally, changes in the mooring line type, as well as the configuration type, and ultimately the location of center of mass and buoyancy, generated varied dynamic responses. The tight mooring lines reduced all motions compared to the loose mooring lines, notably reducing the rotation of the system. The addition of weight to the top deck of the structure assisted in reducing the magnitudes of accelerations following the initial strike of the DB and TVL winds. However, the addition of only ballast to the legs of the base platform resulted in the highest absolute surge maximum of all the systems. Both ballasted systems experienced reduced rotational magnitudes, but the higher frequency, sharp back and forth movements during the TVL and DB flows, than that of the un-ballasted systems. These findings provided clear insight to the significance of the design and environmental conditions on the dynamics and overall stability of floating offshore systems. It is obvious that extreme weather events must be further tested and analyzed to generate an understanding of system reactions to such conditions, and ultimately to contribute to the development of design standards for specific offshore floating systems. This chapter provided direction for future testing of floating system designs and initial insight to the generation of offshore platform and foundation design standards necessary for the safety of future floating structures.

Chapter IV considered the financial aspect of the integration of DERs and innovative technologies into energy systems. This is an important aspect of the importance of innovations in distributed energy resources, as projects must be economically feasible to be considered pragmatic. The chapter analyzes a specific case of implementing a carbon-neutral microgrid at an existing high school. It stresses the importance of generating a financial model specific to the project at hand, considering the location and project-specific needs and resources. An excel model was generated which compared the net present value (NPV) cost and levelized cost of energy (LCOE) of different microgrid scenarios to the cost of the business-as-usual case, where the school ran as it previously did, purchasing energy from the main electrical grid.  It was found that presently, substantial incentives are necessary to render a large microgrid system such as the one proposed in this study a feasible project. Following the prediction of declining technology costs, and an increase in policy support, the implementation of microgrids and various DERs could become feasible. This study also expressed the need to consider more than just economics in the business case of these technologies, including research findings, educational integration at the school, carbon emissions, energy resiliency, reduction of stress on the main electrical grid, control over energy production, and more.

The use of distributed energy resources is an important factor in meeting the high energy demands of the future. DERs provide a solution for reducing energy losses or interruptions due to an overloading of the current energy infrastructure. The work here provides an understanding of unique methods to overcome the barriers to the integration of DERs into many projects.

## Summary of Recommendations for Future Research

It is recommended that the work presented here be used to provide initial insight into overcoming some barriers to DER developments. These studies should be built upon to continue to contribute to this important topic. It is recommended that Canadian developers become involved in the offshore wind scene now by exporting their expertise to projects globally, as it is a rapidly growing field with major potential for ground-breaking innovations. For future decision making of the best methods for Canadian involvement in the offshore wind scene, continuous monitoring of major projects, especially those within North America, must be conducted to follow the successes and lessons learned. In the future, Canada should consider the integration of wind turbines in its waters to export energy generated to densely populated US shorelines. The experimental results presented within this thesis should be considered as initial insight to the effects of different extreme wind conditions on floating offshore structures. These results provide proof of the importance of testing offshore structure stabilities within different wind and weather conditions to obtain full understanding of the potential failure the systems may be subjected to. It also provides proof of the ability to complete research integrating water in the WindEEE dome with the unique wind generation powers of the facility. Further testing should be completed to contribute to the generation of design standards for offshore floating structures, with consideration for the effects of extreme weather conditions. Additionally, to support further penetration of DERs in major projects, the financial model presented here should be updated with future cost projections, incentives, and supports available as well as optimized for the project or location-specific factors. Taken together, this work should provide direction to encourage and support future innovations and integrations of DERs into energy supply mixes.

## Engineering Contributions

Through the studies conducted in this thesis, the following engineering contributions were made:

Chapter II

- A literature review and summary of the growth of the offshore wind industry including key drivers, barriers, major projects, and specifically, North American applications.
- A plan for the best practices for involvement of Canadian developers in the offshore wind industry in the present and future, with suggestions of necessary steps to overcome barriers holding the nation back from installing turbines in its waters.

Chapter III

- A literature review of experimental and numerical testing of offshore or floating systems in various winds and wave conditions.

- The design, execution and analysis of a unique experimental test providing insight to the dynamics of floating systems in Tornado-Like Vortices, Atmospheric Boundary Layer, and Downburst winds.
- These successful experiments proved, for the first time, the ability to conduct studies involving water within the WindEEE Wind Chamber at Western University in London, Ontario.
- A detailed collection of future recommendations providing direction for changes to the initial experimental tests conducted in this study, to gain further understanding of the reactions of floating systems to extreme weather conditions.

Chapter IV

- The development of detailed 30-year financial models of a microgrid system considering project and location-specific factors such as: capital expenses, electricity and natural gas cost projections, CO2 emission credits, declining technology costs, savings from efficiency measures, and demand charge mitigation.
- Presentation of a multi-case evaluation of the business case for the microgrid system, considering both the financial models developed as well as non-monetary benefits such as: increased reliability, environmental impact, carbon savings, research contributions and education.
- A review of past and present Ontario-specific policies and incentives for technologies commonly used in microgrids, and a presentation of how they can impact the business cases of microgrid systems.

# APPENDICES

## Appendix A – Permissions for Previously Published Works

### Chapter II: Should Canada Pursue or Support Offshore Wind Development?

Permissions were provided to use this work within this thesis, provided proper citation is presented.

### Chapter III: Experimental Investigation of the Movement of an Offshore Floating Platform in Straight Wind, Tornadic Wind, and Downburst Conditions

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### Chapter IV: Financial Model of a Carbon-Neutral Microgrid at an Ontario High School

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