



## **Program of Energy Research and Development**

Wind Integration System Operator Research Program

### **Research Summary**

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## Data sources

We encourage critical review of the findings reported in this report and this project. Data sources used are cited where possible. To obtain copies of datasets used (where allowed), please contact the authors of this report. Obtaining non-public datasets may require Non-disclosure agreements (NDAs).

## Questions and feedback

Feedback, question or comments should be directed to the report authors. Alternatively, use one of the methods below:



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*WEICan's 10 MW Wind R&D Park in Prince Edward Island<sup>1</sup>*



*Saskatchewan Research Council's Cowessess First Nation's site<sup>2</sup>*

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<sup>1</sup> More information: <http://weican.ca>

<sup>2</sup> More information: <https://www.nrcan.gc.ca/energy/funding/current-funding-programs/cef/4983>

## Acronyms

AESO	Alberta Electric System Operator
AGC	Automatic Generation Control
AREG	Assigned regulation value (MW)
AS	Ancillary Services
BA	Balancing area
BESS	Battery energy storage system
Hz	Hertz
ISO	Independent System Operator
kW / MW	Kilowatt / Megawatt
MECL	Maritime Electric Company Limited
NRC	National Research Council
NRCan	Natural Resources Canada
PERD	Program of Energy Research & Development
PJM	Pennsylvania-New Jersey-Maryland Interconnection (an RTO)
PLC	Programmable Logic Controller
RG	Renewable Generation
RTU	Remote Terminal Unit
SoC	State of Charge (%)
SRC	Saskatchewan Research Council
TCP	Transmission Control Protocol
TREG	Total Fleet Regulation Capability (MW)
WEICan	Wind Energy Institute of Canada
WPP	Wind Power Plant

# 1 Project summary

## Visual summary of project scenarios

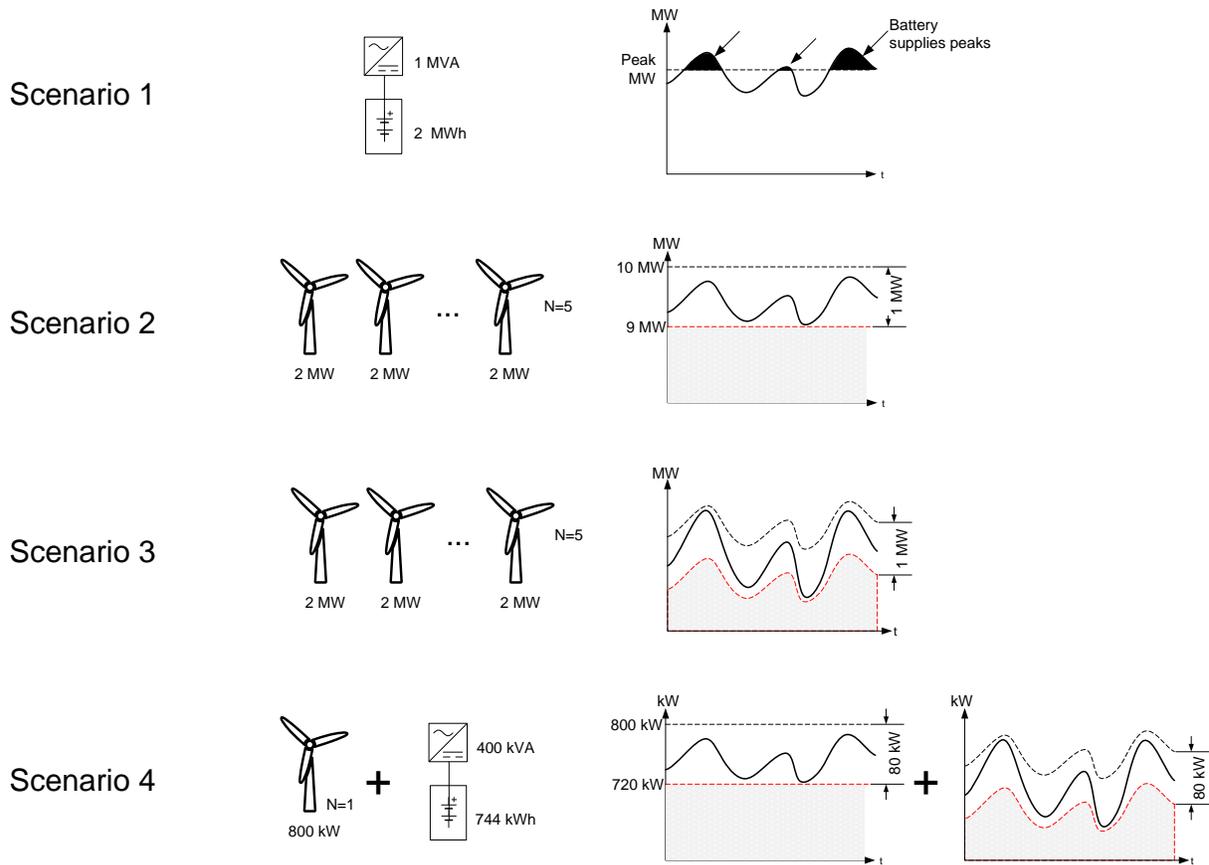


Figure 1: Visual summary of the four project scenarios

Wind generation is a continually expanding source of electrical energy generation in Canada, reaching 13,000 MW of installed capacity (2018) which represents approximately 9%<sup>3</sup> of the total installed capacity from all sources. As more electrical energy is generated by wind, it brings with it challenges to maintaining grid stability. Grid and system operators in many parts of the world are yet to explore and exploit wind generation’s full capabilities. This can be attributed to several reasons. Wind generation is a relatively new technology, having been mainstream for roughly 40 years now as opposed to nearly a century of operation for coal and hydro. Wind has historically represented a small section of the overall generation mix and was therefore only required to provide as much power as the wind would allow. Wind generation was not expected (or required, in most cases) to provide any additional services besides simply generating power. Despite this having changed in recent years<sup>4</sup>, performance data on wind turbines’ abilities is often lacking or not public. NRCan’s PERD project is intended to provide empirical evidence for the ancillary services that wind turbines and storage batteries are capable of providing in

<sup>3</sup> Source: Statcan - Installed plants, annual generating capacity by type of electricity generation (2017): <https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=2510002201>

<sup>4</sup> As an example, see Section 5.6 in the Danish regulator’s requirements for wind generators - Energinet, "Technical regulation 3.2. 5 for wind power plants with a power output greater than 11 kW", 2017

## Project summary

addition to simply generating power. Examples of ancillary services include voltage support, power-frequency support, low-voltage ride through, primary frequency response and operating reserves among others. A total of four scenarios are developed in consultation with system operators and research partners. Two scenarios involve only wind generators, one involves only a battery storage system and one involves both. This work focuses primarily on a wind turbine's ability to provide the service of secondary frequency regulation (aka AGC, Automatic Generation Control).

WEICan's PERD project explores two major themes in four different scenarios.

1. Scenario 1: Using battery energy storage to provide peak electrical demand on a power grid and displace diesel generators
2. Scenarios 2, 3 and 4: Integration challenges with increasing levels of wind generation on the power grid – Providing the ancillary service of secondary frequency regulation from wind turbines and a battery storage system

Scenario 1 is carried out using WEICan's 1 MW / 2 MWh battery energy storage system (BESS). Scenarios 2 & 3 are performed using the Institute's 10 MW Wind R&D Park in North Cape, Prince Edward Island. Scenario 4 is performed at the Saskatchewan Research Council's Cowessess site in Regina, Saskatchewan.

Results from Scenario 1 indicate that the purchase cost of the Institute's battery energy storage system outweighs the income obtainable from providing grid peak power. It is important to note that this conclusion could change with falling battery storage costs and changes in fossil fuel costs.

Results from Scenarios 2 & 3 indicate that the Institute's wind turbines are generally able to perform well when providing secondary frequency regulation. Both scenarios involve power curtailment in order to provide AGC. Performance is measured through the metrics of performance scores from the National Research Council (NRC) of Canada and the Pennsylvania – Jersey – Maryland (PJM) system operator. Performance scores increase with increasing power levels however, some findings are a consequence of the turbine technology (IEC Type V) which is rather uncommon. A financial analysis is performed using measured, annual power generation data from the institute's wind farm combined with spot-price and regulation market data from PJM. Results indicate that providing regulation can be profitable for the wind farm operator despite the curtailment used.

Results from Scenario 4 indicate that an IEC Type IV wind turbine is generally able to provide secondary frequency regulation with a fairly small and consistent error. The performance score metric used in Scenarios 2 & 3 is used here and results indicate performance scores comparable to gas power plants (PJM). As with previous scenarios, power curtailment is required but providing AGC from even a single wind turbine is found to be profitable for the turbine owner. Using battery storage improves the performance score and income but not enough to justify the purchase cost of a battery storage system.

In a broad sense, wind turbines possess the technical ability to provide the service of secondary frequency regulation. Although power curtailment is required, the potential income from the frequency regulation market is greater than the lost energy cost. The feasibility of supplementing the performance of a wind turbine with a battery storage system depends on several factors, most notably, the up-front cost of the battery storage system.

## 2 Intended audience

This is a public report and is intended for a general audience. The readers of this report may or may not have an engineering background and we assume only a basic understanding of concepts like power and energy. We do not assume an understanding of wind turbine technology, battery storage technology or electricity markets. A detailed understanding of these topics is not essential. The relevant concepts behind Automatic Generation Control and the basics of the relevant ancillary service markets are explained.

## 3 Introduction

The Program of Energy Research and Development (PERD) is an NRCan (Natural Resources Canada) – sponsored research program contracted out to WEICan in 2016. The program aimed to test various grid dispatch scenarios which would be developed in consultation with industry stakeholders. Examples of stakeholders include grid / system operators (e.g. Nova Scotia Power, Alberta Electric System Operator, etc.), wind turbine manufacturers and other research groups. The focus of this work is primarily practical demonstrations or applied research and does not focus heavily on the theoretical aspects. Algorithms developed are intentionally designed to be simple and easy to replicate so as to not detract from the end goal: demonstrating the capabilities of the underlying technology in the context of benefiting the electric power grid. This work explores three, broad themes:

1. Using battery energy storage to supply peak electrical demand on the grid during periods where transmission constraints are reached and diesel generators are required
2. Providing ancillary services, specifically secondary frequency regulation (AGC), from wind turbines
3. Using a battery energy storage system to supplement the performance of a wind turbine in providing ancillary services, again, specifically AGC

## 4 Scope

This report presents summaries of the four scenarios developed and run by WEICan under the PERD project. As such, this report focuses on simplified results and presents broad-strokes implications of the findings from the PERD project work. The explanations for topics such as AGC, the operation of the grid and electricity markets that are presented in this report are intended to allow an understanding of the content presented. They are not intended to be exhaustive and readers are directed to the references for a more complete explanation.

For further technical details of the scenarios presented, readers are directed to the list of peer-reviewed publications (Section 14 on page 32). Alternatively, please contact the authors directly.

## 5 Project participants

We thank the following collaborators and participants for their help and input in this project.

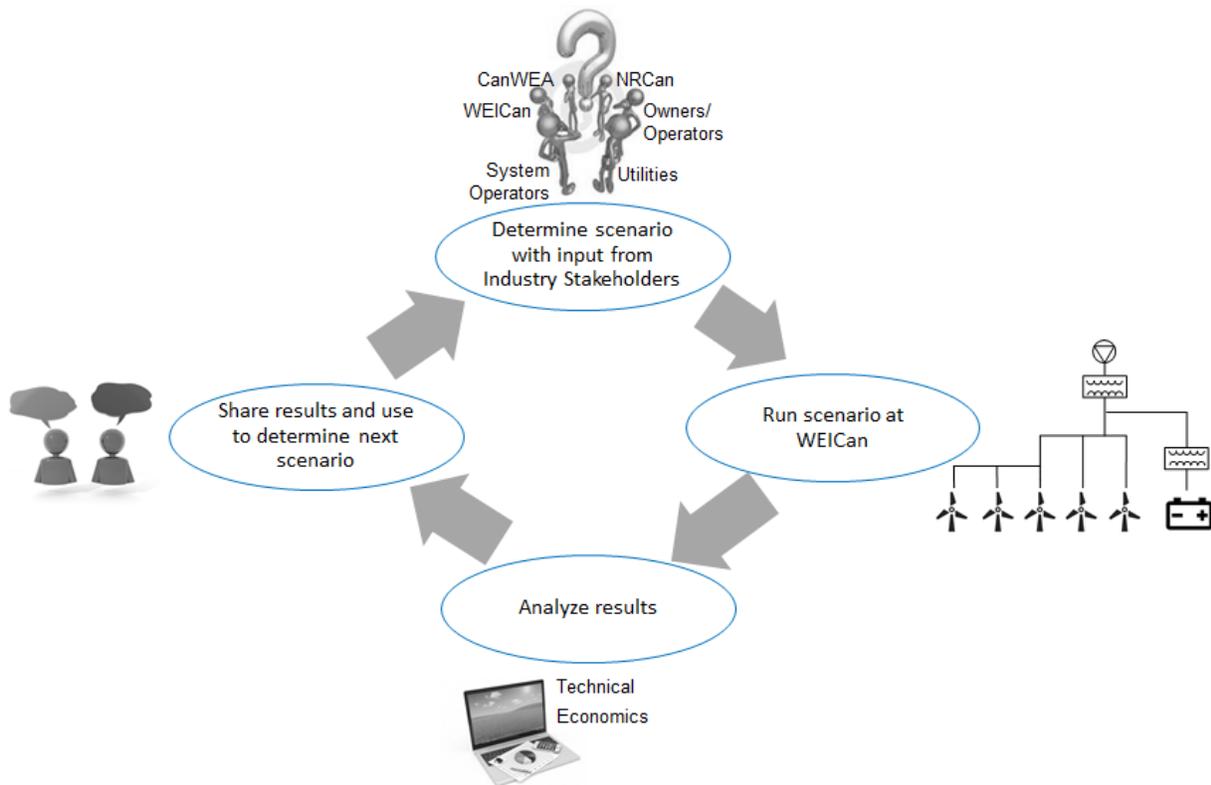
1. Maritime Electric 180 Kent St, Charlottetown,  
PE, C1A 7N2
2. Alberta Electric System Operator Calgary Place 2500, 330 - 5th Ave SW Calgary,  
AB T2P 0L4

## Background

3. Enercon Canada 700 Rue de la Gauchetière Ouest, Montreal, Quebec H3B 4L5
4. Saskatchewan Research Council 15 Innovation Blvd, Suite 125, Saskatoon, SK S7N 2X8
5. Cowessess First Nation 107A Albert Street, Regina SK S4R 2N3

## Scenario development

The scenarios in this project were developed in consultation with the project collaborators mentioned above. A process of continuous feedback was used where results were discussed with system operators such as Alberta's AESO and their feedback was used in developing subsequent scenarios.



## 6 Background

All ten Canadian provinces and two of Canada's three territories have wind generation as part of their electrical energy mix. The cost of generating electrical energy from wind has seen a steady decline since the installation of the first wind turbines and is today competitive with conventional generation sources on a cost per MWh (¢/MWh) basis<sup>5</sup>. Wind energy a non-emitting source of electrical energy and is increasingly being viewed as a means of reducing greenhouse gas emissions from electricity generation.

<sup>5</sup>"Lazard's levelised cost of energy analysis, Version 12.0," 2018.

## Background

Wind generation represents approximately 6%<sup>6</sup> of Canada's electrical energy demand and approximately 5.5%<sup>7</sup> of energy delivered by the US grid.

The Province of Prince Edward Island, for example, has a peak electrical load of around 280 MW with an installed wind generation capacity of 203 MW as of 2018 [1]. Approximately 25% of the Island's annual electrical energy is supplied from wind generation (excluding the 90 MW of wind capacity sold off-island<sup>8</sup>).

In the context of electrical load and electrical generation, it is important to distinguish between power and energy. Instantaneous electrical load is analogous with power and is a measure of the quantity of electrical demand at any given point in time. Power is measured in Watts (W) and electrical appliances are typically rated in multiples of Watts such as kilowatts (kW). Larger measures include megawatts (MW) or gigawatts (GW). A typical household microwave oven is rated at approximately 1000 W or 1 kW. Energy is consumed when an appliance draws power over a certain period of time. A 1 kW microwave oven running continuously for 1 hour will consume 1 kWh (kilowatt-hour) of electrical energy. A helpful analogy is speed and distance when driving a car. Power is analogous to speed (km/h) while energy is analogous to distance travelled (km). Simply knowing the speed of a car at any given time cannot tell you how far it has travelled. If a car travels at a constant speed of 80 km/h for one hour, then it will travel 80 km at the end of one hour. Similarly, knowing only the power rating of a microwave oven is insufficient to determine how much energy it consumes as energy also depends on the time for which power is consumed.

In the PEI example, note that the installed wind generation capacity for PEI consumption (113 MW) represents 40% of the peak power demand (280 MW) however, wind generation supplies only 25% annual energy demand. This is simply because the power output of a wind turbine depends on the prevailing wind speeds. There are periods where the wind speeds are too low for any power generation from wind. On the other hand, during windy periods PEI's wind generation (including the portion sold off-island) regularly supplies more than the island's power demand as demand also varies with time of day and time of year. Averaging the wind production and electricity demand over a year finds that 113 MW of installed generation on PEI supplies, on average 25% of its demand.

### 6.1 The electric power grid

The operation of any electric power grid involves a balance between supply and demand. Generation and load are often not exactly in balance but their relative balance influences system frequency. The system frequency of the North American power grid is nominally 60 Hz and typically does not vary by more than 0.1 Hz [2]. Imbalances between supply and demand manifest as deviations from nominal grid frequency. Figure 2 is taken from a NERC report and shows a good representation of the factors that affect grid frequency. Other factors that affect the quality of electricity supply include voltage changes, harmonics, etc but these are not directly relevant to the content of this report<sup>9</sup>.

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<sup>6</sup> Source: <https://canwea.ca/wind-energy/installed-capacity>

<sup>7</sup> Source: AWEA: <https://www.awea.org/resources/press-releases/2017/us-wind-generation-reached-5-5-of-the-grid-in-2016>

<sup>8</sup> See the Government of PEI's website for real-time figures of wind generation and the fraction consumed on-island <https://www.princeedwardisland.ca/en/feature/pei-wind-energy/>

<sup>9</sup> See the NERC reliability standards for more information. <https://www.nerc.com/pa/Stand/Pages/Default.aspx>

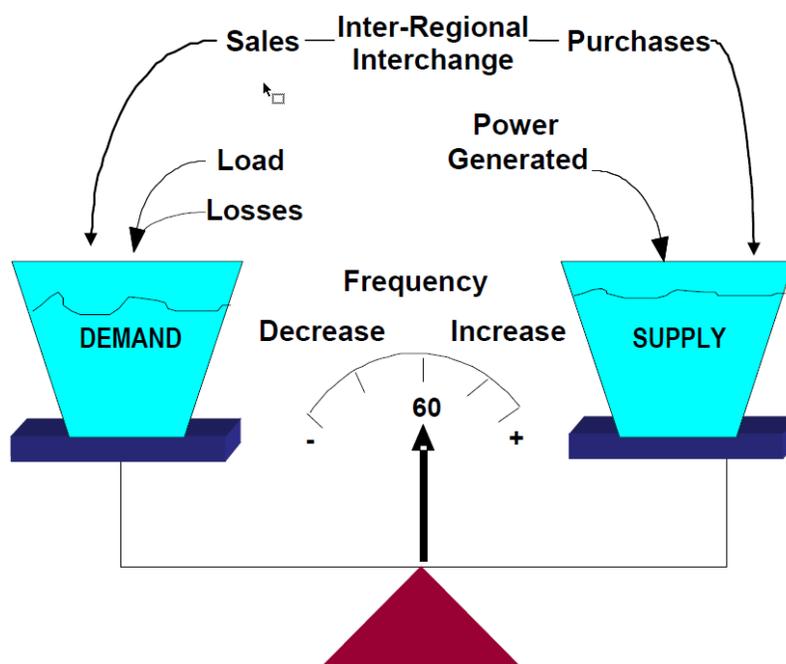


Figure 2: Graphical representation of the relation between demand, supply and frequency [2]

## 6.2 Battery storage

The electric grid operates with almost no electrical energy storage. Although large hydro-electric dams are a form of energy storage, they are distinct from the electrical energy stored in batteries. As of the end of 2017, about 708 MW (with 867 MWh of energy storage capacity) of grid-scale battery storage is operational in the USA. This represents roughly 0.07% of installed power capacity [3] i.e. it is almost insignificant. From the electric grid's viewpoint, batteries simply represent a means of energy storage as the chemistry and technology behind them are not very relevant.

Grid-scale batteries are able to provide several services to the grid in addition to delivering and absorbing power. They accomplish this through the use of sophisticated power electronics. In the context of this report, Scenario 1 explores the feasibility of one use-case of battery storage: providing power to meet peak electrical demand on the grid during periods of low wind. Scenario 4 explores the ability of a battery to improve the ancillary service performance of a single wind turbine and its ability to provide that ancillary service.

## 6.3 Wind turbines

A wind turbine is a means of generating electrical energy from the kinetic energy in the wind. Modern, utility-scale wind turbines are sophisticated machines that are capable of various additional services in addition to simply generating power. A limitation of wind turbine is in the name itself – wind. Their ability to generate power depends on the prevailing winds and is therefore both variable and uncertain.

- Variable because their power output depends on variable wind speeds
- Uncertain because future wind speeds can never be predicted with perfect accuracy

Wind turbines today are operated as 'take-all' generators. This means that the larger power grid is obligated to absorb all generated power and also accommodate the variable and uncertain nature of

## Background

wind power. As the installed capacity of wind generators grows, they often displace existing generation such as coal, gas, nuclear or hydro generators. These generators are different from variable generations such as wind in that their power output can be changed in a controllable manner. A gas power plant, for example, can simply burn more natural gas to increase its power output. A wind turbine cannot increase its power output above what is available in the prevailing wind. One way of dealing with the nature of wind generation is through operational reserves. This is an already established operation strategy for the power grid that was developed to deal with contingencies such as power stations going offline or changes in demand. Here, certain generators are kept on standby and are called on to increase or decrease their power outputs depending on the grid's needs at any point in time.

A further consequence of wind generators displacing conventional generators is in respect to the additional services provided by conventional generators.

### 6.4 Ancillary services

Ancillary services represent a set of services that operate as a complement to the primary grid service of supplying energy. Depending on the nature of the service, ancillary services may or may not depend on power. Examples of ancillary services that depend on active power include spinning reserve, frequency support, regulation services and grid inertia. Ancillary services that do not depend on active power include voltage regulation, reactive power support and fault ride-through. Some services such as regulation, may be procured on a competitive market. Others, such as grid inertia, are provided as a consequence of the generation technology used i.e. large, spinning masses with significant rotational inertia and are not procured on a competitive market. Conventional generators are typically not paid for inertia as they provide it as a consequence of generating power with large, spinning turbines. As wind generators displace conventional generation capacity on the larger grid, they reduce the amount of inertia on the grid which could lead to grid stability problems [4].

This report focuses specifically on the ancillary service of secondary frequency regulation, often referred to as AGC (Automatic Generation Control).

### 6.5 Secondary frequency regulation

One method of maintaining the supply-demand balance on the grid in the time frame of minutes is secondary frequency regulation. This involves small changes to the power outputs of several generators and is co-ordinated by the system operators over a significant geographical area, typically an entire province or several states. Figure 3 illustrates the different regions of frequency response. Note that modern power electronics allows wind generators to operate in all regions, including inertial response. Some wind turbine manufacturers refer to this as “synthetic inertia”. This report focuses specifically on the region of secondary frequency response in Figure 3. Here, the system operator makes small changes to the active power output of generators in an attempt to balance demand and supply and therefore to keep grid frequency as close to nominal (60 Hz) as possible.

The economic goal for any power producer is to maximise profit and most electricity markets allow for two major means to achieve this. The first is the energy market where generators offer bids to supply energy at a certain price. The system operator selects from among the generators' offers in the most economical manner.

The second is the ancillary services market which includes providing services such as secondary frequency regulation. Power generators can choose to bid in either one of the markets or in both. Note

## Background

that providing a service such as up-regulation requires the generator to operate below its rated power. This is because AGC can call for either an increase or decrease in power from a generator and headroom must be available if an increase in power output is requested. Typically, generators bid on both markets as they are paid for keeping some power on standby for regulation services.

A graphical representation of this process is the 10 MW generator shown in Figure 4 (a). This shows one hour of power generation from a coal, gas or hydro. Here, 9 MW of the available power generation range is offered on the energy market and this value stays constant for the duration of the hour. The range between 9 MW and 10 MW is offered on the regulation market. The system operator sends the generator a power target (in MW) every four seconds. These power targets range between 9 MW and 10 MW depending on the amount of regulation required at any point. Note that the dashed red line (at 9 MW) is horizontal and does not change in value over time. This is a consequence of the way that power is generated by a conventional generator. The power output is controlled by fuel flow i.e. if more power is required, simply burn more coal, gas, etc.

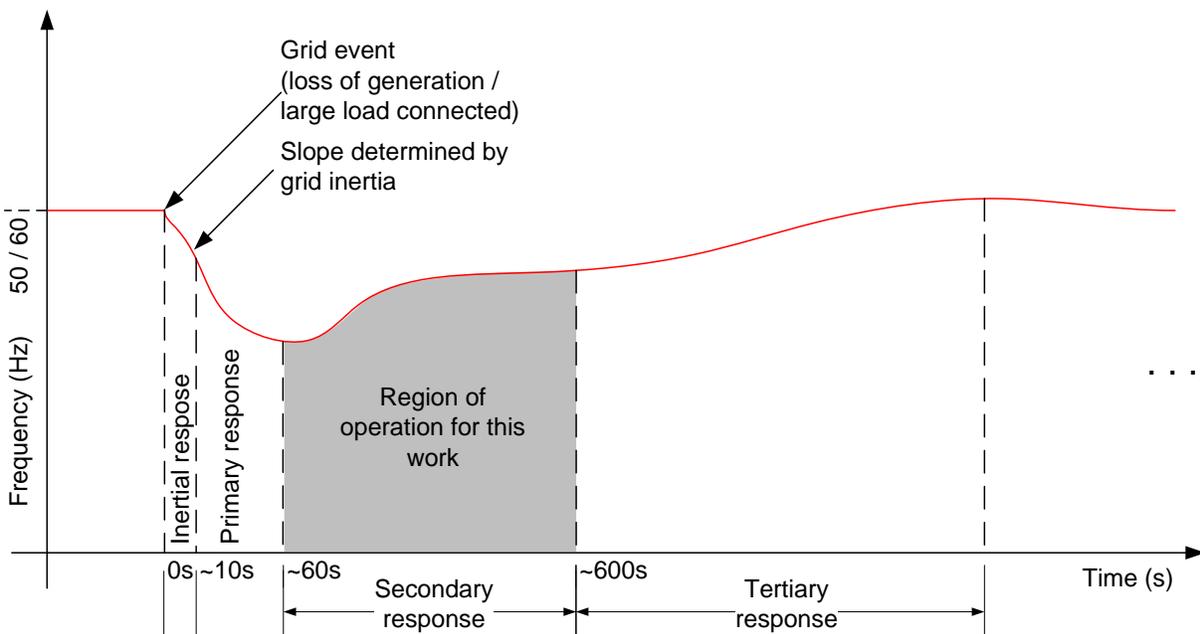


Figure 3: Illustrating the different regions of frequency response; based on [2]

### 6.6 Challenges in providing secondary frequency regulation from wind turbines

The primary challenge in a wind turbine providing AGC is from the nature of how it generates power. The fuel for a wind turbine is the flow of air over its rotor, i.e. the wind speed. As such, the output of a wind turbine is uncertain, variable and is constrained by the power available in the wind. A wind turbine cannot increase its power output beyond what is available in the prevailing wind. All these factors combine to make providing AGC from a wind turbine challenging.

Consider the uncertainty of wind forecasts. Unlike with a conventional power generator where the amount of possible production is constant, it is impossible to predict future wind speeds with perfect accuracy. As the power output of a wind turbine depends on wind speeds, it becomes difficult to commit

## Background

to future power generation levels. If the wind speeds and therefore power generated drop to below what was committed, there is nothing that can be done.

Consider the variability of wind speeds. This makes it difficult to predict and guarantee a minimum level of power generation when using a wind turbine. Contrast this with a conventional generator where power outputs can be controlled with fuel flow. This is the reason behind the varying dashed red and black lines in Figure 4 (b).

Both these factors combine to produce Figure 4 (b) which depicts providing AGC from a variable generator such as a wind turbine. Observe that the magnitude of the regulation region is the same in both Figure 4 (a) and (b) at 1 MW. The nature of the region, however, is different. With a conventional generator, the limits of the regulation region are known in advance and are usually held constant. The dashed lines showing the limits of the regulation region in Figure 4 (b) vary with the variations in wind speed. This represents a challenge for the system operator.

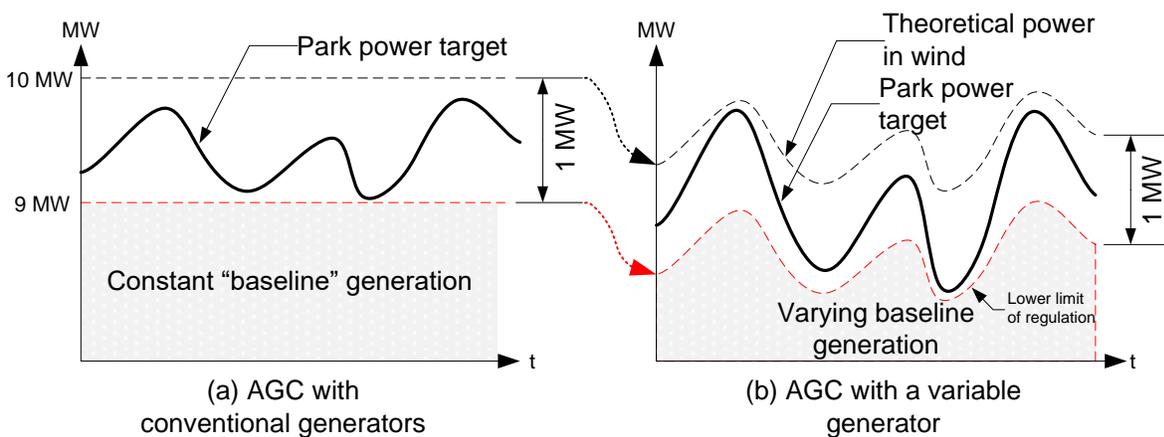


Figure 4: Providing AGC from a conventional generator (a) versus a variable generator (b)

## 6.7 Wind turbine power curve

The power curve of a wind turbine relates wind speed to power production. In simpler terms, knowing the prevailing wind speed allows you to estimate the power production from a certain wind turbine using the power curve. The minimum wind speed at which a wind turbine is able to generate power is called the cut-in wind speed. The wind speed at which a wind turbine produces its rated power is called its rated wind speed. Observe from Figure 5 how the value of generated power increases between cut-in and rated wind speeds (Region 2) and then stays constant (Region 3). The point at which the power curve flattens is called the 'knee' of the power curve. Although not shown in this power curve, at a high enough wind speed, a wind turbine will shut off to prevent damage. In other words, the power curve does not remain flat for all wind speeds above rated wind speed.

A consequence of the nature of the power curve is that above rated wind speed, providing AGC from a wind turbine is functionally identical to providing it from a conventional generator. This is because the power output of the wind turbine ceases to be dependent on the wind speed and stays relatively constant. Recall that the wind speed can vary significantly and any dips or lulls in the wind will affect the power output.

## Background

Below the knee of the power curve, power output depends on the prevailing wind speed. Accurately predicting the power output of a wind turbine in this region (Region 2) is impossible due to the fact that predicting wind speed with perfect accuracy is not possible.

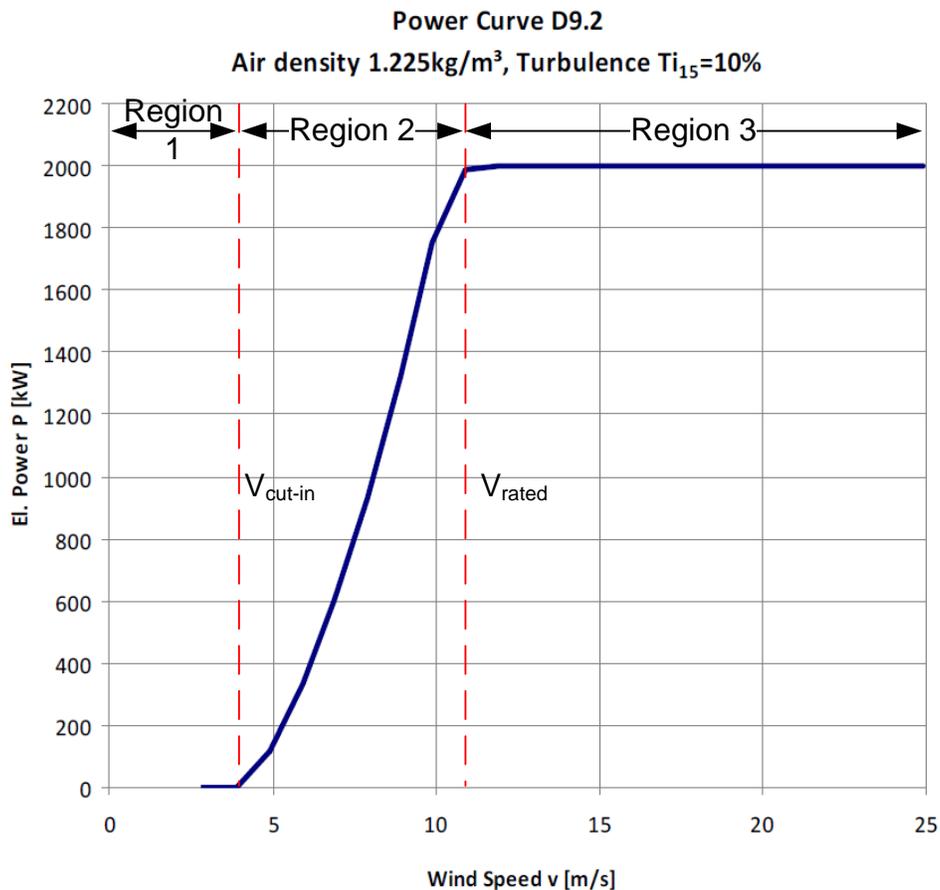


Figure 5: Power curve of WEICan's DeWind D 9.2 wind turbines

## 6.8 Performance scores

When a generator participates in the secondary frequency regulation market, it is paid for two services:

1. Remaining on standby to provide regulation services
2. Responding to a regulation signal and providing regulation services

The payment for remaining on standby depends on the quantity of regulation offered (in MW) and is paid even if the generator provides no regulation.

The response of the generator to an external regulation signal determines the payment for the second quantity. This response depends on the generator technology used. A coal plant, for example, will respond slower than an equivalent gas-based plant. A performance score is used to quantify this response. Performance scores range from 0 to 1 and are usually expressed as a percentage with a 100% performance score corresponding to an ideal response. We use two performance score methods in this work:

1. Natural Resources Canada method [5]

## 2. PJM method [6]

The error between the target power and the actual power is one component of the performance score calculation. More error worsens the performance score. Other components of the performance score include time delay and response precision. Although we do not cover the details of each method in this report, it is important to note that results from the two methods are not directly comparable i.e. a performance score of 90% calculated with the NRC method is not comparable to a performance score of 65% with the PJM method.

For comparison to performance scores reported later, the table below shows performance scores for existing generation technologies:

*Table 1: Performance scores as reported for existing generation technologies*

Technology	NRC $\eta$ [5]	PJM $\eta$ [7]
Coal	67%	76% (Reg A <sup>10</sup> )
Hydro	86%	78% (Reg D)
Gas	75%	91% (Reg D)
Energy storage	-	92%

## 6.9 Financial aspects

This work is not intended to present a comprehensive financial analysis of storage or wind farms participating in the regulation and energy markets. The results of the analyses presented here are based on simplifying assumptions which can be found in the published work from this project (see Section 13). We ignore costs such as maintenance arising from wear and tear of turbine components. All the methods of providing frequency regulation from wind turbine require some amount of power curtailment. This represents energy that could be sold on the energy market but that is not. This represents an opportunity cost. For profitable operation, any additional income derived must entirely offset this opportunity cost.

Note that financial implications presented here are from the point of view of the wind farm owner and not the system operator. A wind farm owner is motivated to increase income from the wind farm. A system operator's motive is to procure system services (and energy) in the most economical way.

## 6.10 Assumptions and limits of this work

The control methods in this project are intentionally simple. They are intended to serve as a proof-of-concept and not as sophisticated methods with maximisation or minimisation targets. Several aspects of wind turbine and wind farm control are not taken into account in this work. Notably, when providing services like secondary frequency regulation from wind farms, numerous factors must be considered. For example, a typical wind farm has wind turbines separated in space (i.e. spread over a certain geographic area). Depending on the orientation of the wind turbines relative to each other and also on the prevailing wind direction, certain turbines in a farm may be in the wake of other turbines. A helpful

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<sup>10</sup> For a comparison between PJM's Reg A and Reg D signals, see PJM's 'Regulation Market - Learning Centre' page, Available at <https://learn.pjm.com/three-priorities/buying-and-selling-energy/ancillary-services-market/regulation-market.aspx>

## Project scenario summaries

analogy is that of aircraft taking off from an airport. A smaller and lighter aircraft may find itself in the wake of a larger, heavier aircraft which may cause the lighter aircraft to experience turbulence. The same is true of the winds experienced by a wind turbine that is downstream of another. This may affect the power that the downwind turbine is able to generate and may also create other challenges such as mechanical loads<sup>11</sup>. This work does not account for wake effects and mechanical loading of individual wind turbines in a wind farm.

We also make several simplifying assumptions, particularly in our algorithms and financial calculations. For example, we assume that a power curve constructed using nacelle wind speed data and live measurements of nacelle wind speed provide an accurate estimate of the power available in the wind. More sophisticated methods of estimating the power in the wind exist<sup>12</sup> but these are beyond the scope of this project. Our financial calculations do not account for second-by-second variations in wind speeds and we use hourly averages for power for determining energy output. While this decreases accuracy, it does allow for more generalised conclusions to be drawn.

Finally, this work documents results from IEC Type 5 (uncommon) and Type 4 wind turbines. We do not have access to results from Type 3 wind turbines and so cannot comment on their ability to provide ancillary services as described in this report.

## 7 Project scenario summaries

The table below lists the four scenarios carried out as part of this project. Following the table are brief descriptions of what was tested in each scenario. These are intended as brief summaries of each scenario and focus on the key differences between scenarios. Scenarios 3 & 4 build on the results from Scenarios 2 & 3 respectively and extend the test in different ways. More details of each scenario are in subsequent sections of this report.

- Scenario 1 Diesel displacement with a 1 MW / 2 MWh storage system
- Scenario 2 Wind power providing frequency regulation
- Scenario 3 Wind power providing frequency regulation under varying generation conditions
- Scenario 4 Type IV wind turbine providing frequency regulation in parallel with a battery system

	Location	Duration	Regulation offer
Scenario 1	North Cape, PE	1 Month	1 MW / 2 MWh
Scenario 2	North Cape, PE	30 minutes	1 MW (10%)
Scenario 3	North Cape, PE	4.5 hours	1 MW (10%)
Scenario 4	Regina, SK	> 15 hours of testing	80 kW (10%) - Turbine 200 kW - Battery

<sup>11</sup> See Section 2 in ECN's 2013 report titled 'Wind farm modeling and control: an inventory'. Available at <https://www.ecn.nl/publications/PdfFetch.aspx?nr=ECN-E--13-058>

<sup>12</sup> See work done at the Technical University of Denmark, DTU. Examples include the PossPOW project and works such as 'Estimation of the possible power of a wind farm'. Available at [http://orbit.dtu.dk/files/102382796/Estimation\\_of\\_the\\_Possible\\_Power.pdf](http://orbit.dtu.dk/files/102382796/Estimation_of_the_Possible_Power.pdf)

## Scenario 1

### 7.1 Scenario 1- Diesel displacement with a 1 MW / 2 MWh storage system

This scenario examines the feasibility of providing peak electrical demand from a battery energy storage system instead of PEI's existing diesel generators. Typically, on calm cold days with limited wind generation, PEI's connection to the continental electricity grid, an undersea cable, reached its operating power maximum and any extra power was provided from on-island diesel peaker plants.

### 7.2 Scenario 2- Wind power providing frequency regulation

This scenario examines the ability of WEICan's 10 MW wind farm (IEC Type V) to provide AGC (i.e. secondary frequency regulation). A 30 minute test is carried out above the turbine's rated wind speeds using a historical AGC signal.

### 7.3 Scenario 3- Wind power providing frequency regulation under varying generation conditions

This scenario examines the ability of WEICan's 10 MW wind farm (IEC Type V) to provide AGC (i.e. secondary frequency regulation). A 4.5 hour test is carried out below the wind turbine's rated wind speeds where the power output of the turbines varies with wind speed. A historical AGC signal is used.

### 7.4 Scenario 4- Type IV wind turbine providing frequency regulation in parallel with a battery system

Two major configurations are examined here. One, the ability of an IEC Type IV wind turbine to provide AGC (i.e. secondary frequency regulation) both above and below rated wind speeds. Two, the ability of a battery storage system to improve the wind turbine's ability to provide AGC. Both 30 minute and 4.5 hour historical AGC signals are used.

## 8 Scenario 1

### 8.1 Location

WEICan's 1 MW / 2 MWh sodium-nickel-chloride battery in North Cape, PEI

### 8.2 Aims

To examine the technical and financial feasibility of using a battery energy storage system to provide peak power to an island grid during transmission constraints thereby displacing diesel generation with energy from a storage system.

### 8.3 Methodology

PEI's electrical tie to the continental American grid is via an undersea cable to New Brunswick that crosses the Northumberland Strait<sup>13</sup>. Prior to the expansion in 2017, the cable had limited power transfer capacity and was unable to meet PEI's peak power demand. Maritime Electric, PEI's electric utility, operated diesel generation sets on the island when periods of peak power demand corresponded to periods of low wind production.

Based on the wind forecast, the battery was dispatched during March 2016 to discharge during periods when the undersea cable was expected to reach its maximum power capacity. The local utility gave input

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<sup>13</sup> See <https://www.princeedwardisland.ca/fr/information/communautes-terres-et-environnement/pei-nb-cable-interconnection-upgrade-project-pei> for more information

## Scenario 1

on when these periods were expected. The battery was charged once the diesel generators were expected to be finished providing electricity i.e. not during periods of peak demand. Prince Edward Island had 204 MW of installed wind capacity, an import capacity of 200 MW and a peak load of 230 MW during March 2016. Diesel generators were required during 6 calm, cold days to offload the submarine cables. The longest period was 5 hours where 45 MWh of energy was required with a peak of 16 MW.

### 8.4 Results

The battery's discharge overlapped with 4 of the 6 periods when diesel generators were used to offload the submarine cables in March 2016. This resulted in 3.7 MWh of energy being sent to the network to displace diesel generation. Although 1.5 MWh of AC power is discharged each time, during two discharge periods only 1 of the 2 hours had the diesel generators operating. The battery spent 78% of its time in idle mode waiting for periods when diesel generators were expected to be used. This idle time adversely affected the overall efficiency as WEICan's specific battery technology required power for climate control and auxiliary loads. In Figure 6 all of the discharge periods are shown along with the electricity load, wind production, and diesel production.

The cost of WEICan's battery energy storage system is \$40,000 per month driven by its high capital cost and a seven year life expectancy. The payments received by the local utility for providing capacity and energy over the month of March was \$3,480, only 9% of the amortised value. Optimising discharge periods by allowing the energy control centre direct access would ensure discharging always overlapped with diesel events. This would improve the financial performance but a significant reduction in the cost of battery energy storage systems is required before it becomes a cost effective way to provide energy during transmission constraints.

Providing additional services such as secondary frequency regulation (Scenario 4) from a battery energy storage system has the potential to provide additional income<sup>14</sup>.

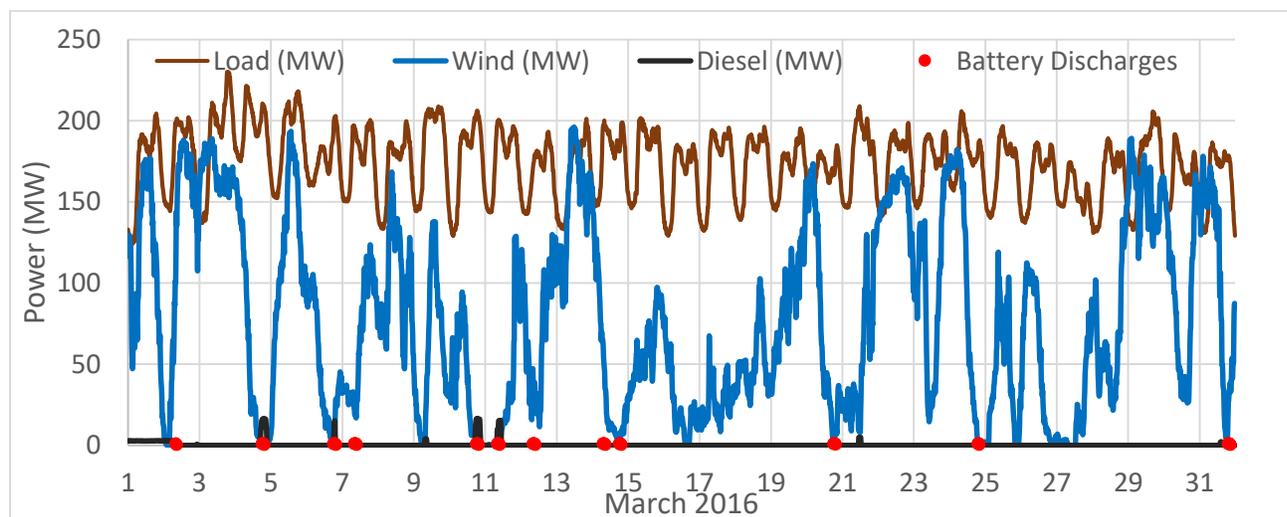


Figure 6: Prince Edward Island electricity load, wind power, diesel power, and discharge periods for March 2016

<sup>14</sup> See also 'Demonstrating Stacked Services of a Battery in a Wind R&D Park' by David Watson; Cameron Hastie ; Brady Gaudette ; Marianne Rodgers in IEEE Transactions on Power Systems, 2018

## Scenario 2

### 9 Scenario 2

#### 9.1 Location

WEICan's 10 MW, 5 turbine Wind R&D Park in North Cape, PEI

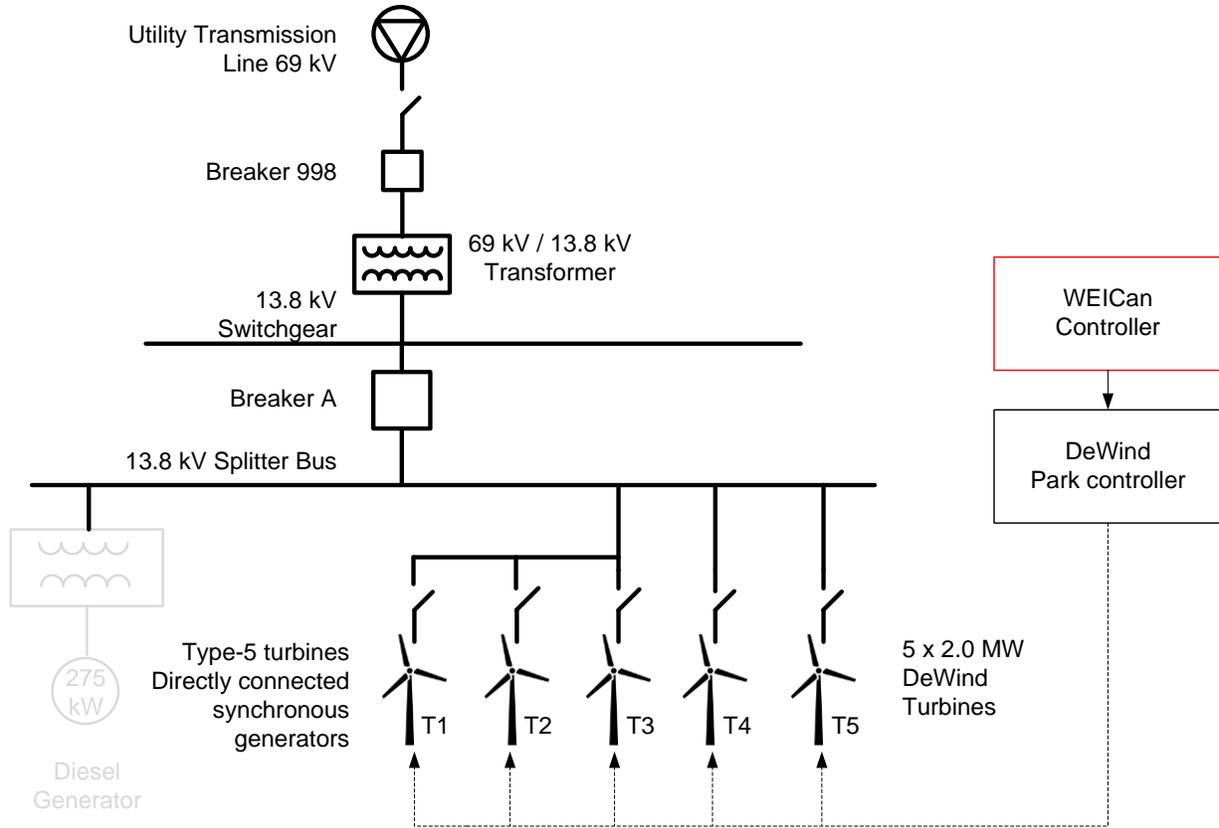


Figure 7: Simplified layout of WEICan's 10 MW wind R&D park in North Cape, Prince Edward Island

#### 9.2 Aims

To demonstrate the ability of a wind farm to follow an external, 4 s AGC signal when the prevailing speed is greater than the turbine's rated wind speed.

## Scenario 3

### 9.3 Results

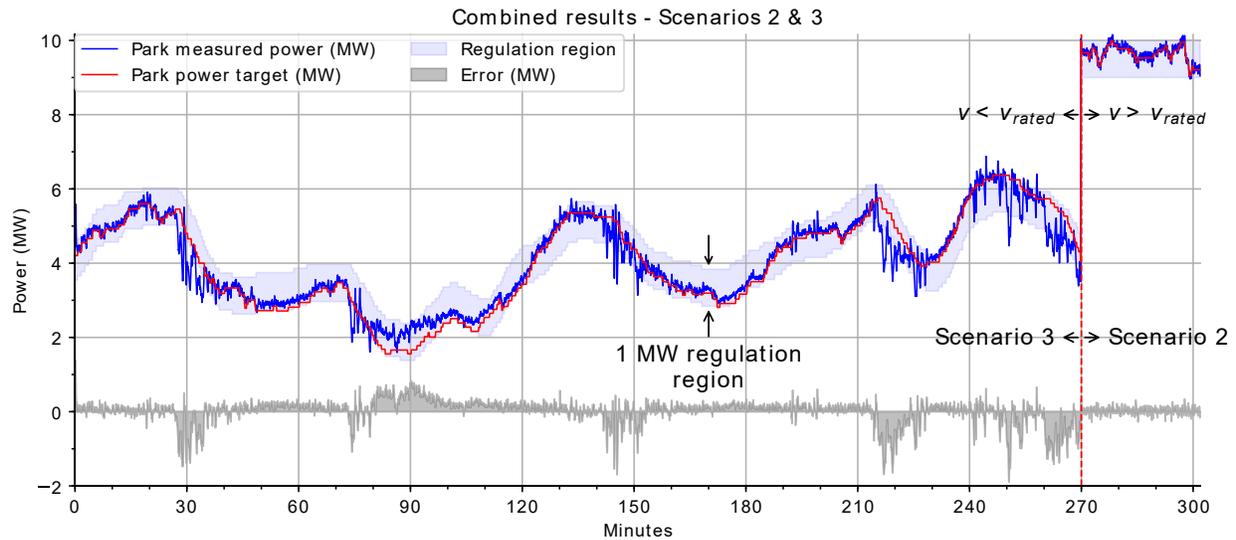


Figure 8: Combined results for Scenario 2 & Scenario 3

In Scenario 2, a 30 minute, historical AGC signal was sent to WEICan’s 10 MW wind farm. A curtailment of 10% i.e. 1 MW was applied and the AGC setpoints varied between 9 MW and 10 MW. Wind speeds during the test were above the turbine’s rated wind speeds. This meant that power output from the individual turbines was constant as long as the wind speeds did not drop to below the turbines’ rated wind speed. The uncurtailed power output of the wind farm was therefore a constant 10 MW. Power targets were simply sent to the wind park and the park controller distributed these among the individual turbines. Results are shown in Figure 8 (right of red vertical line) and the performance scores are summarised in Table 2.

Table 2: Scenario 2 Performance score summary<sup>15</sup>

Above rated wind speeds	NRC [5]	PJM [6]
$\eta$ (30 minutes)	94%	74%

## 10 Scenario 3

### 10.1 Location

WEICan’s 10 MW, 5 turbine Wind R&D Park in North Cape, PEI

### 10.2 Aims

To demonstrate the ability of a wind farm to follow an external, 4 s AGC signal when the prevailing speed is below the turbine’s rated wind speed. Like Scenario 2, this was performed on WEICan’s 10 MW wind farm in North Cape, Prince Edward Island.

### 10.3 Algorithm

The control method used had to be modified relative to what was used in Scenario 2. An outline is shown in Figure 9. The individual turbines were operating below their rated wind speeds (Region II of the

<sup>15</sup> Compare with Table 1 on Page 17

### Scenario 3

power curve) and their power outputs depend on the prevailing wind speed. A power curve was constructed for each individual turbine using past data. This power curve used wind speeds measured at the turbine nacelle. The wind speeds measured at the nacelle of an individual turbine were averaged and fed into the historical power curve to estimate the power in the wind. This was repeated for each of the five turbines and then summed. This sum represents the theoretical power that the wind park as a whole should produce.

To create room for regulation services, a fixed amount of curtailment was applied. To this curtailed value, the values of the historical AGC signal were added to calculate a target for the park as a whole. This target value was sent to the park controller which distributed it among the individual turbines.

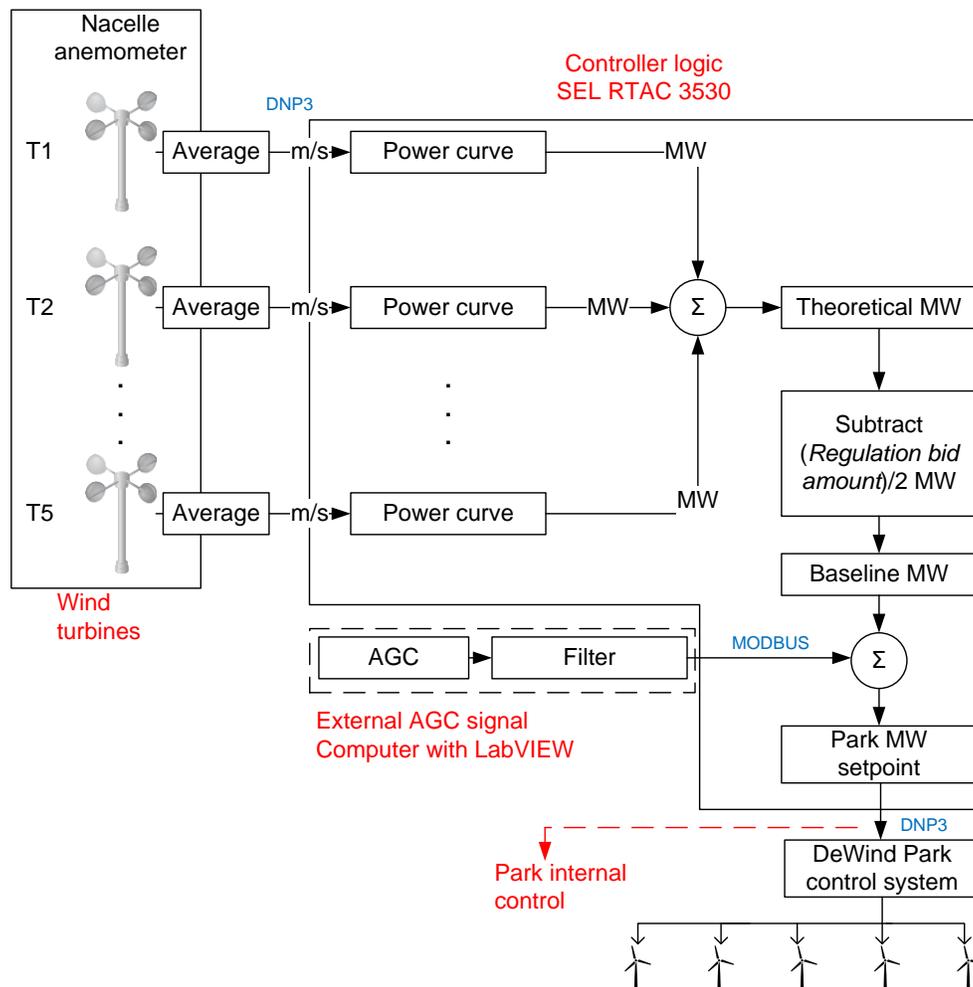


Figure 9: Scenario 3 algorithm

### 10.4 Results

Results from the Scenario 3 test are shown in Figure 8. As in Scenario 2, 10% of the wind farm's rated power is offered on the regulation market. The performance scores for Scenario 3 (Table 3) are slightly lower than those for Scenario 2. Although there are several reasons for this, the effect is an increase in error between the target power and the actual generated power. Observe from Figure 8 that the error

## Scenario 4

magnitude (grey region) is higher in Scenario 3 relative to Scenario 2 (left and right of red, vertical line). Despite this, the wind park is able to follow power targets reasonably well.

Table 3: Scenario 3 performance scores & summary of Scenarios 2 & 3

Above rated wind speeds	NRC [5]	PJM [6]
$\eta$ (4.5 hours)	78%	64%
$\eta$ (net of Scenarios 2 & 3, 5 hours)	81%	65%

For the financial analysis, the PJM performance score of 64% was used along with one year of power generation data from WEICan's wind farm and one year of electricity market data from PJM [8].

Calculations show that with a 1 MW regulation market offer and a performance score of 64%, the additional income from the regulation market is US \$ 6200, annually. This figure represents the additional income from the wind farm participating in the regulation and energy markets versus participating in the energy market alone. Although not a significant sum, the conclusion is encouraging. Despite the opportunity cost of lost energy, participation in the regulation market has the potential to be profitable.

## 11 Scenario 4

### 11.1 Location

Saskatchewan Research Council's Cowessess Wind and Storage test site in Regina, Saskatchewan [9]. This consists of a single, 800 kW Type IV wind turbine and 744 kWh of battery storage connected through a 400 kW inverter.

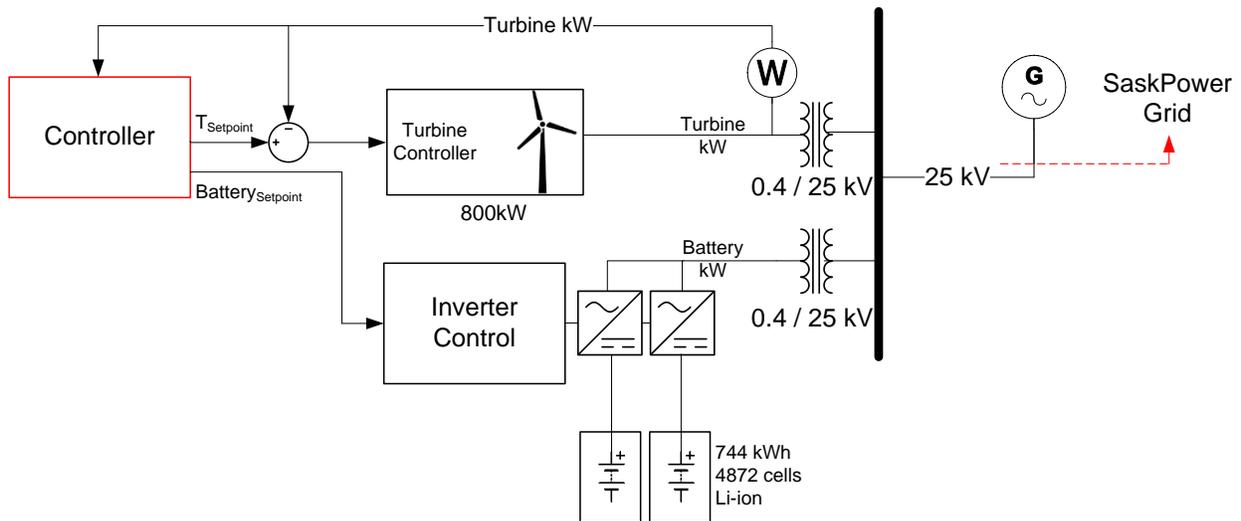


Figure 10: Simplified site layout of SRC's Cowessess site

### 11.2 Aims

1. To demonstrate the ability of a battery storage system to provide secondary frequency regulation

## Scenario 4

2. To demonstrate the ability of a single Type IV wind turbine to provide secondary frequency regulation in response to a 4 s, historical AGC signal above and below rated wind speeds
3. To evaluate whether a battery storage system can improve the performance score of the wind turbine in providing AGC

### 11.3 Algorithms

Since different algorithms are used for each test, only the key features are presented here.

Test 1 sends target power values to the battery and examines its response through a performance score.

Test 2 sends power setpoints to the wind turbine which follows them, similar to Scenario 2. This test is performed when the prevailing wind speed is greater than the wind turbine's rated wind speed.

Test 3 uses an algorithm that is functionally identical to that of Scenario 3. The curtailment applied is 40 kW, i.e. half the regulation offer of 80 kW. The turbine power setpoint is calculated based on a power curve (based on nacelle wind speed averages) and the AGC signal requirement.

Test 5 does not curtail the wind turbine, but instead uses the battery to account for the error between the expected turbine power (based on nacelle wind speed averages) in addition to the AGC signal requirement.

When the battery is used, its state of charge is allowed to vary between 30% & 80%.

### 11.4 Results

Scenario 4 included four different tests on SRC's wind turbine and battery system [9]. This report does not present results from all tests for the sake of brevity. Details of the tests performed are summarised in Table 4 and Table 5. To maintain consistency, a 10% regulation offer (80 kW) is used in Scenario 4, which is identical to that of Scenarios 2 and 3. Test 4 was not performed and is therefore excluded from the tables below.

The major differences between Scenario 4 and Scenarios 2 and 3 are that a battery was added to the testing, the turbine technology, and the fact that a single turbine is used versus a wind farm in Scenarios 2 and 3. The turbine technology in Scenario 4 is classified as IEC Type IV<sup>16</sup>. This means that a full converter with power electronics is used and 100% of the wind turbine's active power output flows through the power electronics.<sup>17</sup>

As expected, the tables below show that the best performance scores are obtained when using the battery alone. As long as the battery has stored energy to deliver, it is able to accurately follow power targets. In Test 1B, the battery's State-of-charge (SoC) drops below the allowed minimum (30%) and it ceases to follow the external AGC signal.

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<sup>16</sup> See 'Next edition of IEC 61400-27 - Electrical simulation models for wind power plants'  
[http://orbit.dtu.dk/files/142072087/Next\\_edition\\_of\\_IEC\\_61400\\_27.pdf](http://orbit.dtu.dk/files/142072087/Next_edition_of_IEC_61400_27.pdf)

<sup>17</sup> See 'Wind Turbine Plant Capabilities Report – 2013 Wind Integration Studies' from the Australian Energy Market Operator available at [https://www.aemo.com.au/-/media/Files/PDF/Wind\\_Turbine\\_Plant\\_Capabilities\\_Report.pdf](https://www.aemo.com.au/-/media/Files/PDF/Wind_Turbine_Plant_Capabilities_Report.pdf)

## Scenario 4

Table 4: Scenario 4 test summary

Test	Duration	Regulation offer
1. Battery only		
a. Initial SOC = 50%	30 minutes	200 kW
b. Initial SOC = 30%	30 minutes	200 kW
2. Wind turbine only, above rated wind speed	30 minutes	80 kW
2.a Wind turbine only, above rated wind speed	30 minutes	200 kW
3. Wind turbine only, below rated wind speed	4.5 hours	80 kW
5. Wind turbine and battery below rated wind speed	4.5 hours	80 kW

Table 5: Scenario 4 test overview

	Duration	Primary AGC provider	Secondary AGC provider	Battery operational?	Wind turbine operational?
Test 1	30 minutes	Battery	-	Yes	No
Test 2	30 minutes	Wind turbine	-	No	Yes
Test 3	4.5 hours	Wind turbine	-	No	Yes
Test 5	4.5 hours	Battery	Wind turbine	Yes	Yes

Table 6: Scenario 4 performance score results<sup>18</sup>

		NRC performance score (%)	PJM performance score (%)
Test 1	Battery providing AGC alone	97.4	93.6
Test 2*	Wind turbine only, above rated wind speed*	82.0	54.5
Test 2a	Wind turbine only, above rated wind speed	85.4	83.9
Test 3	Wind turbine only, below rated wind speed	88.6	65.4
Test 5	Wind turbine and battery below rated wind speed	95.3	71.7

\* Results affected by scaling error which was corrected in test 2a

<sup>18</sup> Compare with Table 1 on Page 17

Scenario 4

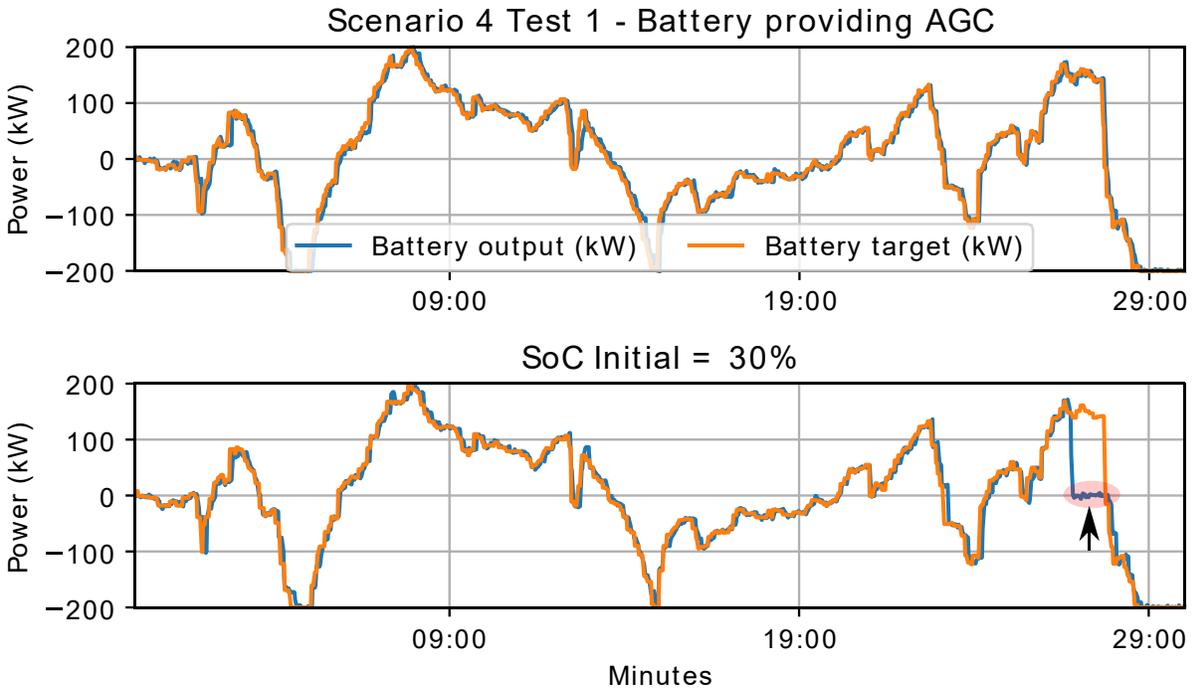


Figure 11: Results from Tests 1A and 1B (lower). Arrow shows duration for which battery SoC was too low to provide AGC

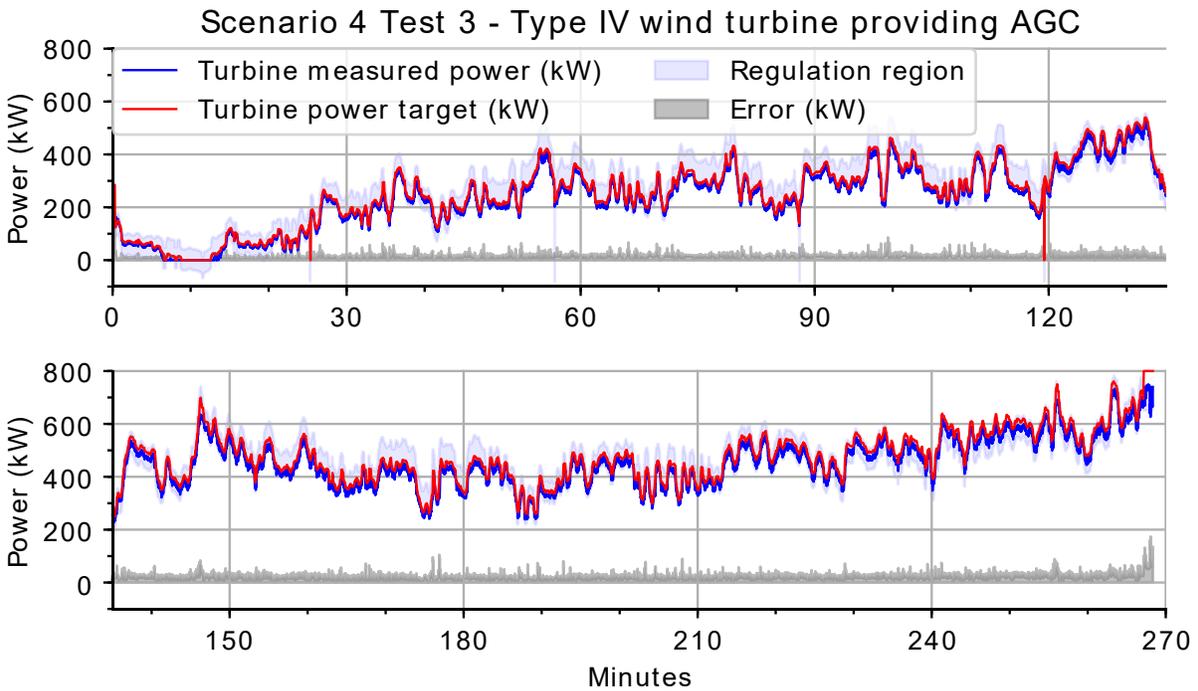


Figure 12: Providing AGC with a Type IV wind turbine below rated wind speed

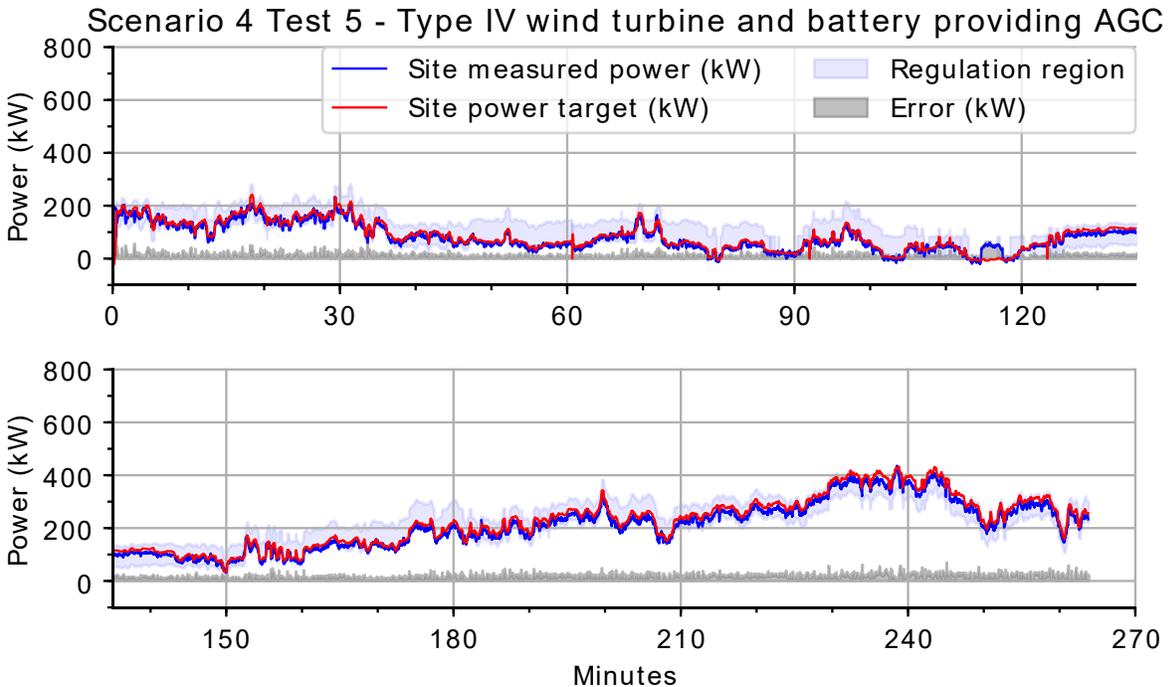


Figure 13: Providing AGC with a Type IV wind turbine and battery storage, below rated wind speed

Note from Table 6 that the performance scores reported with the wind turbine operating alone are an improvement over the scores reported in Scenario 2 and 3 both above and below rated wind speed. This is primarily due to the fact that an IEC Type 4 wind turbine is used in Scenario 4 which reduces error and therefore improves the performance score. Part of the reason for reduced error is that a Type 4 wind turbine uses power electronics for active power control, a system that is capable of faster and more precise control as opposed to the mechanical systems used in Type 1, Type 2 and Type 5 wind turbine designs. Note also that the results of Test 2 were affected by a scaling error. A repeat of this test with similar conditions and identical test parameters was not possible hence Test 2a is offered a representative alternative. Several factors combine to improve the performance score here including the corrected turbine scaling factors and the increased regulation offer (200 kW versus 80 kW).

Calculations for the financial analysis were done in a manner similar to that of Scenario 3. One year of power production data from the turbine site was used along with one year of historical price data from the PJM electricity market. This was combined with the PJM performance scores calculated above.

When providing AGC from the wind turbine alone (Test 2, Test 3), financial calculations show that a modest 2.7% additional income is possible. This is the increase in income when the wind turbine participates in the regulation and energy markets versus participating in the energy market alone. This points to the fact that with existing market structures, even a single wind turbine can provide secondary regulation in a profitable manner. This is despite the opportunity cost of power curtailment.

In Test 1, a battery was used to provide 200 kW of regulation. Using PJM pricing and assuming a capital cost of USD 800,000, the battery is unable to make an annual profit with a gross income of \$41,000 and an annual amortisation cost of \$66,300. From this simplified analysis an annual profit is expected if all 400 kW were offered for regulation.

## Future work

When providing AGC from the battery along with the wind turbine (Test 5), note that the wind turbine is not curtailed. All the required AGC comes from the battery. Financial calculations show that over one year, this method has the potential to generate an additional 23% of gross income over providing energy from the turbine alone. The increase is mainly due to the increase in performance score when using the battery. Note, however, that the profit / loss equation here is heavily influenced by the installation cost of the battery system and its expected lifetime. With our assumptions, the increase in income is not sufficient to offset the annual amortisation value of the battery. Other factors such as battery downtime, required maintenance cycles, battery conversion inefficiencies and control errors limit potential profit but are not examined in detail in this project. Longer-term studies are required to quantify lifetime profit, particularly with battery systems, particularly as battery capacity degrades with time.

## 12 Future work

The PERD project examined two broad scenarios. The first was displacing diesel generation using battery storage. Future work might include tests with different battery technologies with varied operational requirements. More study into the sizing of such a battery system is also required.

The second group of scenarios involve providing secondary frequency regulation from wind turbines. Future work here might involve tests with larger wind farms (as opposed to single turbines) and tests with different wind turbine technologies. Additional work is required to assess the economic aspects of providing ancillary services from wind turbines from the point of view of the system operator. Also, when providing AGC from wind generators / farms, more work is required to determine optimal allocations of regulation bids.

## 13 Peer-reviewed publications

The following is a list of peer-reviewed publications that use data and results from this work. Some publications are freely available on the internet. Please contact the authors of this document for copies of any of the papers listed below.

1. David Watson, Marianne Rodgers '*Utility-Scale Storage Providing Peak Power to Displace On-Island Diesel Generation*' in *Journal of Energy Storage*, 2019
2. Ehsan Nasrolahpour, Carrie Houston, Scott Harper, Marianne Rodgers, Hamidreza Zareipour, William D. Rosehart, '*Bidding Strategy in Energy and Regulation Markets for A Wind Power Plant*' in IREP'2017 symposium, Espinho, Portugal, 2017
3. Eldrich Rebello, David Watson, Marianne Rodgers '*Developing, implementing and testing up and down regulation to provide AGC from a 10 MW wind farm during varying wind conditions*' In *Journal of Physics: Conference Series*, vol. 1102, no. 1, p. 012032. IOP Publishing, 2018
4. Eldrich Rebello, David Watson, Marianne Rodgers '*Performance analysis of a 10 MW wind farm in providing secondary frequency regulation: Experimental aspects*' in *IEEE Transactions on Power Systems*, 2019  
*Publications from Scenario 4 are being prepared at the time of writing of this report. Future revisions to this report will include published work from Scenario 4's results.*

## 14 Presentations

The following is a list of presentation that include work from this project. Copies of presentations can be obtained from the authors of this report.

### **Oral presentations**

1. S. Harper, D. Watson, Wind R&D Park, Standing Committee on Infrastructure and Energy, Charlottetown, PE, February 2016 (Invited)
2. S. Harper, Collaboration Opportunities Between a Utility and a Wind R&D Park, Maritime Electric, Charlottetown, PE, November 2017
3. S. Harper, Operational Strategies for a Wind Park, CanWEA, Montreal, PQ, October 2017
4. E. Nasrolahpour, C. Houston, S. Harper, M. Rodgers, H. Zareipour, W. Rosehart, Bidding Strategy in Energy and Regulation Markets for a Wind Power Plant, IREP Symposium, Espinho, Portugal, August 2017
5. S. Harper, Operational Strategies for a Wind Park, CanWEA, Calgary, AB, November 2016
6. E Rebello, Marianne Rodgers, University of Calgary, October 2018
7. E Rebello, 'Developing, implementing and testing up and down regulation to provide AGC from a 10 MW wind farm during varying wind conditions' Wind Europe, September 2018
8. E Rebello, 'Practical Results – Providing secondary frequency regulation from a wind plus battery storage system' CanWEA Annual Conference & Exhibition, Calgary, 2018
9. S Harper, E Rebello, 'Wind power frequency regulation' Maritime Electric, Charlottetown, November 2017
10. E Rebello 'Practical results: Providing Secondary Frequency Regulation from Wind Turbines and Battery Storage', Engineers PEI Lunch & Learn, February 2019

### **Poster Presentations**

11. M.P. Rodgers, S. Harper, Wind Energy Institute of Canada Energy Storage Use Cases (Presented by B. Schenkman, Sandia National Laboratory), Department of Energy Office of Electricity Annual Peer Review, Washington, DC, USA. September 2016
12. D. Watson, M. Rodgers, Displacing Diesel Peaker Usage with a 1 MW/2 MWh Storage System, Energy Storage Association, Charlotte, NC, April 2016

## 15 References

- [1] Government of Prince Edward Island, "PEI Wind Energy," [Online]. Available: <https://www.princeedwardisland.ca/en/feature/pei-wind-energy/>. [Accessed 07 Feb 2018].
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- [5] K. Kabiri and D. Song, "Regulating reserve performance assessment for the Alberta electric system operator," Natural Reserach Council Canada, Ottawa, 2016.
- [6] C. Piong, "PJM Manual 12: Balancing Operations Revision: 37," 16 November 2017. [Online]. Available: <http://www.pjm.com/~media/documents/manuals/m12.ashx>. [Accessed April 2018].
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- [8] PJM Interconnection LLC, "PJM Data Miner 2," [Online]. Available: <http://www.pjm.com/markets-and-operations/etools/data-miner.aspx>. [Accessed 10 Apr 2018].
- [9] R. Jansen, M. Sulatisky, A. Farber and a. D. Muyres., "Demonstration of a utility-scale lithium-ion battery system with a wind turbine," Electrical Energy Storage Applications and Technologies Conference, 2013.
- [10] Lazard, "Lazard's levelised cost of energy analysis, Version 12.0," 2018.