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Smart Renewables and Electrification Systems (SRES)

Comprehensive Literature Review on Wind Energy Development, Applications and Challenges

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List of Abbreviations

Abbreviation	Definition
AGC	Automatic generation control
APC	Active power control
AVR	Automatic voltage regulator
CanREA	Canadian Renewable Energy Association
CanWEA	Canadian Wind Energy Association
CAPEX	Capital expenditure
CER	Canada Energy Regulator
CSA	Canadian Standards Association
DAWT	Diffuser augmented wind turbine
DFIG	Doubly-fed induction generator
DOE	Department of Energy
ESS	Energy storage systems
FRT	Fault ride-through
GFL	Grid following
GFM	Grid forming
GHG	Greenhouse gas
HAWT	Horizontal axis wind turbines
IEC	International Electrotechnical Commission
INL	Idaho National Laboratory
LCA	Life cycle analysis
LCC	Life cycle cost
LCOE	Levelized cost of electricity
LVRT	Low voltage ride-through
MIRACL	Microgrids, infrastructure resilience, and advanced controls launchpad
MRS	Multi-rotor system
NREL	National Renewable Energy Laboratory
O&M	Operation and maintenance
OPEX	Operational expenditure
PCC	Point of common coupling
PNNL	Pacific Northwest National Laboratory
PPAs	Power purchase agreements
PLL	Phase-locked loop
REMPD	Renewable energy materials properties database
SAM	System advisor model
SCADA	Supervisory control and data acquisition
SCR	Short circuit ratio
SDR	Series dynamic resistor
SPIFT	Single point impact fatigue testing
STATCOM	Static synchronous compensator
TRL	Technology readiness level
VAWT	Vertical axis wind turbines
WETO	Wind Energy Technology Office
WOMBAT	Windfarm operations and maintenance cost-benefit analysis tool

1. Introduction

Canada has committed to achieving net-zero emissions by 2050, as per the Canadian Net-Zero Emissions Accountability Act that was passed in 2021. Broadly, modelers are projecting that increased electrification and the transition to a clean electricity grid will contribute significantly to reaching these goals. Consequently, in preparation for the forthcoming transformation, the electricity sector must evaluate which technologies will support progress into the future. Renewable energy-based generation will undoubtedly be important. In particular, wind has emerged as an efficient, non-polluting and inexhaustible source of energy. After hydropower, wind turbine generators are the largest renewable energy-based sources of electricity in Canada [1], and the capacity for wind power continues to grow [2]. Nonetheless, an increased reliance on wind energy for electricity poses several challenges. Namely, the variability of wind speeds and the asynchronous connection of wind turbine generators will have important implications on the stability and reliability of the electrical grid.

Given the anticipated role of wind energy as an important source of net-zero electricity in Canada, this report seeks to elucidate the challenges associated with the grid integration of wind turbine generators. It examines factors affecting: (1) technological readiness; (2) adoption and integration; (3) environmental considerations, and; (4) grid services. The presented review details the current status of each of the aforementioned topics and highlights the remaining barriers to integration in order to ensure the delivery of stable and secure electricity in Canada's clean energy future.

2. Technological Readiness

2.1. Industry Trends and Research

Since the 2000s, wind turbines have grown in size (both in height and blade length) to generate more electricity per turbine, thereby reducing the cost of energy. Currently, land-based turbines can be as tall as 98 m (322 ft) and offshore wind turbines are projected to reach a hub height of 150 m (500 ft) by 2035 [3]. To sweep larger areas, thereby harnessing more wind for increased electricity generation, the blade length/rotor diameter is also increasing in size. The average rotor diameter of newly installed land-based turbines is 130 m (430 ft). **Figure 1** gives the historical trends in turbine capacity, hub height and rotor diameter [3].

There are two principal wind turbine technologies that have been designed for land or offshore use: (1) horizontal axis wind turbines (HAWT), and (2) vertical axis wind turbines (VAWT). The most commonly deployed wind technology is the HAWT. Typical ratings of land-based HAWTs range from 500 kW to 5 MW with an average installed capacity of 3.2 MW [3], [4]. Offshore HAWT capacities are even larger; a record capacity of 16 MW was achieved in China as of June 2023 [5], [6].

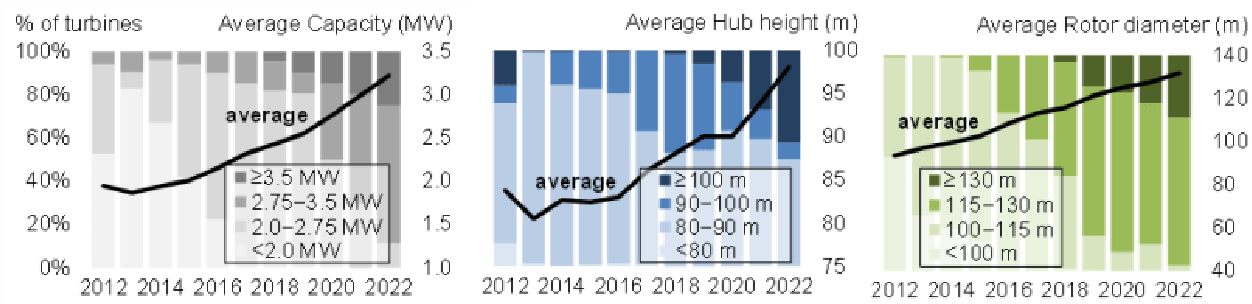


Figure 1. Land-based wind turbine trends for capacity, hub height and rotor diameter [3].

Within the offshore HAWT technology, different foundation/floating designs exist, including monopile foundations, tripod foundations, tension-leg floating platforms, semi-submersible floating platforms, spar buoy floating platforms, etc. Fixed-foundation offshore wind turbines are available commercially, while the technology readiness level (TRL) of their floating counterparts ranges from 4-9 with spar-buoy and semi-submersible concepts having a TRL of 8-9 [7]. Conversely, floating VAWTs have a lower TRL as they have yet to be tested at large scales [5]. Beyond these concepts, research is ongoing on other designs such as floating hybrid energy platforms (TRL 1-5), wind turbines with tip rotors (TRL 1-2), multi-rotor system (MRS) wind turbines (TRL 2-6), diffuser augmented wind turbines (DAWTs) (TRL 5-6), magnetic levitation wind turbines, and cross axis wind turbines [5].

Current research and development is also looking to improve wind forecasting for utilities and customers, having the potential to save millions of dollars [8]. From an international workshop on the "Grand Vision for Wind Energy," three main challenges in wind energy research were identified and summarized as follows [9]:

1) *"Improved understanding of the physics of atmospheric flow in the critical zone of wind power plant operation;*
2) *More research on materials, aerodynamics, structural dynamics, and offshore wind hydrodynamics of large wind turbines;*
3) *Optimization and control of fleets of wind plants working synergistically within the larger electric grid system"*

Furthermore, there has been a need to improve the robustness of turbines to be able to ride through faults on the transmission system. This improvement will allow wind turbines to act similarly to conventional generators by providing more flexibility with respect to their shutdown modes for grid events [4]. The U.S. Department of Energy's (DOE's) Wind Energy Technologies Office (WETO) has been a global leader in wind energy research for land-based, offshore, and distributed wind to enable low-cost wind energy, and address market barriers and system integration [10].

2.2. Lifecycle Cost and Life Expectancy

The lifecycle cost (LCC) of a wind farm is the sum of the costs for development (C_{Dev}), the wind turbine (C_{WT}), the electrical apparatus (C_{Elec}), civil work and installation (C_{Civil}), and operation & maintenance ($C_{O\&M}$), as described in Equation (1) [11].

$$LCC = C_{Dev} + C_{WT} + C_{Elec} + C_{Civil} + C_{O\&M} \quad (1)$$

The development costs can include costs related to land, legal permits, financing, geotechnical studies and topographical studies [11]. The cost for the wind turbine includes the costs to procure and deliver the tower, blades, nacelle, generator, hub and gearbox [11]. The costs related to mounting and civil work include the costs for the foundation, access roads, laying/connecting electrical cables, etc. [11]. Furthermore, the electrical apparatus costs consist of the costs for the transformer, earthing protections, Supervisory Control and Data Acquisition (SCADA) systems, static synchronous compensator (STATCOM), etc. [11]. Lastly, the operation and maintenance costs are any annual costs used to keep the wind farm running during its lifespan.

For simplicity, Equation 1 is often reduced to [12]:

$$LCC = CAPEX + LCR + OPEX \tag{2}$$

where,

- $CAPEX$ is the capital expenditure;
- LCR is the lifecycle replacement cost (e.g., recycling), and;
- $OPEX$ is the operational expenditure.

While the lifecycle replacement cost is challenging to obtain because more research is needed to better assess the options for end-of-life, the CAPEX and OPEX can be obtained from the National Renewable Energy Laboratory (NREL) site for offshore and land-based wind turbines [13],[14] respectively.

The life expectancy of wind turbines has increased from 20 years in the early 2000s, to 25 years in the mid 2010s and to 30 years today [15]. According to project developers, sponsors and long term owners, the average life expectancy of a wind turbine is 29.6 years, but it can range from 25 to 40 years [15]. In Canada, most power purchase agreements (PPAs) are 20 to 25 years in length, and while the average life span of wind turbines is 29.6 years, few wind farms have been decommissioned or repowered to date. Nonetheless, this will become increasingly more common in the next five to ten years.

2.3. Levelized Cost of Electricity

The levelized cost of electricity (LCOE) for wind energy quantifies the production cost per kilowatt hour. As shown in Equation 3, the LCOE is the ratio of the total cost of a wind system to the total energy yield over its lifetime.

$$LCOE = \frac{Total\ lifetime\ cost\ [\$]}{Total\ lifetime\ energy\ output\ [kWh]} \tag{3}$$

The LCOE can be further expanded to:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{4}$$

where,

- I_t is the investment in year 't' which includes initial capital investment minus subsidies;
- M_t is the operation and maintenance cost in year 't';
- F_t is the fuel cost in year 't' (which is zero for wind energy);
- E_t is the energy yield (kWh or MWh) in year t;
- r is the discount rate, and;
- t is the number of years of lifetime of the system.

The recycling or decommissioning costs of wind energy are not often included LCOE because wind turbine end-of-life management is a growing field of study and best practices are still not well-understood. The LCOE can also be described as the price at which the generated electricity should be sold in order for the system to break even at the end of its lifetime.

As shown in **Figure 2**, a report by Dunsky concluded that the LCOE of wind energy deployments are now competitive compared to natural gas plants [16].

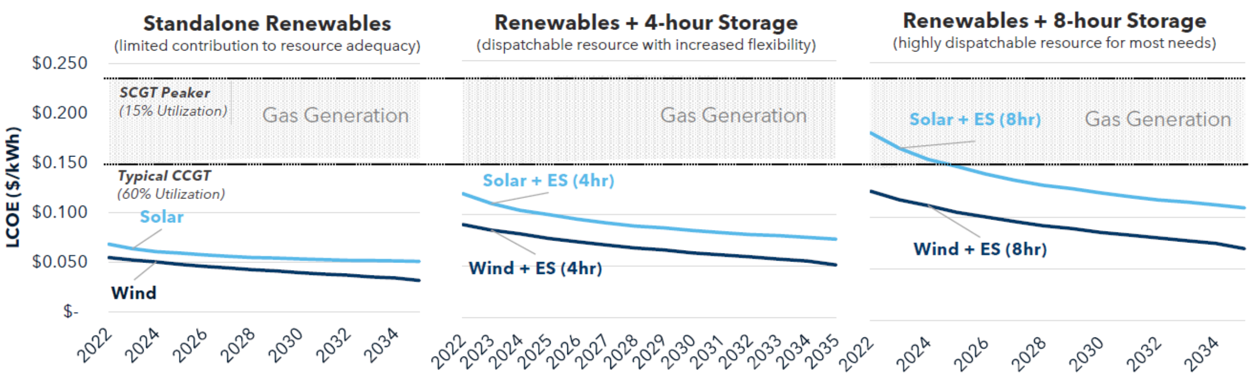


Figure 2. Comparison between PV, wind, and gas plant LCOE, including energy storage options for renewables. Costs shown are in Canadian dollars.

This comparative analysis was performed for the provinces of Ontario and Alberta, and it concluded that the cost of wind energy production is lower than that of natural gas when taking carbon pricing into account. Moreover, as shown in Dunsky's forecasts in **Figure 3** b), the cost of wind energy is expected to decrease into 2035. **Figure 3** a) also gives the CAPEX variation in Alberta and Ontario [16].

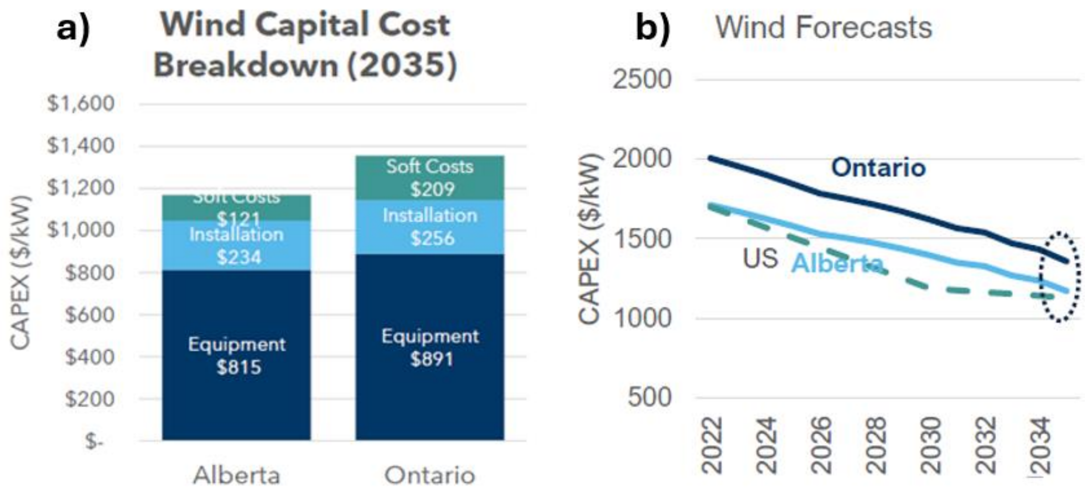


Figure 3. a) Wind capital cost breakdown in 2035. b) Wind CAPEX forecast for Alberta (blue) and Ontario (black). Costs shown are in Canadian dollars.

The difference in LCOE between regions is mostly due to varying resource potentials (e.g., wind speeds), other project level drivers such as interconnection costs, equipment costs, soft costs (e.g. equipment transportation, taxes, engineering, procurement, and construction), and installation costs (i.e., labor). **Table 1**, taken from NREL's wind energy review, further demonstrates how the LCOE changes for different wind technologies.

Table 1. Levelized cost of energy for different wind technologies in 2021 U.S. dollars (USD) [17].

		Land-Based	Offshore		Distributed		
Parameter	Unit	Utility-Scale Land-Based	Utility-Scale (Fixed-Bottom)	Utility-Scale (Floating)	Single-Turbine (Residential)	Single-Turbine (Commercial)	Single-Turbine (Large)
Wind turbine rating	MW	3	8	8	20 (kW)	100 (kW)	1.5
Capital expenditures (CapEx)	$/kW	1,501	3,871	5,577	5,675	4,300	3,540
Fixed charge rate (FCR) [real]	%	5.88	5.82	5.82	5.88	5.42	5.42
Operational expenditures (OpEx)	$/kW/yr	40	111	118	35	35	35
Net annual energy production	MWh/MW/yr	3,775	4,295	3,336	2,580	2,846	3,326
Levelized Cost of Energy (LCOE)	$/MWh	34	78	133	143	94	68

Table 1 shows that a distributed residential turbine has the highest LCOE (143 USD/MWh), followed closely by floating offshore wind (133 USD/MWh), while utility-scale land-based wind has the lowest

value (34 USD/MWh). The high LCOEs are mainly due to the low deployment rates of floating offshore wind and distributed wind. The cost dynamics of renewable energy are well described by experience curves, where costs decrease by a fixed percentage as capacity doubles [18]. Evidence of this is given by the reduction in the operation and maintenance costs (O&M) of onshore wind by 25% from 2005 to 2017 in Germany [18]. To further reduce costs, an algorithm has been proposed for generating optimal turbine maintenance schedules. The algorithm helps to prevent the costly failure of wind turbines that have reached the end of their manufacturing warranty by efficiently managing limited maintenance resources [19]. Overall, with better assembly processes, more efficient/innovative operational and maintenance procedures, and higher deployment rates, the LCOE for offshore and distributed wind is expected to decrease in the future.

Another LCOE analysis comparing different renewable energies with conventional generators further emphasizes that wind energy can be competitive with photovoltaic energy and conventional sources. As shown in **Figure 4**, onshore wind is one of the most cost-effective renewable energy options.

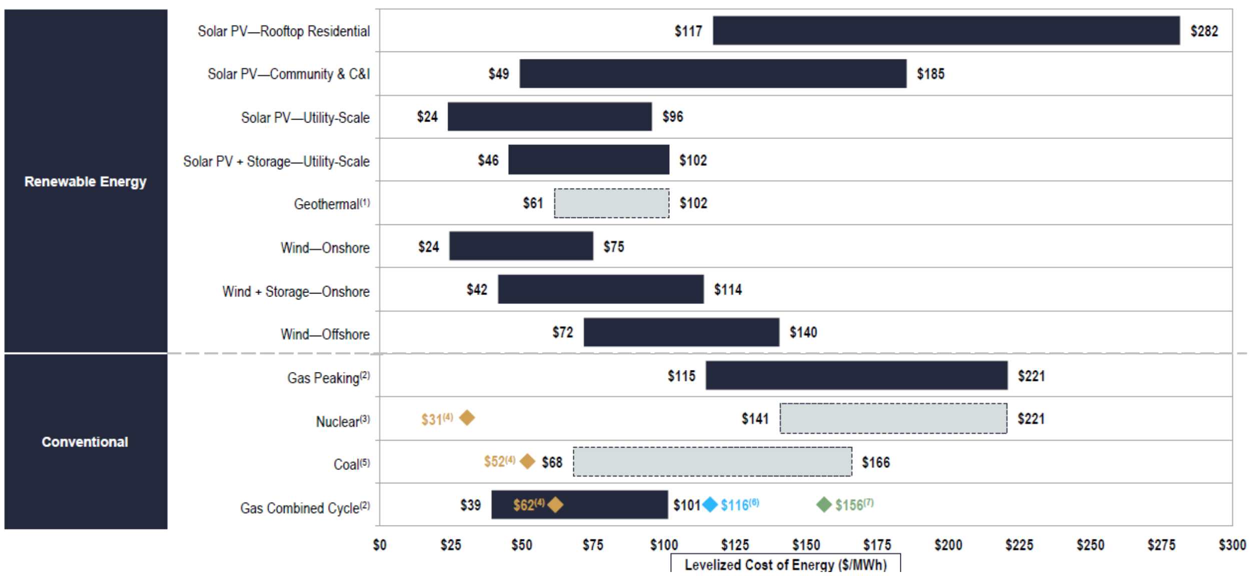


Figure 4. Levelized cost of energy comparison in USD [20].

Moreover, **Figure 5** gives the percentage breakdown of the LCOE for different wind technologies. **Figure 5** demonstrates that the largest expense for utility-scale land-based and distributed wind turbines is the turbine CAPEX. Conversely, for offshore wind turbines, the operational expenditures and the balance of system CAPEXs (i.e., development costs, assembly costs, etc.) are more significant. While these trends are common across many analyses and literature reviews, it is important to note that the exact breakdown and final LCOE values will vary according to region.

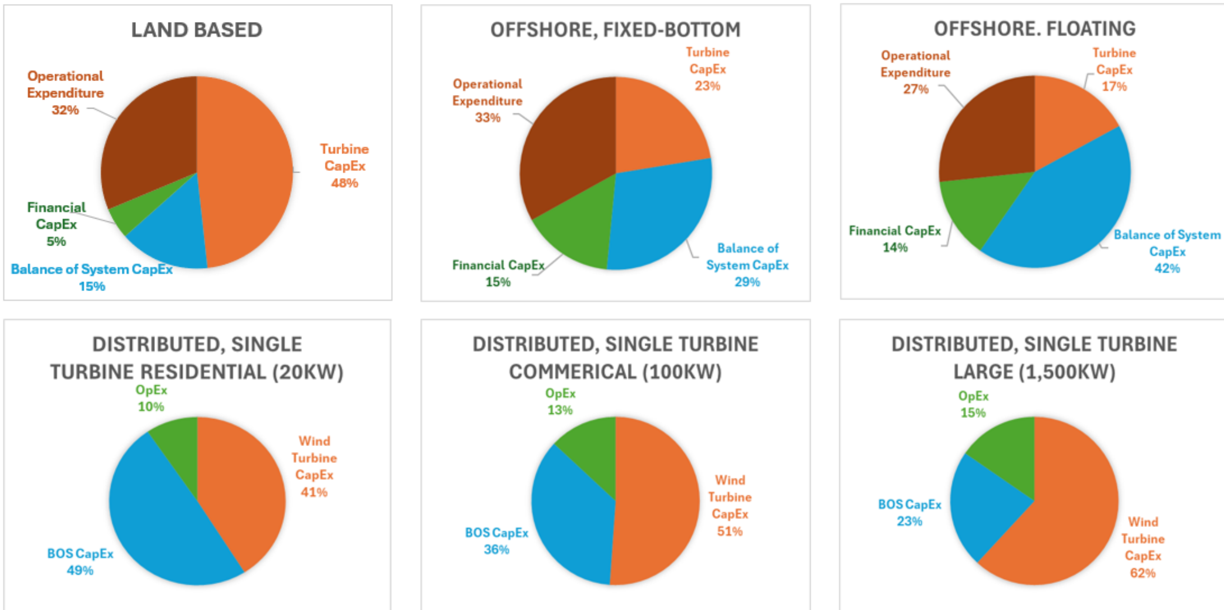


Figure 5. LCOE breakdown for land-based, offshore-fixed, offshore-floating and distributed wind.

2.4. Reliability

Energy reliability is the ability of a power system such as wind energy to withstand failures, uncontrolled events, or the unforeseen loss of system components while consistently delivering electricity at the same quantity and quality [21], [22]. The Canadian Standards Association (CSA) has a guide to Canadian wind turbine codes and standards that considers safety, design, installation practices, etc. More specifically, the CSA-F416-87 standard considers safety, design and operational criteria, while the CSA-F417-M91 standard considers wind turbine performance [23]. Both standards adopt the International Electrotechnical Commission (IEC) standards from IEC-61400, but are adjusted for deployment in Canada [23]. Additional wind turbine standards are given in Section 3.2.

There are several factors that can affect reliability in the short, medium or long term. For instance, changes in wind speeds can affect short term power output. Currently, commercial wind turbines are configured to maximize energy production within a window of variable wind speeds. When wind speeds exceed the rated turbine speed, the electrical output is capped at its maximum value; when wind speeds are lower than the rated turbine speed, the electrical output will fluctuate in response [4]. This dependency on wind speeds may create voltage variations on the grid and result in compromised reliability. Nonetheless, the magnitude of these fluctuations can be modulated by implementing pitch regulation schemes, improved blade aerodynamic designs, and wider operating speed ranges [4]. In particular, sophisticated pitch control (i.e., controlling the rotor speed by adjusting the angle of the turbine blades to the wind) can provide grid support by allowing turbines to participate in Automatic Generation Control (AGC), where the turbine operates at a level below its maximum capacity so that it can ramp up to provide increased power output and grid reliability (i.e., grid services) when required [4].

Vulnerabilities and causes of wind turbine failure are a well researched topic that typically affect reliability in the medium to long term. **Table 2** provides a summary of wind turbine vulnerabilities and how they impact or cause failures on the system.

Table 2. Vulnerabilities of wind turbines and corresponding impacts on the system.

Vulnerability	Impacts/Failures
Lightning	Commonly seen in monsoon areas, lightning can strike the blade tip which can cause separation of the skins near the tip or shear webs [24]. Lightning protection systems exist for conventional wind turbines and work by safely conducting energy from lightning strikes to the Earth [25].
Hail/Icing/Snow	Icing refers to any type of accumulation of ice or snow. In-cloud icing forms rime, while precipitation icing can form glaze, drizzle or wet snow [26]. Hail can erode the blades, compromising aerodynamic performance via the formation of cracks or by allowing water to penetrate the bond line (i.e., structural damage to the leading edge) [24]. Ice accretion on the blades caused by freezing rain can degrade the performance and durability of the turbine and cause safety concerns associated with ice shedding [27]. Icing can be reduced passively (blade design) or actively (blade heating) [27]. However, due to global warming, the impacts of icing have been reduced in recent years [28]. Other than production losses and reduced turbine lifespan due to increased vibration and fatigue loads, icing can lead to measurement and control errors, as well as mechanical and electrical failures [26].
Rain	Rain can cause surface damage, mostly to the leading edge of the blade. There are many approaches or techniques to test for erosion such as the rain erosion tester, the pulsating jet erosion test rig, or the single point impact fatigue testing (SPIFT) [24].
Sand	Sand can cause blade erosion, leading to similar impacts as hail.
Extremely low temperatures	Under extremely low temperatures, metals and other materials can weaken and equipment/tools can break or stop functioning. Oil or grease rated for low temperatures should be used to prevent it from thickening and negatively impacting generators, gearboxes, motors, etc. [26].
Humidity	High humidity can cause electrical faults, corrosion and bacteria growth. Many commercial systems exist for reducing humidity levels; most employ desiccants and rely on principles of adsorption [29].
Air Density	Air temperature is inversely proportional to air density; as temperature increases, density decreases. Importantly, air density is proportional to the energy density of the wind, such that decreased air density results in reduced power production [27].
Degradation of permafrost	Global warming is degrading the permafrost. This will have profound impacts on the design/construction of wind turbine foundations and service roads [28].
Sea ice	Drifting sea ice is an issue for offshore wind turbines due to the load impacts it can have on the turbine foundation [27], [30].

Flooding	Wind turbines in coastal locations will be impacted by rising sea levels or flooding which will increase the load that the turbine foundation has to support and may cause erosion [27].
Manufacturing defects	Despite stringent quality control measures, manufacturing defects are always possible. In India, where the wind industry is not yet mature, manufacturing defects and operational errors are among the leading causes of turbine failure [24].

While the mechanisms of failure outlined in **Table 2** can occur at any time, depending on the age of the turbine, some are more likely to occur than others. **Figure 6** gives the results of a survey that investigated wind turbine blade failure modes as a function of turbine age and location (India or Europe) [31]. In Europe, where the wind industry is mature, blade failure within the first five years of operation is infrequent and dominated by surface damage (caused by erosion or the impact of small objects). Contrastingly, newer wind energy markets, like India, experience greater rates of premature failure, where manufacturing and operation-related defects are significant contributors.

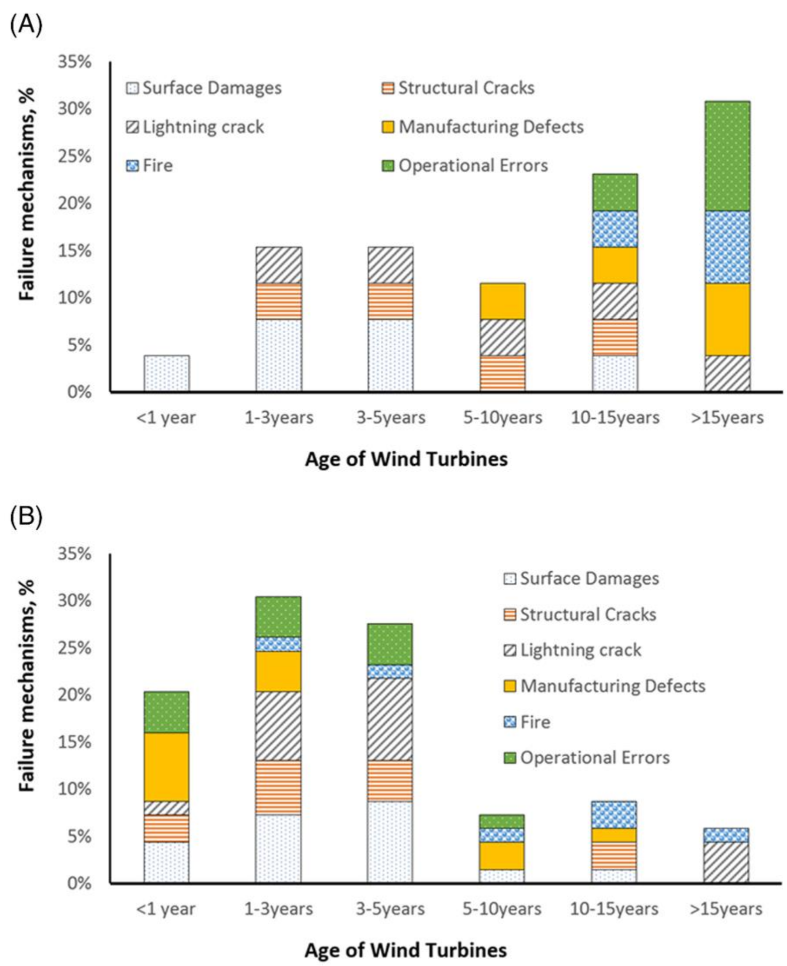


Figure 6. Frequency of wind turbine blade failure mechanisms as a function of the age of wind turbines in (A) Europe and B) India [31].

In this study, 86.5% of survey responses corresponded to onshore wind turbines, while the remaining 13.5% corresponded to offshore turbines [31]. Due to their prevalence, most studies focus on land-based/onshore wind turbine analyses. It should therefore be noted that the frequency and mechanism of offshore turbine failure will differ due to a difference in operating environments and turbine construction. This difference is further illustrated in **Figure 7**, which demonstrates that offshore wind farms have higher annual failure rates of the gearbox, generator, tower, transformer, power converter, rotor blades, etc. compared to land-based/onshore wind turbines [32].

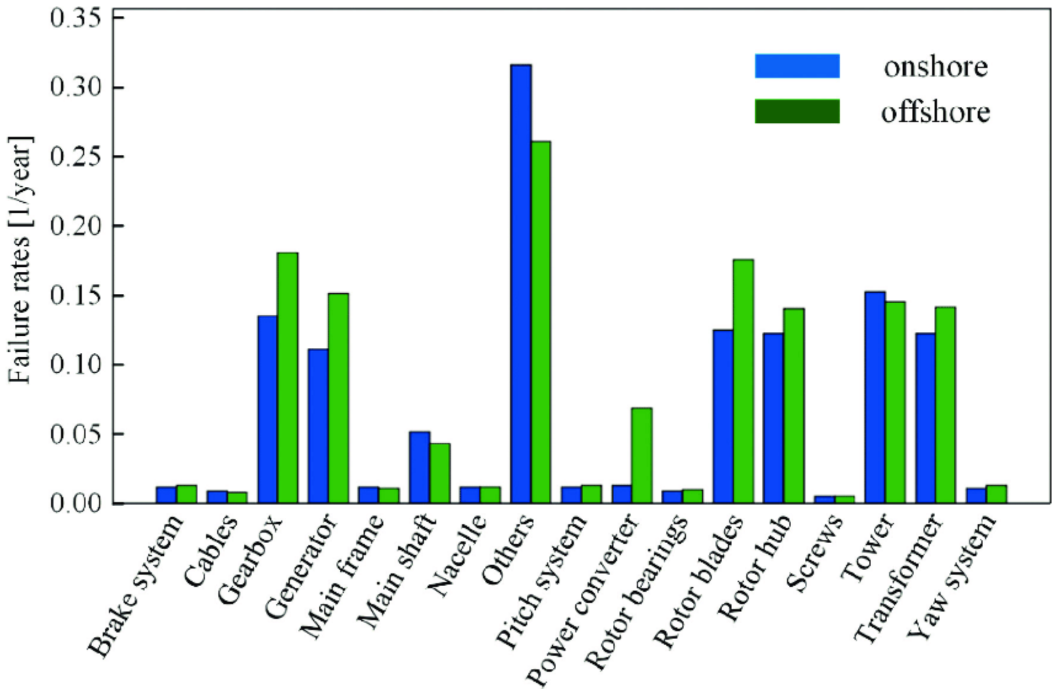


Figure 7. Subassembly failure rates of onshore and offshore wind turbines [32].

The decline of a wind turbine's energy output over time for a given wind speed is referred to as its rate of degradation. Various studies have sought to quantify turbine degradation rates that can be used for benchmarking [33], [34], [35]. One such study analyzed data collected from 282 wind farms in the United Kingdom and concluded that the load factor declines by 1.6 ± 0.2% per year, corresponding to a 12% reduction in energy output over a turbine's twenty year lifespan [34]. A similar study conducted in Sweden looked at 2640 turbines constructed before 2007 and reported a lifetime energy loss of 6% [35]. Finally, a smaller-scale study considered a single 850 kW Vestas turbine operating in Ireland from 2008 to 2019; it found that the turbine's performance degraded by 5% over 13 years, which, upon extrapolation, is in very good agreement with the results published for the United Kingdom wind farm analysis [33]. Even so, it is expected that many factors will influence turbine degradation rates, including location and year of manufacturing, resulting in a range of acceptable values. It is also important to note that the cited studies [33], [34], [35] only considered land-based wind turbines; the different environmental conditions and wind speeds to which offshore turbines are exposed will certainly impact their degradation rates [36].

Moreover, the question remains as to whether degradation is linear, quadratic or logarithmic with age [33], [34]. Additionally, while wind turbine vulnerabilities and failure mechanisms are generally wellknown (see **Table 2**), there is a gap in the literature correlating these failures with the degradation rate. The following were given as potential causes for the observed decrease in performance over time, but not furthered analyzed:

- Fouling of the blades [34];
- Reduction of component efficiencies such as the gearbox (contributed to ~30% of observed degradation [33]), bearings and generator [34];
- Turbine availability and lost time for maintenance/repairs (i.e., older turbines fail more frequently and take longer to repair) [34], and;
- Early turbine death (i.e., one turbine failing in the farm impacts the overall wind farm performance) [34]

More research is required to determine which components are most susceptible to degradation and their level of impact on overall performance. This information will help make better deployment decisions: for example, if direct-drive gearless wind turbines experience slower rates of degradation than their gear-based counterparts, it may be more efficient to deploy them preferentially [33]. Similarly, wind farm data should be made more detailed (to include wind resource assessments) and accessible to facilitate a more widespread understanding of turbine degradation.

2.5. Supply Chain

The wind energy supply chain encompasses components such as the blades, tower, drivetrain – including the generator, gearbox and power electronics – and turbine assembly [37]. Better composite materials, manufacturing processes and automation have resulted in increased productivity and more wind turbine installations [37]. The supply chain in Canada is well established. At a national level, knowledge in project development and construction, operation and maintenance, and component and equipment manufacturing are readily available. However, differences between provinces and territories exist. For instance, jurisdictions considered to be early adopters of wind energy technologies, such as Ontario and Quebec, often benefit from local manufacturing facilities, supplier warehouses, training centers and service offices that have established themselves in regions where demand for turbine components and related equipment is high [38], [39]. Since it is difficult to break into a well-established market, provinces and territories that are lagging in adoption may have to rely on out-of-province services, incur larger procurement costs and forgo the associated benefits to their economies [38]. Nonetheless, late technological adoption can be advantageous in that costs have decreased over time due to global economies of scale and turbine technologies have already undergone several iterations of improvements [38]. For this reason, the Canadian Wind Energy Association (CanWEA) commissioned a report in 2017 analyzing the local wind energy supply chain in Alberta, a relatively late adopter of turbine technologies. [38]. **Table 3** summarizes the report’s findings and recommendations for improvement.

Main recommendations to improve wind energy supply chains in Alberta include developing more local expertise, improving project planning and upgrading the power systems. The study also notes a lack of equipment, component and materials manufacturers in Alberta, thereby rendering them reliant on importation. Marine Renewables Canada has recently released a call for proposals to conduct a similar supply chain assessment for the Atlantic provinces that would include on- and offshore wind considerations [40].

Table 3. Limitations and recommendations for improvements to Alberta's wind energy supply chain. Information summarized from [38].

Project development and construction	Operation and maintenance	Component and equipment manufacturing
• Develop more expertise on site development/ construction and tower erection. • Improve plans for project roll-outs to prevent labour and equipment resources overlap, and conflicts with the oil and gas industry. • Upgrade sub-stations, transmission lines and cabling. • Improve transportation and route planning for large turbine components and equipment.	• Develop specialized expertise in maintenance of turbine components. This can be improved by providing more wind turbine maintenance training in post-secondary institutions.	• Lack of expertise and capacity for manufacture components such as nacelles, machine heads, hubs, electronic components, gearboxes and generators. The majority of equipment and components are imported from other provinces and countries. • Limited fibreglass or carbon fibre material manufacturing in Alberta.

Wind turbine manufacturing largely occurs outside of Canada. The Canadian Wind Turbine Database indicates that the three manufacturers with the most wind turbines deployed in Canada are Enercon, Siemens and Vestas [41]. **Table 11** in Appendix A lists the manufacturers who have turbines deployed in Canada and provides their corresponding models numbers and province/territory of installation.

Enercon is a wind turbine manufacturer based in Aurich, Germany. It manufactures its hubs and nacelles in Germany, generators in Germany, Poland and Portugal, and rotor blades in Portugal and Turkey [42]. Enercon collaborates with partners in China and India for the manufacturing of its rotor blades and generators [42]. Vestas is a Danish manufacturer and installer of wind turbines. It is the largest worldwide manufacturer of wind turbines and manufactures blades, nacelles and generators in countries including Denmark, Germany, Italy, Spain, the United Kingdom, Turkey, China, India, the United States, Brazil and Mexico [43]. Lastly, Siemens Gamesa, based in Spain, is the second largest wind turbine manufacturer. It has factories in China, India, Taiwan, Denmark, Germany, Spain, Turkey, the United Kingdom, the United States and Brazil [44]. Recently, problems with rotor blades and faulty gears on Siemens Gamesa's newer wind turbines has caused reliability issues and economic problems which may result in completely closing or pausing factory production at some locations [45].

The manufacturing of wind turbine components is mainly performed by foreign companies. While the supply chain in Canada is well-established, unforeseen global and local events can still impact turbine supply chains and raw material prices; to this day, COVID-19 continues to impact many of Vestas' projects [46].

Another important factor to consider in the analysis of wind turbine supply chains are the logistics of transporting the equipment to the installation site and performing operation and maintenance. The logistics surrounding onshore wind turbine deployment are somewhat simpler than their offshore counterparts. However, this does not minimize the importance of planning transportation routes for onshore wind turbines, especially for remote projects. Logistical expertise is needed to ensure that the components arrive onsite in a timely, reliable, and cost-effective manner. The size and weight of the components play a large role in selecting the optimal route and mode of transportation; delays based on the route chosen can negatively impact the project timeline [47]. Transportation logistics companies commonly employed in Canada are Mammoet, Transport Watson, NCSG and Equipment Express [48]. Additional companies can be found in Canada's Wind Energy Industry Directory [48].

For offshore wind, more logistical challenges exist regarding installation, power transmission and maintenance procedures due to the harsher environmental conditions. For instance, fixed foundations (which, as of 2021, were the most frequently deployed type of offshore turbine) require constant maintenance, resulting in O&M contributing significantly to the LCOE [49]. More research is needed to establish and optimize transportation and O&M logistics for offshore wind energy, especially in a Canadian context. To address this issue, NREL is currently looking into an Open-Source Framework for Operational Analysis of wind plants, and a Windfarm Operations and Maintenance cost-Benefit Analysis Tool (WOMBAT) [50].

2.6. Availability

The term availability reflects a wind turbine or farm's potential to generate electricity, and can be influenced by grid connectivity, wind conditions, the turbine's technical capabilities, etc. Distinguishing between various availability types is crucial for accurate performance evaluation [51].

System availability provides a comprehensive assessment of a wind farm's overall power generation capacity under suitable weather and grid conditions. It encompasses all downtime, regardless of the cause, offering a holistic view of the farm's performance [51]. This metric is valuable for assessing the farm's overall reliability and contribution to the power grid [51].

In contrast, turbine availability isolates the performance of the turbine, itself, and excludes downtime caused by external factors such as grid outages or balance-of-plant issues. This metric takes into account only the factors that directly impact the turbine's reliability, including maintenance, faults, weather events and cable issues [26]. By isolating these internal factors, turbine availability offers insights into the inherent performance and reliability of the turbine technology [51].

Another useful metric is the contractual availability, which is typically negotiated in turbine supply or service agreements and establishes a project's performance goals. The contractual availability must be monitored to ensure that contractual obligations are met [51]. Definitions of contractual availability are non-standardized and serve contract-specific purposes; they may exclude specific downtimes, such as periods of extended maintenance or grid curtailment. While important for project management and for satisfying contractual obligations, the project-specific nature of contractual availabilities prevents direct comparison of performance across projects or models [51].

To overcome limitations imposed by contractual considerations, the technical availability seeks to provide a standardized means of evaluating a turbine's performance (i.e., without unique exclusions). It considers the power generated within specified operating ranges and is calculated based on time in operation or energy production. This metric provides a more objective portrayal of the technology's inherent performance and allows for consistent comparisons across projects and models [51].

Availability is either calculated based on time or production data. Where time is used, the availability is the amount of time during which the turbine is operational divided by the total time in consideration. Similarly, the production-based availability is calculated by dividing the energy that is actually produced by the maximum amount of energy that could have been produced, given the wind conditions. The selection of the most appropriate availability metric hinges on the purpose of the assessment. [26]. Importantly, while time-based calculations are simpler, they treat all time losses equally, and fail to capture the increased energy losses for downtimes occurring during high-wind periods. Conversely, production-based calculations consider fluctuations in wind speed by weighting availability based on potential energy production, offering a more precise representation of actual energy losses [51].

2.7. Social Acceptability

A lack of social acceptability can hinder or inhibit wind energy deployment. As shown in **Figure 8**, when Canadians were asked to assign percentages to sources of electricity generation that they believed would be representative of Canada's generation mix in 2050, wind was ranked as the fourth largest contributor (12%) [52].

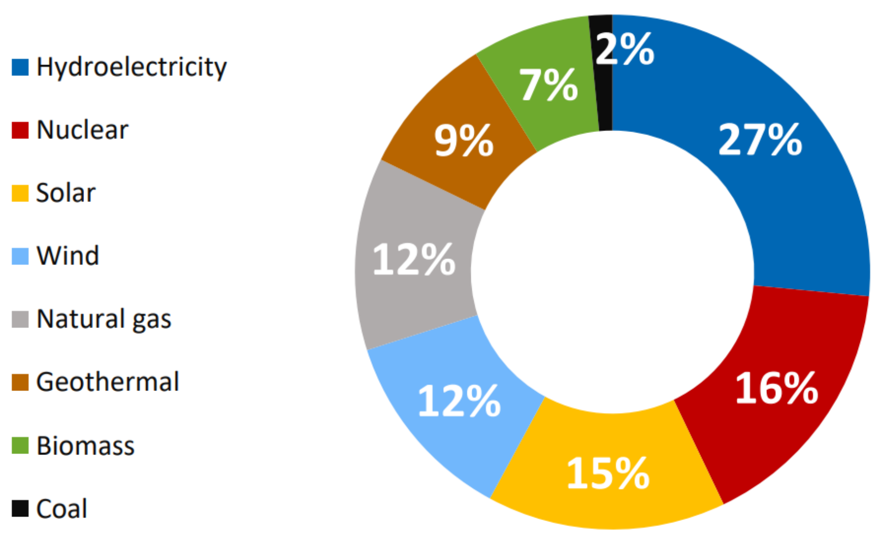


*Chart based on mean proportions
**Weighted to the true population proportion.
**Charts may not add up to 100 due to rounding.

Source: Nanos Research, RDD dual frame hybrid telephone and online random survey, July 30 to August 2, 2023, n=976, accurate 3.2 percentage points plus or minus, 19 times out of 20.

POSITIVE ENERGY NANOS

Figure 8. Sources of electricity generation in Canada in 2050, as predicted by Canadian survey respondents in 2023 [52].

On average, Canadians believe that hydroelectricity will be the most significant contributor to Canada's future electricity mix (27%), followed by nuclear (16%) and solar energy (15%). Forty percent of respondents stated that their assignment was made because they value clean energy and reducing environmental impacts. For others, long term reliability of energy production (24%) and diversified energy production (21%) were more important [52]. Other motivations included feasibility of resources, cost effectiveness, viability or they were unsure. In another survey, Canadians were asked to rank the types of electricity generation facilities they would be most comfortable having in their communities[52]. The results are given in **Figure 9**. Only 5% of respondents were most comfortable having wind turbines in their community. Nonetheless, wind is generally well-accepted, as 20%, 21% and 18% of people ranked it as their second, third and fourth most-comfortable options, respectively [52].

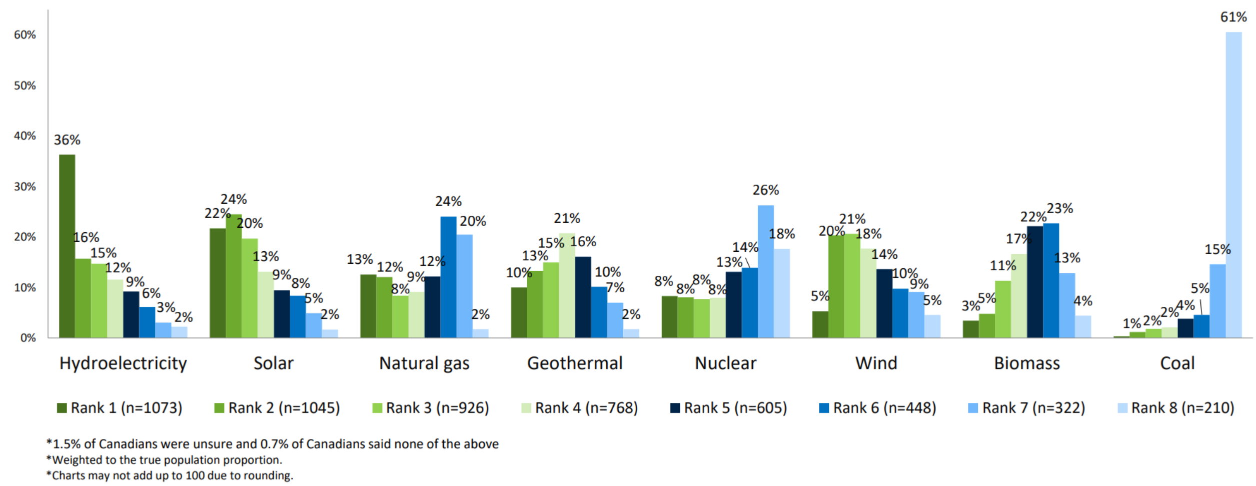


Figure 9. Canadians' comfort levels with the installation of electricity generation facilities in their communities, where 1 is the most comfortable and 8 is the least comfortable [52].

As a follow-up question, respondents were asked to explain the motivation behind their top ranking and **Table 4** provides their responses. Of those who claimed they would be most comfortable with wind installations in their community, the majority (56.7%) owed their response to environmental friendliness; only a small minority of people (1.7%) chose wind for its reliability [52].

Table 4. Canadians' motivations for ranking types of electricity generation facilities as most comfortable to have in their communities. Note that 'n = x' refers to the number of respondents who ranked that particular technology first [52].

TOP RESPONSES	Most comfortable with:									
	Total (n=955)	Hydroelectricity (n=360)	Wind (n=54)	Solar (n=216)	Geothermal (n=86)	Biomass (n=37)	Nuclear (n=65)	Coal (n=3)**	Natural gas (n=119)
It's clean/better for the environment/less intrusive/less impact on environment	38.8%	38.7%	56.7%	46.9%	47.3%	43.0%	35.7%		14.5%
It's accessible/available/already exists/it's tried and tested	25.7%	31.5%	23.9%	17.0%	16.8%	5.7%	25.7%		39.2%
It's safe/there are less risks	20.8%	16.0%	18.4%	28.9%	31.0%	12.8%	21.2%		19.5%
It's reliable	9.8%	11.5%	1.7%	2.5%	5.6%	5.8%	17.2%		21.9%
It's affordable/cost effective	8.8%	7.4%	6.0%	9.6%	8.1%	2.5%	15.9%		11.7%

Overall, Canadians tend to prefer solar energy over wind; they perceive wind to be noisier, more unreliable, to take up more space, and to be more harmful to wildlife such as birds and bats [53]. The IEA Wind TCP Task 28 on the Social Science of Wind Energy Acceptance is an ongoing international collaboration that seeks to better understand the social acceptability of wind energy. Beginning in 2018, they have contributed several salient publications on this topic [54]. For example, they have reported on sentiments of general annoyance in response to shadow flicker [55] and the obstruction of light from wind turbines [56] that contribute to negatively impacting the public perception of wind energy. These factors and the results from other studies of social acceptability must be considered in project planning and policymaking to further improve wind energy deployment.

3. Adoption and Grid Integration

3.1. Installation Potential

Canada's large geographical size and its strong wind resource both on- and offshore provide a high wind energy installation potential. **Figure 10** gives a map of the average wind speeds across Canada at a height of 100 m.

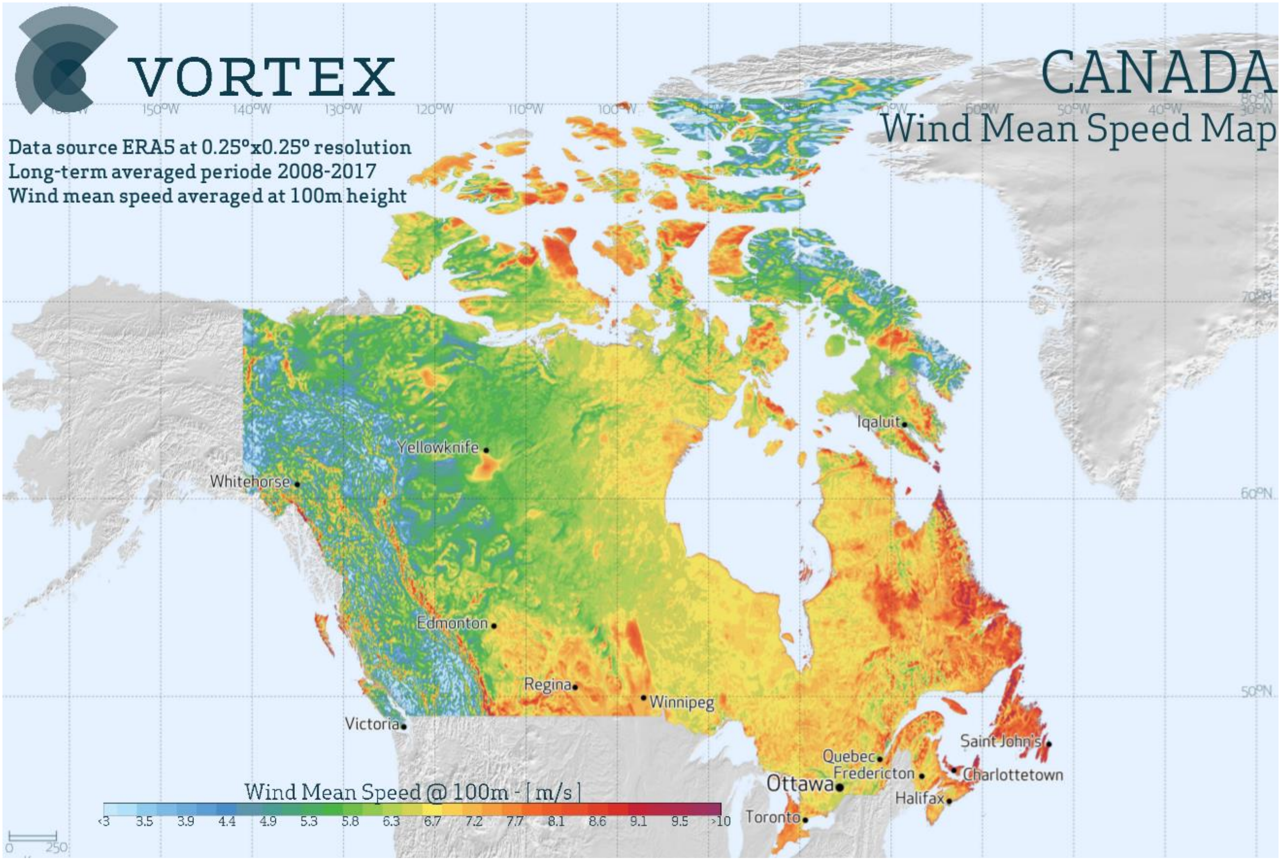


Figure 10. Canada's onshore wind resource map at 100 m height, modelled with a 3 km spatial resolution [57].

From the wind resource map, it can be discerned that southern Alberta, Saskatchewan and the maritime provinces are locations with some of the greatest wind power potential. Worldwide mean wind speed and wind power density potential maps are given in **Figure 11** and **Figure 12**, respectively.

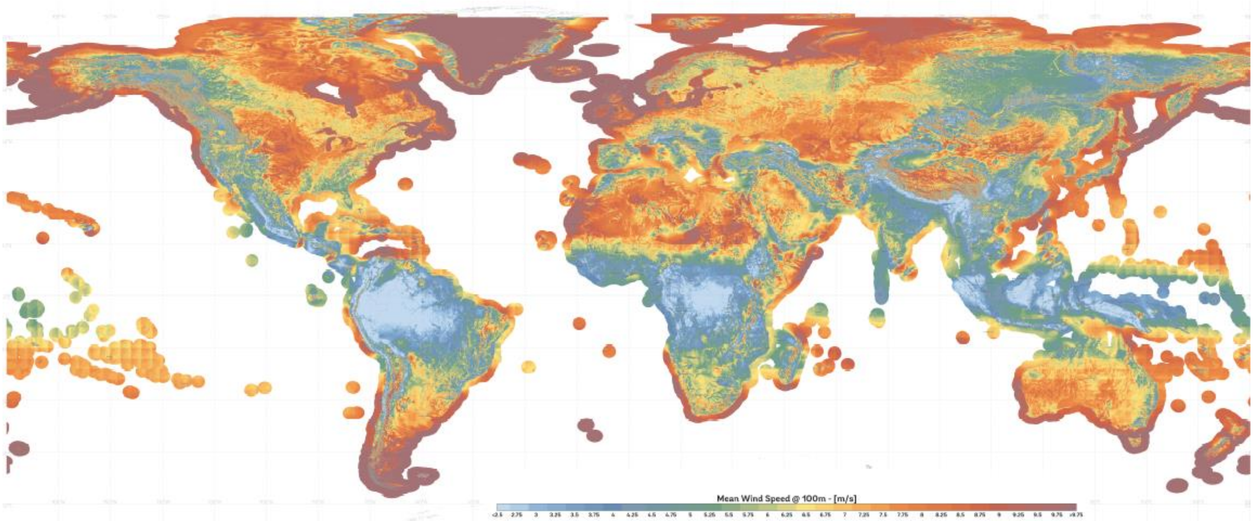


Figure 11. Map of worldwide mean wind speeds [58].

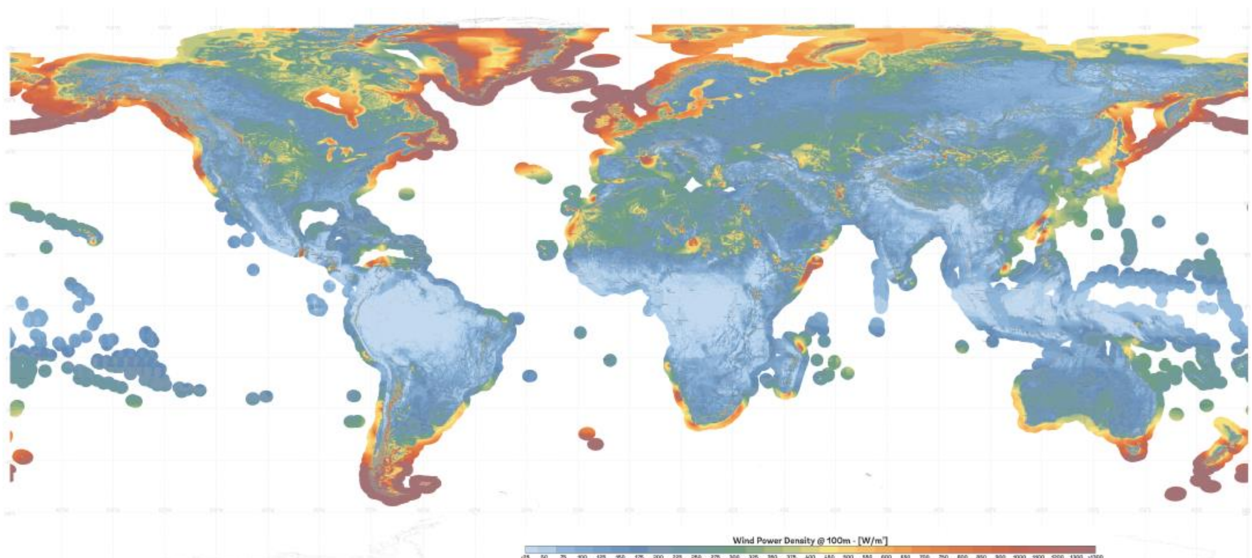


Figure 12. Map of worldwide wind power potential [58].

Figure 12 maps the wind power potential across the world; it considers the mean wind power density at 100 m above surface level and the power that can be extracted by wind turbines [58]. In terms of its wind power potential, Canada is favourably positioned on the global market. However, despite advantages in land and wind availability, barriers related to social acceptance and environmental restrictions (see Section **Error! Reference source not found.**) can limit deployment.

Other factors determining wind viability include proximity to loads, transmission lines and distribution lines. Distributed wind refers to small- and medium-sized turbines that are located near the load (i.e., homes, buildings, communities, etc.) or distribution lines. The U.S. Department of Energy is making concerted efforts through their Microgrids, Infrastructure Resilience, and Advanced

Controls Launchpad (MIRACL) project to better integrate distributed wind energy into distribution, islanded, hybrid and microgrid systems [59].

In general, variable energy sources are considered to have poor system resilience due to their intermittent nature. The lack of resilience comes from a potential incapacity to provide energy at any moment it may be required (e.g., in the face of physical threats, natural disasters or cyberattacks). However, the MIRACL project found that diversification offers resilience. They examined various case studies and found that by pairing distributed wind with other technologies like solar photovoltaics and/or energy storage, high levels of resiliency can be achieved [60], [61].

According to an assessment conducted by NREL in 2022, the United States have an estimated 1,400 GW of distributed wind installation potential [62]. However, less than 0.01% of that capacity has been deployed to-date [60]. High project costs coupled with a lack of knowledge/tools for accurately predicting performance are cited as barriers to adoption [63]. In other words, consumers and policymakers may be wary of distributed wind because they tend to have limited confidence in profitability, due, in part, to the inaccessibility of wind resource assessment data and a lack of validated wind energy and storage models at the distributed scale [63]. The MIRACL team is targeting this issue by developing a modeling tool that can demonstrate the value of distributed wind [59]. In fact, the (MIRACL) Data Hub was specifically created to provide a centralized, accessible and secure repository of wind energy and microgrid data from multiple locations [59]. This data hub gives researchers who request accounts access to live distributed wind data [59]. Similarly, future projects led by Idaho National Laboratory (INL), NREL and Pacific Northwest National Laboratory (PNNL) will include a study of rural load centers' energy and resilience needs with the goal of streamlining and encouraging adoption of distributed wind energy [59]. While progress and research in distributed wind deployment is evident in the United States, similar initiatives in Canada are lacking.

Wind farms are often located in areas with suitable wind resources, and not necessarily in proximity to load centers. Therefore, the availability of transmission infrastructure constitutes another important consideration for wind installation. Where the infrastructure is insufficient or nonexistent, an upgrade connection cost must be included in the project budget.

Installation potential is also influenced by policies as these play an important role in driving or hindering deployment. When policies apply regionally, it may lead to significant differences in deployment across provinces and territories.

Furthermore, technical experts are essential to improve technologies and processes that support wind deployment – particularly in the case of offshore wind. Therein, installation is more challenging and requires specialized techniques and equipment such as tugboats, crane barges and installation vessels.

3.2. Standardization Status

The IEC is one of the leading organizations that develops and publishes international standards on systems, products and services, including wind turbines. The CSA adopts IEC standards after making modifications to ensure they apply in a Canadian context. For the purpose of this review, only a partial list of wind turbine standards is discussed, with an emphasis on standards related to wind turbines providing grid services.

The main IEC standard for wind turbines is IEC-61400: "Wind Energy Generation Systems" [64]. It covers design requirements, performance measurements, structural testing of rotor blades, lightning protection, and measurements of mechanical loads and acoustic loads [65]. Part 21 (IEC-61400-21: "Measurement and assessment of electrical characteristics"), which was last updated in 2019, relates specifically to grid services [66]. It was updated from its 2008 version to include:

- frequency control measurements;
- updated reactive power control and capability measurements, including voltage and cosϕ control;
- inertia control response measurements;
- overvoltage ride through test procedures;
- updated undervoltage ride through test procedures based on wind turbine capability, and;
- new methods for the harmonic assessment.

Furthermore, when wind power plants are prequalified to provide ancillary services, Part 25 (IEC-61400-25: "Communications for monitoring and control of wind power plants") plays a key role in ensuring appropriate communication between the grid operator and the wind power plant. In particular, suitable connection availability, transmission speed and network latency are essential in providing grid services [67]. For this reason, some turbine manufacturers are implementing technologies that can send automatic and rapid (<1 millisecond) signals to the grid operator [67].

Lastly, Part 27 (IEC-61400-27: "Electrical simulation models") defines four generic model types for wind turbines that are available commercially. A description of each is provided in Section 5.

Other standards applicable to wind turbine systems include:

- IEC 60050-415: "International Electrotechnical Vocabulary - Wind turbine generator systems"
- IEC 60076-16: "Power transformers - Transformers for wind turbine applications"
- CSA C61400: "Wind energy generation systems" (i.e., the Canada-adapted version of IEC 61400)
- CSA C22.2 No. 272:20 "Wind turbine electrical systems"
- ISO 12494:2017: *"Atmospheric icing of structures"*
- ANSI/AGMA 6006-B20: *"Standard for Design and Specifications of Gearboxes for Wind Turbines"*

The implementation of these standards is critical to reduce failure rate and provide confidence in a wind farm's ability to operate successfully for the duration of its lifespan. The standards continue to be updated on an ongoing to reflect advancements in manufacturing, measurement methods and deployment.

3.3. Current Level of Adoption

In 2022, wind generated 6.6% of Canada's electricity [68]. The total cumulative wind energy capacity in Canada, as of December 31st, 2023, is 16,986.3 MW; the provincial/territorial breakdown is given in **Table 5**. The data in **Table 5** demonstrates that Ontario is the province with the highest cumulative wind energy capacity, followed by Alberta and Quebec. Their capacities represent 32.6%, 26.2%, and

24.0%, respectively, of Canada's total installed capacity in 2023. Deployment in the northern territories of Canada is extremely limited.

Table 5. Canada's installed cumulative wind capacity per province or territory in 2023 [69].

Province/Territory	Wind Capacity (MW)
British Columbia	742.7
Alberta	4,453.14
Saskatchewan	628.9
Manitoba	258.45
Ontario	5,535.5
Quebec	4,071.9
New Brunswick	397.4
Nova Scotia	623.4
Prince Edward Island	203.56
Newfoundland-and-Labrador	54.7
Yukon	4
Northwest Territories	12.64
Nunavut	0
Canada Total	**16,986.3**

While Canada currently has a decent level of wind energy penetration, it falls short of the capacity needed to meet net-zero goals by 2050. The Canadian Renewable Energy Association's (CanREA) "2050 Vision: Powering Canada's Journey to Net-Zero" report stated that the current installed capacity for wind, solar and energy storage is below the target capacity, as shown in **Figure 13** [69]. More specifically, CanREA's net-zero scenario calls for a wind energy capacity of 109 GW in 2050 [70], necessitating a 540% increase in capacity between now and then.

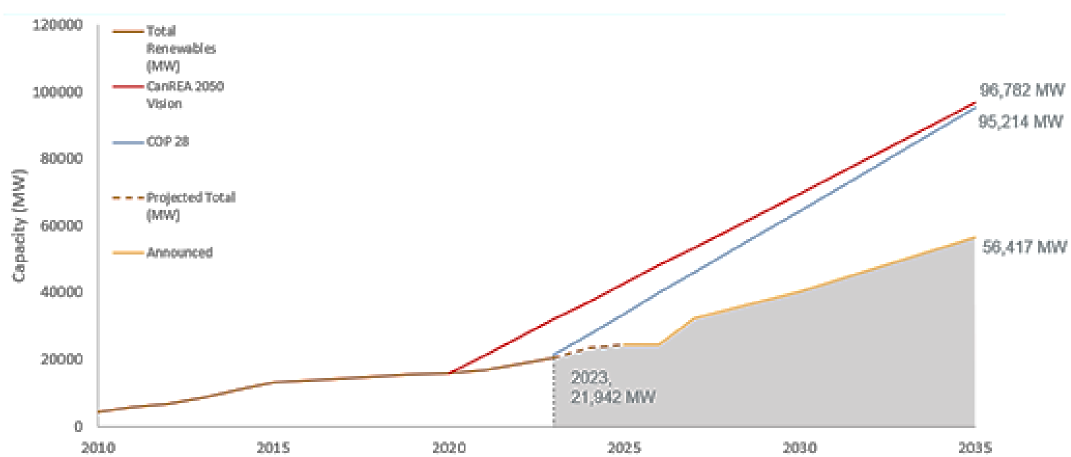


Figure 13. CanREA's projected and current (2023) installed capacity for wind, solar and energy storage [69].

The Government of Canada's Canada Energy Regulator (CER) agency, under the Natural Resources portfolio, has published similar results from their own modelling of Canada's energy future in **Figure 14** [71]. Firstly, it predicts a significant increase in electricity demand in 2050, particularly under net-zero greenhouse gas (GHG) emission constraints. Moreover, CER forecasts that hydro and onshore wind will be the largest sources of this generation in 2050. However, while current hydro levels are similar to their 2050 target values, considerable increases in wind installation are required to meet the future electricity demand. Interestingly, **Figure 14** also differentiates between onshore and offshore wind, depicting a more significant reliance on onshore wind, even under the current measures scenario. Nevertheless, offshore wind is expected to contribute to Canada's net-zero energy future.

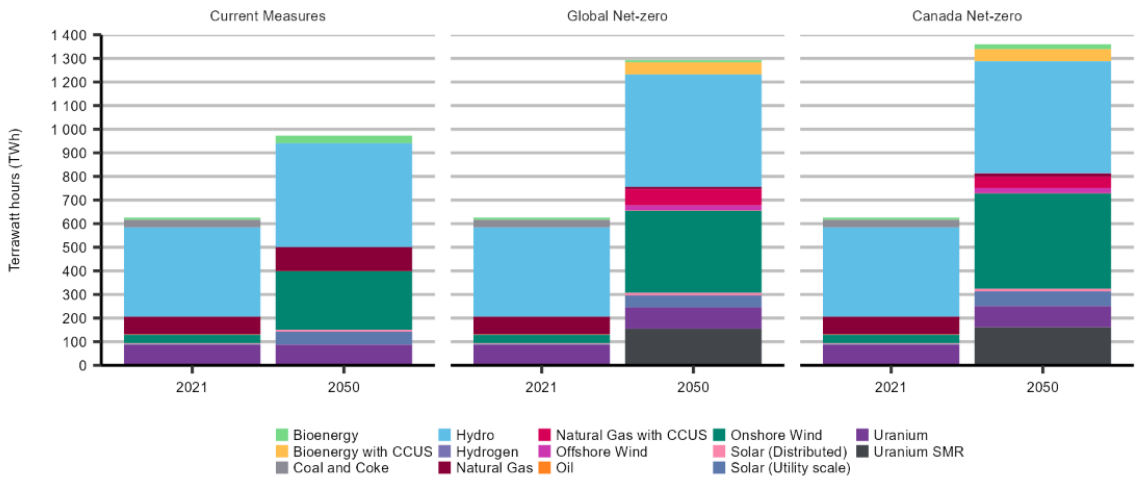


Figure 14. Canada Energy Regulator's electricity generation by fuel and technology, in 2021 and 2050, for scenarios reflecting current measures and net-zero pathways [71].

Despite the installed capacity of wind energy falling behind target values, approximately 1.7 GW of utility-scale wind was installed in Canada in 2023, constituting a 70% increase over the previous year (1 GW) [72]. Wind energy deployment varies greatly throughout Canada, with the greatest growth in 2023 seen in Atlantic Canada, Alberta and the North. In particular, Alberta saw 1,671 MW of growth in 2023, and the Yukon, the Northwest Territories and New Brunswick added 3. 8 MW, 3.2 MW and 42 MW, respectively [69]. Other provinces saw little to no wind energy growth in 2023 due to a lack of centralized procurements and corporate purchase power agreements, although additional capacity is expected in the near-term, as several projects are under development and will be online as soon as 2024.

Currently, all of the wind turbines in Canada are land-based [73], but offshore turbines are expected in the future as the industry improves its manufacturing practices, develops economies of scale, and reduces costs associated with installation and maintenance. This trend in deployment is apparent globally: from 2012 to 2021, the capacity of land-based wind turbines tripled, and the capacity of offshore wind turbines increased by around thirteen times [50]. While no offshore turbines have been installed in Canada to-date, there has been significant interest from developers [74]. Moreover, the Nova Scotia government has set a target of 5 GW of offshore wind leases by 2030 [75].

Government policies and regulations at the federal and provincial levels have played crucial roles in promoting wind energy adoption in Canada. Measures such as renewable energy targets, feed-in tariffs, renewable energy procurement programs, and carbon pricing mechanisms have incentivized investment in wind power projects. While federal and provincial actions can have a positive impact and drive wind projects forward, the opposite can also be true. In Alberta, a pause on approvals for all new renewable energy projects was announced in August 2023. The pause did not affect projects in 2023 and 2024, but it will have an impact in 2025 and beyond due to increased investor uncertainty [69].

3.4. Performance Model

Wind performance models are generally well established. They are critical for planning, sizing, financing and designing projects. Modeling tools used in the industry include WindPRO, Openwind, and WindFarmer – all of which are proprietary software. NREL has also developed a free and open-sourced software called the System Advisor Model (SAM) which can be used for photovoltaics, concentrating solar, wind and biomass projects. Regardless of the software, wind performance models generally require similar inputs, including site information, meteorological data, turbine design specifications (e.g., the turbine power output and energy production which can be characterized by a power curve [76]), and turbine configuration. They also implement general wind turbine energy assumptions, such as the Betz limit, which stipulates that the theoretical maximum power efficiency is 0.59 (i.e., no more than 59% of the available energy in the wind can be extracted by the wind turbine) [77].

As discussed in Section 3.1, there exists an important barrier in implementing performance models for distributed wind turbines due to a lack of available resource data, and the limited time and tight budgets typically associated with smaller-scale projects. Having well established performance models helps to drive wind energy projects, which in turn can provide many economic benefits such as jobs, a new source of revenue (generally to farmers) for land-leasing, and an increased local tax base [78].

In terms of dynamic modeling, more research is needed to develop fast response physical models that can simulate the impact wind turbines will have on the power system under dynamic events such as loss of load, insufficient wind energy, voltage ride-throughs, and short circuits [79]. Power system simulation tools used for dynamic modeling do exist, and include PSCAD/EMTDC, SIMPOW, PSLF, or PSSE. However, dynamic models of wind plants for power system studies are not usually built in to these models and need to be developed independently [79]. This is due to the complexity of modelling advanced commercial turbine technologies that implement proprietary designs and control schemes [4]. Furthermore, the existing dynamic models cannot handle unbalanced faults, are not sufficiently detailed (e.g., model the generator alone), and are not validated with real data [79]. Currently, models typically focus on the system ride-through. Consequently, insufficient attention is given to the dynamic behavior of the power system [4], a crucial aspect for assessing system stability and the potential to provide grid services. NREL has identified this gap and has been working on using models to examine the inertial response of wind turbines when a unit trip occurs on the grid, and to simulate controls that enable wind turbines to offer inertial support [79].

4. Environmental Considerations

4.1. CO_2 Emissions

The embedded emissions of a wind turbine are the sum of all the GHG emissions required to bring that turbine to market, but do not include emissions associated with turbine operation or end-of-life. Conversely, a cradle-to-grave life cycle analysis (LCA) can be conducted to estimate the total GHG emissions associated with a turbine across its entire life cycle. The GHG emissions of a wind turbine system are quantified in terms of grams of CO_2-equivalent (CO_2-eq) per kilowatt hour of energy generation (g/kWh). Parameters such as turbine size, capacity factor, manufacturing materials, type of turbine foundation, and end-of-life management (i.e., recycling, landfilling, etc.) impact the emissions. The construction of components (i.e., material extraction and manufacturing) is responsible for 80% to 90% of total GHG emissions, for offshore and onshore wind turbines, respectively, making it the dominant source of GHG emissions across a turbine's life cycle [80]. Within this category, the production of towers is the most significant GHG emitter, followed by the preparation of materials needed for construction [81]. The operational phase of a turbine's life cycle and its disposal account for 5 to 20% of the CO_2-eq emissions; offshore wind turbines contribute even more significantly due to the necessity of marine transportation, complexity of maintenance, longer travel distances and severity of damages from harsh environmental conditions [80], [82]. Moreover, end-of-life management can have important implications on GHG emissions: recycling a turbine can result in a reduction CO_2 emissions by of 55.4% compared to landfilling [81].

Some variation in GHG emissions between turbines is expected, as a result of differences in installation location, turbine design, etc. A recent meta-analysis compared the GHG footprints of various onshore and offshore turbine systems. The results, given in terms of gCO_2/kWh, are plotted in **Figure 15**.

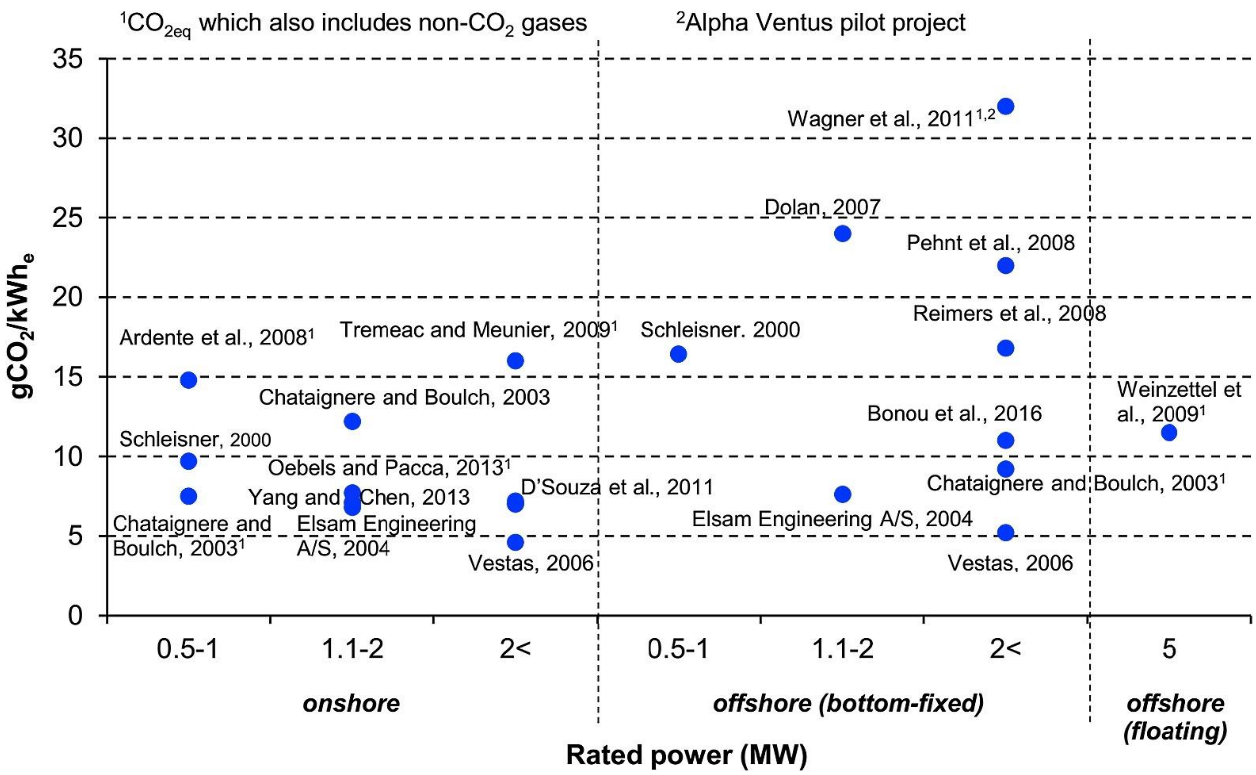


Figure 15. Comparison of GHG footprints for onshore and offshore wind turbines from various literature sources [80].

Figure 15 shows that the highest GHG emissions are attributed to offshore turbines. This is due to the use of longer, submerged transmission cables, and larger amounts of material and energy required to support installation in marine conditions [80]. Similar outcomes were obtained from a model of offshore wind farms in China [82]. Nonetheless, **Figure 15** reveals many instances for which the emissions associated with offshore turbines are very similar to their onshore counterparts.

Furthermore, while emissions vary across literature sources, the average environmental impact of wind turbines (11 gCO_2eq/kWh [83], [84], [85]) is low compared to other electricity generation technologies. For example, emissions from hydroelectric plants (15 - 40 gCO_2eq/kWh), photovoltaics (50 - 100 gCO_2eq/kWh), natural gas (400 - 500 gCO_2eq/kWh), oil (780 - 900 gCO_2eq/kWh) and coal (900 - 1200 gCO_2eq/kWh) are all considerably higher [80].

A lack of knowledge exists regarding the emissions associated with the more novel wind energy concepts, such as offshore floating units and those that utilize other types of foundations. Also, due to their relatively new appearance on the market, the amount of published emissions information for offshore wind farms is more limited than for onshore ones. Moreover, where published data exists, values tend to be highly variable, making it difficult to discern correlations or trends [82].

4.2. Decommissioning and Recycling

It is estimated that by 2050, approximately 43 million tons of waste will be generated worldwide from wind turbine blades, alone [86]. In Canada, cumulative wind turbine end-of-life waste is expected to amount to 831,000 tonnes by 2030 and 4.5 million tonnes by 2050 [87]. Recycling critical turbine materials will not only help to reduce the consumption of global resources, but also alleviate supply chain issues [81]. Currently, it is economically feasible to recycle 85% - 90% of a wind turbine's total mass, given the value of concrete, iron and steel in secondary markets [87]. However, cost and complexity are preventative to blade recycling [87]. The blades are typically made of fiberglass, which is composed of glass and plastic strands and built to withstand harsh weathering, making it difficult to process in the recycling stage [88]. Once the wind turbine is decommissioned, the recyclable plastics and metal components used in the outer shell, shafts, gears and electrical components are recycled and have a monetary value, while the blades, nacelle covers, and rotor covers made of composite materials typically become waste [88].

In Canada, since the first commercial turbines were deployed in the 1990s, very few turbines have been decommissioned to-date. In fact, as a result of quality components and good maintenance practices, they are expected to operate into the 2030s [89]. Consequently, there exists limited experience in turbine decommissioning and recycling in Canada. To this end, CanREA and its members are preparing for an increase in wind turbine recycling demand and developing approaches to close the circular economy loop [89].

In Cowley Ridge, Alberta, TransAlta's commercial wind farm successfully recycled 90% of its turbines, by mass, and obtained ~1,252,000 kilograms of metal [87]. The sale of this metal was used to cover 50% of the decommissioning costs. TransAlta also recovered large quantities of lubricants and dielectric fluids. In the future, this could be managed by the used oil Extended Producer Responsibility (EPR) schemes (i.e., regulations that put the burden of recycling on the manufacturer, rather than the end-user) that are already in place in many of the provinces [87]. However, while the decommissioning of the Cowley Ridge wind farm was considered an environmental success, the blades were landfilled since no recycling pathways were economically viable. This highlights critical technical and economic gaps in implementing blade recycling processes in Canada.

Investigations into the improvement of blade recycling methods are ongoing in industry and academia. Vestas, Aarhus University, the Danish Technological Institute and Olin, an epoxy manufacturer, have partnered to develop a chemical process for recycling epoxy – the material responsible for holding the glass or carbon fiber of the blades together [90]. They are hoping to recycle the used epoxy from decommissioned turbine blades into a virgin-grade epoxy that can be used in the construction of new turbines. The successful, large scale demonstration of such a technology has the potential to revolutionize blade recycling. In fact, while few have been deemed economically feasible at scale, many methods for recycling turbine blades have been proposed. Those most recognized are summarized in **Figure 16**.

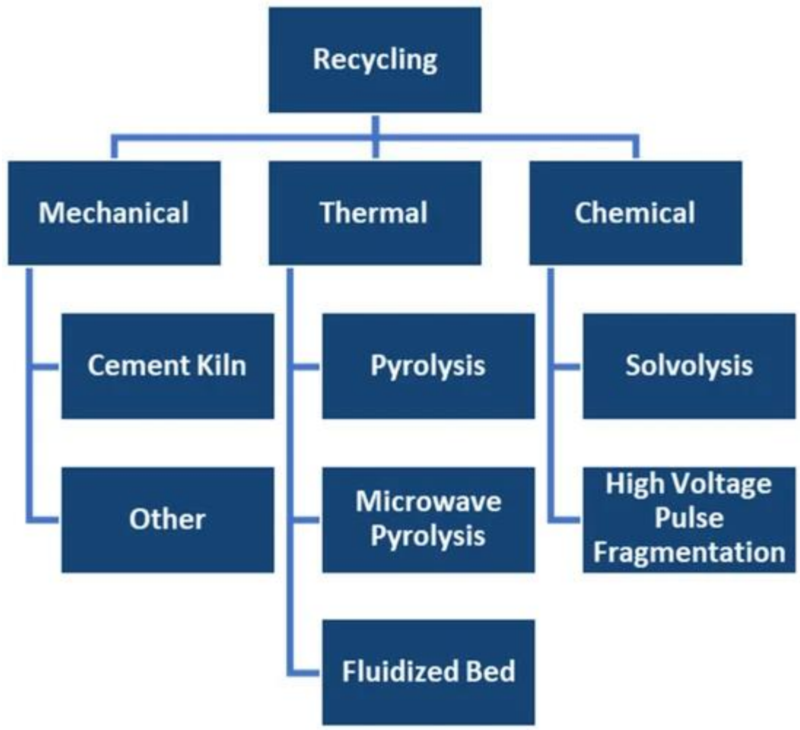


Figure 16. Potential methods for recycling wind turbine blades [91].

Mechanical blade recycling methods use machines such as shredders, crushers, mills or grinders to divide the composite material into small pieces that can be re-used as fillers, reinforcements or raw-materials [91]. Turbine blades are about 70% silica by mass – an important material in cement manufacturing [92]. Consequently, the mechanically recycled blades are most often re-used as raw materials for the production of cement, in a procedure referred to as co-processing [91]. While it remains costly, the United States and some European countries have adopted this process to recycle a fraction of their wind turbine blades. For instance, the Veolia recycling plant in Louisiana has the capacity to mechanically recycle 250 turbine blades every month [92]. Furthermore, the collaboration between a German cement factory and a Danish fiber composite manufacturer demonstrated that composite blade waste can substitute up to 10% of the raw materials needed in cement manufacturing (the presence of boron in blade composites slows cement cure times and prevents substitution beyond 10%), thereby reducing the CO_2 footprint of cement manufacturing by 16% [91].

Thermal recycling methods include pyrolysis, microwave pyrolysis and fluidized bed recycling. Pyrolysis is the heating of materials in the absence of oxygen in order to break down the organic components while leaving all inorganic constituents, like fibers, intact [91]. Microwave pyrolysis employs a similar technique, however it uses microwaves to heat materials under nitrogen atmosphere and requires lower temperatures [91]. This method is preferred as it minimizes thermal degradation, improving the quality of the recycled fibers and making them more competitive with market-grade virgin fibers. Lastly, the fluidized bed process uses a silica sand bed that is heated by hot air to vaporize the organic part of the composite while retaining the inorganic material [93]. Fluidized bed recycling of turbine blades remains in its infancy and has a very low TRL [91].

Blades can also be recycled chemically by solvolysis, which uses temperature, pressure and a catalyst solvent to break down the bonds of polymer products [91]. This process allows for the recovery of both fibers and monomers from the resin. However, downsides include a loss of extracted material strength due to exposure to high temperatures, and the need to use a specific type of solvent, temperature, and pressure for each composition of composite material [91]. Furthermore, large-scale solvolysis is technologically complex, costly and the chemicals used are hazardous to the environment.

Figure 17 gives the TRL of each recycling method and scores them according to environmental friendliness (i.e., waste management) and level of investment needed for process scale deployment.

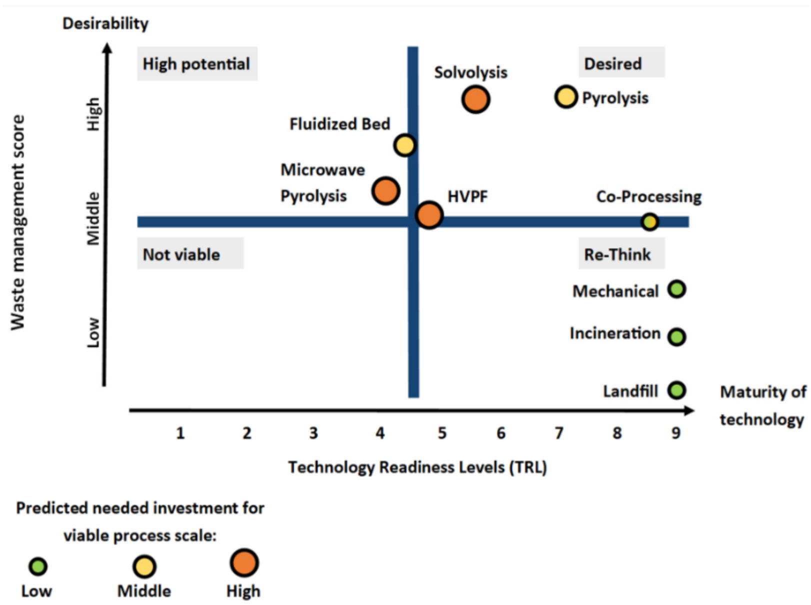


Figure 17. Technology readiness levels, waste management scores and predicted levels of investment needed for various blade recycling and decommissioning methods [91].

Currently, the most viable, environmentally friendly, and economically appropriate recycling method for wind turbine blades is co-processing. The European Commission recognizes the co-processing of recycled blades through cement production as a pathway towards a circular wind energy economy [91]. Nonetheless, gaps and limitations in these recycling processes remain, and further research is required to optimize processing parameters (i.e., heating temperature, reaction time, etc.) to improve the quality of recycled products, reduce costs, and scale processes [93]. Research on hybrid methods, such as microwave-assisted chemical recycling, that can combine the advantages of mechanical, thermal and/or chemical recycling is also being conducted to address the inherent limitations of the individual recycling techniques.

Overall, the wind energy industry is still in the early stages of blade recycling, and turbine manufacturers, universities, and other institutions have been diligently working to develop recycling processes to avoid the estimated 43 million tons of blade waste expected by 2050. Developing new blade materials that are more readily recyclable is another pathway toward wind turbine circularity that is currently being investigated by NREL [94]. Moreover, developing standards and regulations for the decommissioning of wind turbines would ensure implementation of recycling processes, even when they are more costly than landfilling. Currently, Canada does not have any regulations or policies that standardize the decommissioning or capture the value of end-of-life wind turbines [87].

4.3. Raw Material Availability

NREL created a database called the Renewable Energy Materials Properties Database (REMPD) to quantify the amount and type of materials needed for both wind and solar power plants [95]. The data also summarizes material uses, availability, countries of origin and other properties. Currently, more than 200 materials are needed to deploy wind energy, but for simplification purposes of the database, the materials have been grouped into seven major categories: concrete, aggregate, steel, composites & polymers, cast iron, other metals & alloys, and other materials. The material categories for which materials are not easily available globally are steel, composites & polymers, and cast iron. Information pertaining to these is given in **Table 6**.

Table 6. Materials used in the wind energy sector with limited availability, according to the REMPD [95].

Material Category	Primary Role in Wind Energy Generation Facilities	Other Significant Uses	Land-Based Wind Material Intensity (kg/MW)	Offshore Wind Material Intensity (kg/MW)	Source (Percentage of Global Production by Country of Origin)
Steel	All components (tower, hub, nacelle, blade, land-based foundation, offshore substructure, cables, substation, etc.)	Construction, transportation (automotive), metal products, machinery and appliances	107,000–179,000	130,000–419,000	China (54%) India (6%) Japan (5%) United States (5%) Others (30%)
Composites and polymers	Blade, nacelle, cables, land-based foundation, substation, hub, tower	Consumer goods, packaging, transportation (automotive, marine, aerospace)	18,000–39,000	10,000–28,000	China (8%) Canada (8%) Germany (6%) Russia (5%) Saudi Arabia (9%) South Korea (8%) Thailand (7%) United States (5%) Others (44%)
Cast iron	Nacelle, hub, substation	Construction, machinery and appliances	9,000–15,000	7,000–14,000	China (63%) India (6%) Japan (6%) Others (25%)

More specifically, the materials that have the highest risk of supply chain disruptions and are considered to be the most vulnerable are listed in **Table 7**.

Table 7. Role of critical minerals and other materials related to wind energy [95].

Vulnerable Materials	Role in Wind Energy Generation Facilities
Aluminum	Power cables, nacelle/tower internal equipment
Chromium, cobalt, manganese, nickel, niobium, titanium, vanadium	Steel alloying elements
Graphite, lithium, nickel	Batteries
Dysprosium, neodymium, praseodymium, terbium	Rare-earth permanent magnets
Gallium	Wide-bandgap semiconductors for power electronics
Tin	Bronze
Zinc	Anticorrosion coatings (galvanization)
Carbon fiber	Blades
Electrical steel	Nacelle, substation

Table 7 describes the impact on wind energy deployment that would be caused by a limited supply of critical materials such as neodymium, dysprosium, and praseodymium (which play a large role in the manufacturing of generators for direct-drive turbines), and nickel or cobalt (which are used in steel). The global supply of these critical materials is currently insufficient to meet the deployment demand necessary to achieve net-zero goals [95]. For example, to meet estimated U.S wind deployments, rare earth metals like dysprosium and neodymium could exceed 10% of current global production by 2042 and the demand for carbon fiber could surpass current global supplies before 2030 [95]. It should be noted that the report and database created by NREL was intended for analysis of U.S. wind energy deployments. While the results can be applied to Canada, a similar analysis could specifically elucidate Canada's susceptibility to material supply limitations and determine its role in bolstering production of critical materials, researching material alternatives, and driving policy changes.

4.4. Resilience to Extreme Weather

In a climate change context, the resilience of a wind turbine is defined as its "ability to anticipate, absorb, accommodate and recover from the effects of a potentially hazardous event related to climate change" [22], [96]. The evolution of wind turbine technologies in response to real and anticipated changes in climate is a topic of focus among researchers. In particular, there is a need to improve the climate resilience of offshore turbines since their size and location make them more susceptible to extreme climate events. However, limited research on this topic exists.

Extreme weather events include floods, tornadoes, ice storms, hurricanes, wildfires, blizzards, hurricanes, etc. and can lead to turbine vulnerabilities, as summarized in **Table 2** in Section 2.4. In order of increasing severity, the three most impactful extreme weather events in Canada in 2022 were a spring flood in Manitoba, a windstorm/derecho in Ontario and Quebec, and a cyclone (Fiona) on the east coast [97]. Extreme weather events are difficult to predict and can occur across the country at all times of the year. As a result, they have the potential to cause significant damage to wind turbines for which special design precautions are not taken. For example icing on turbine blades can result in losses of 0.005% to 50% of annual power [98]. Moreover, a study that modeled the effects of cyclones on offshore wind turbines found that unfeathered and feathered turbines are susceptible to a 20.8% and 5.8% reduction in fatigue life, respectively [99]. The study demonstrates the importance of considering extreme weather events in the turbine design phase [99].

A design decision that can be applied to absorb the impact of strong wind speeds is the inclusion of lift modification devices that can reduce wind loads [100]. For offshore wind turbines, a reassessment of the blade design might be necessary to handle a larger range of incoming wind angles. Equipping offshore turbines with light detection and ranging (LiDAR) may help to optimize perfomance by giving them time to adjust to upcoming wind loads [100]. Designing taller fixed-foundations for offshore turbines is another resiliency measure that developers will need to consider in anticipation of rising sea levels. Similar considerations are required in the design of floating offshore turbines.

To protect against blizzards and ice storms, hydrophobic coatings can be applied to the blades to minimize ice buildup [100]. This climate resilience measure is particularly important for Canadian turbines that are regularly subject to extreme winter storms and freezing rain.

The U.S. Department of Energy's MIRACL project provides an end-to-end, cyclical process for evaluating resilience and implementing it in energy delivery systems [101]. Overall, this project emphasizes the importance of equipping energy systems to be resilient in their unique geographies and climates.

The incorporation of climate resiliency considerations in wind turbine models will provide assurance as to the longterm performance of a turbine in the face of climate change and extreme weather events. Researchers from Denmark have deveoped a probabilistic framework for resilience modeling and analysis of offshore wind farms [102]. The generic framwork is represented schematically in **Figure 18**, and considers exposure events that may lead to the failure of turbine components, resulting in direct or indirect consequences. Direct consequences are any losses associated with the failure of the component, itself, such as the cost for repairs. Conversely, indirect consequences are associated with the loss of system functionalities and services caused by the failure of a component, such as those resulting from a lack of power produced by the turbine.

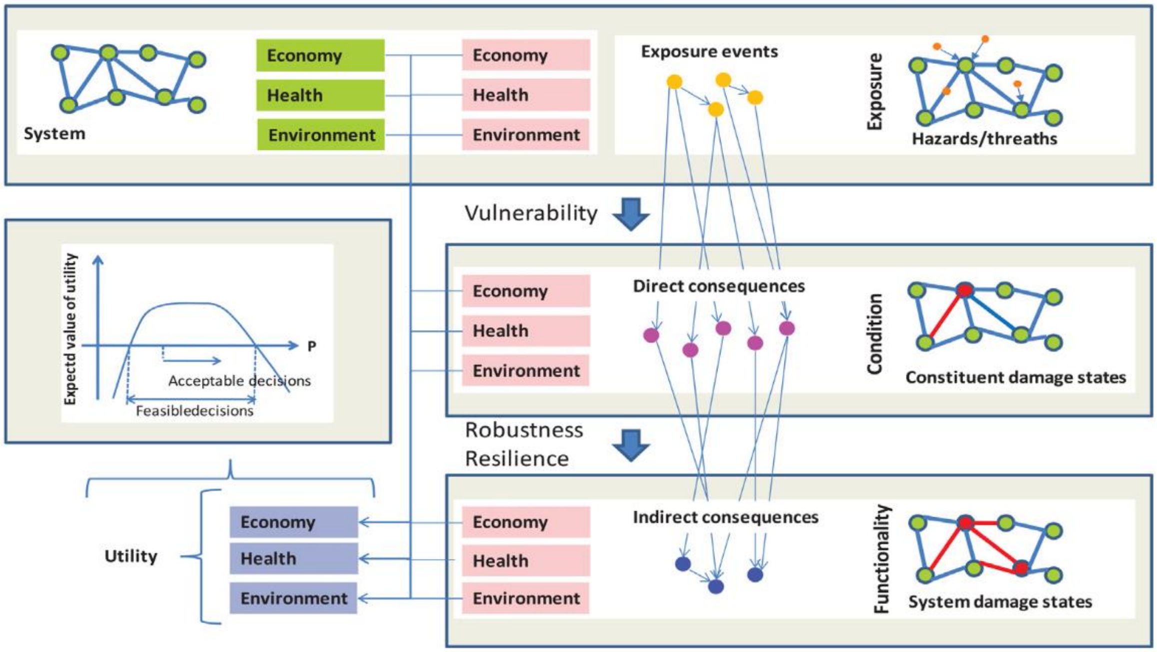


Figure 18. Generic framework for resilience modeling and analysis of offshore wind farms [102].

The study successfully demonstrated that resiliency frameworks can be incorporated in current industry modeling techniques and tools. This work and others like it will help to ensure that wind energy sources can provide reliable grid services in harsh climates.

5. Grid Support

Thus far, this report has framed the dependence of wind turbine deployment on factors such as cost, maturity of supply chains, public support, resource availability and climate resilience. However, grid operators may elect to set permissible wind penetration levels, depending on the ability of wind turbine generators to provide grid-supporting functions. The grid must have a minimum level of stability in order to be deemed fit for purpose. However, as increasing numbers of asynchronous generators replace conventional synchronous generators, the stability of the grid is called into question. Currently, there is a lack of consensus on the level of wind energy penetration that could support a reliable grid. Present control functionalities are reported to support stable grid operations under maximum penetration rates varying from 20% [103] to 35% [104] to 70% [105]. While discrepancies exist, it is nonetheless clear that penetration is limited by the ability of wind turbine generators to support the grid. Consequently, as net-zero deadlines loom and the world shifts towards an even greater reliance on inverter-based resources, advancements will be required to safeguard the stability of future grids that have few or no remaining conventional synchronous generators.

Grid operators have recently released grid codes that mandate the compliance of wind turbine generators with specific voltage sag ride-through, frequency regulation, and active and reactive power regulation requirements [106]. With this in mind, researchers are investigating the ability of wind turbine generators to provide grid services and are looking to address challenges likely to arise in grids with high inverter-based resource penetration, such as: (1) reduced inertia; (2) degraded strength and short circuit current levels, and; (3) difficulty damping system oscillations [107], [108].

The inherent control capabilities of wind turbine generators depend on their configurations. Part 27 of the IEC-61400 standard defines four generic model types for wind turbines that are available commercially. **Figure 19** provides a schematic representation of each model type.

Type 1 designs feature conventional asynchronous generators (i.e., squirrel cage induction generators) that are connected directly to the grid without power conversion. The gearbox is responsible for converting the relatively slow speed of the blades to a much faster speed. The difference between this speed and the synchronous speed of the generator is called the slip. When the generator is driven above synchronous speed, there exists negative slip and electricity is generated. Type 1 turbines operate at nearly fixed speeds (slips between 0% and -1% [109]) corresponding to the frequency of the grid and its induction generator consumes reactive power to create the electromagnetic field in the rotor [110].

Type 2 turbines employ wound rotor induction generators. They include a variable resistor connected to the rotor of the generator that consumes variable amounts of power in order to change the slip of the generator. While the resistance can cause excessive heat loss, it allows for operation at a wider range of speeds (at slips from 0% to -10 [109]) and permits some flexibility in energy capture. If pitch angle control is implemented, the operating slip can be kept closer to its rated value to limit heat loss [109]. Moreover, the resistor provides some regulation of the power output to the grid [110].

Type 3 turbines add variable frequency AC excitation (instead of resistance, as in the case of Type 2 designs) to the circuit of the generator rotor via a voltage-source rotor-side converter. In this way, the magnitude and phase of the rotor current can be adjusted almost instantaneously by power electronics, effecting significant control over the active power output to the grid. The rotor-side converter is also connected back-to-back with a line-side converter, allowing for bi-directional power flow with the grid and reactive power control. This enables: (1) the injection of power to the grid at speeds exceeding the synchronous speed, and (2) the consumption of a small amount of power from the grid to permit operation at speeds slower than the synchronous speed. The converters are typically sized to 30% of the machine rating. Notably, Type 3 turbines can generate electricity at a much wider range of wind speeds and regulate their output power and voltage to provide ancillary services to the grid [110]. At high wind speeds, pitch control limits rotor speeds to their rated values [111].

Type 4 designs allow turbines to rotate at their optimal speeds. As a result, they generate power with variable frequency. Connection of Type 4 turbines to the fixed frequency grid is made possible via a full-scale back-to-back frequency converter (composed of a rotor- and line-side converter) that matches the frequency of the generator’s output power to that of the grid. This also enables elimination of the gearbox, preventing gearbox-related failure. Thanks to the flexibility offered by the frequency converter, wound rotor synchronous generators, permanent magnet synchronous generators or squirrel cage induction generators may be used. Importantly, Type 4 turbines can provide reactive power control. However, unlike in Type 3 turbines, the converters used in Type 4 configurations must be sized to the full rating of the machine [110].

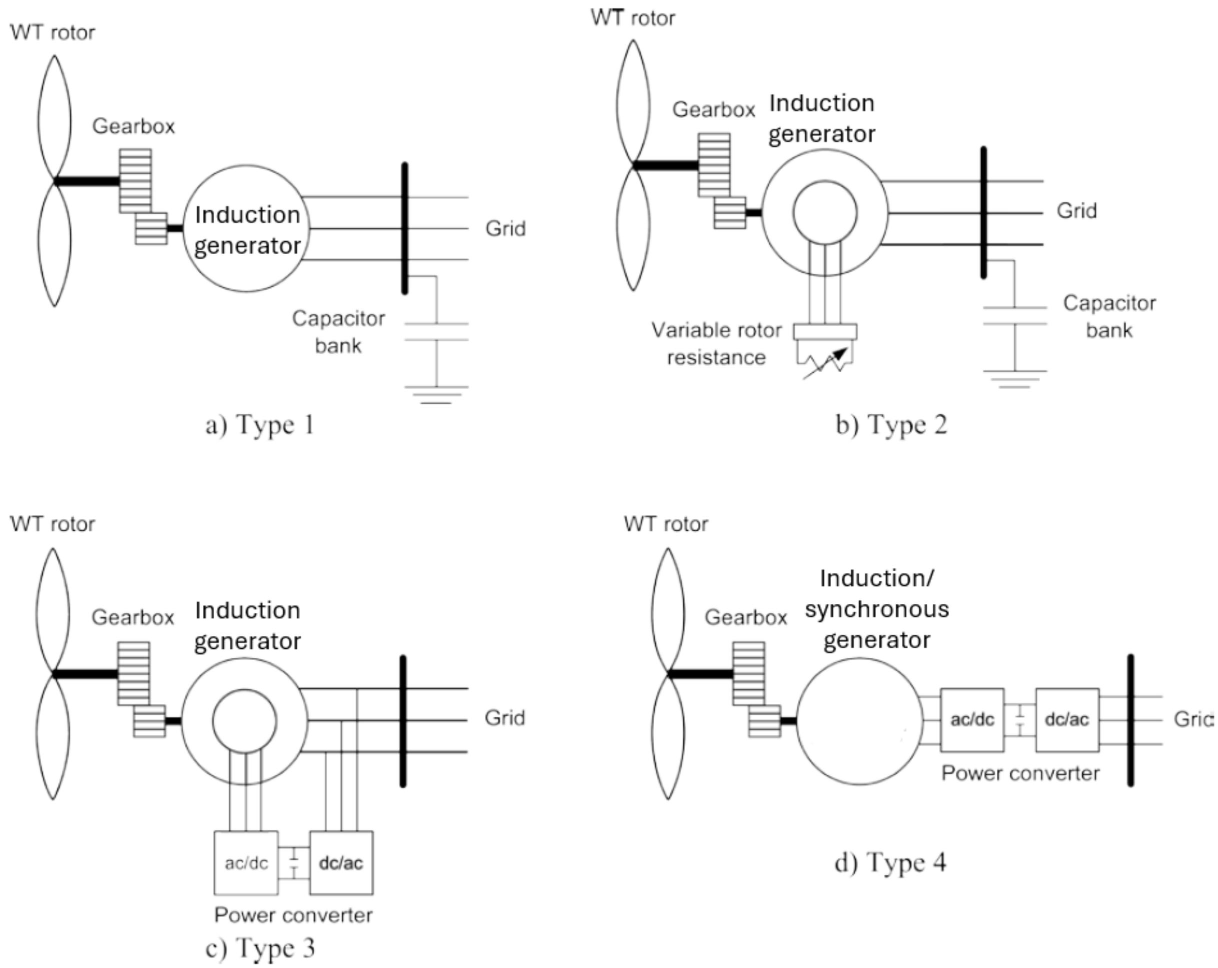


Figure 19. Schematic representation of IEC-61400-27 wind turbine models, including: a) Type 1 conventional asynchronous generators, b) Type 2 variable rotor-resistance asynchronous generators, c) Type 3 doubly-fed asynchronous generators (DFIG), and d) Type 4 full-converter turbines [112].

In addition to the commercially available wind turbine model types defined in IEC-61400-27, an additional model – Type 5 – has emerged as a potential solution to the stability and reliability challenges of future grids [107]. The configuration of a typical Type 5 wind turbine generator is given in **Figure 20**.

Type 5 designs employ the variable speed drive trains of typical wind turbines but connect them to a torque/speed converter capable of converting the input variable rotor speed to a constant output speed. This enables the use of a synchronous generator that can operate at a fixed speed corresponding to the grid frequency and permits direct connection to the grid. The key difference is that type 5 wind turbine generators are synchronous and operate without the need for power converters, thereby offering support capabilities comparable to conventional power plants [110].

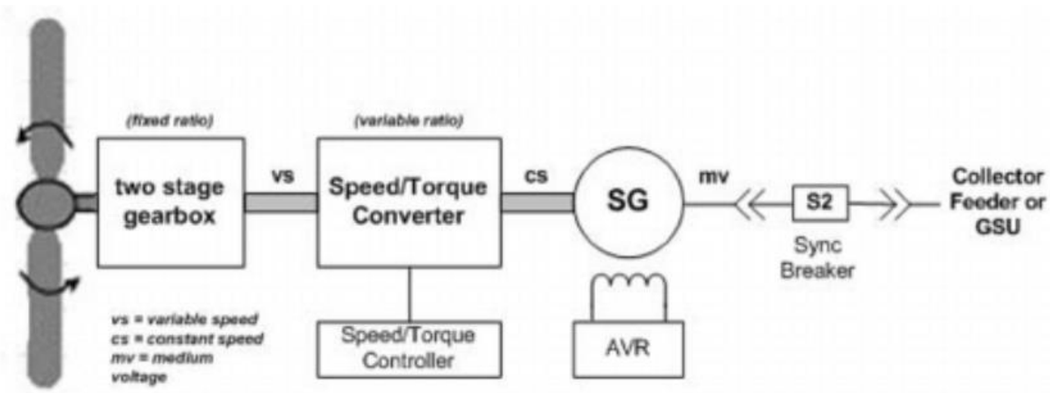


Figure 20. Configuration of a typical Type 5 wind turbine generator [110].

In general, Type 1 and 2 turbines are not recommended in North America for new transmission applications, as they do not offer voltage control, draw excessive current for starting, offer limited reactive power control (using power factor correction capacitors [110]), and operate at limited speeds [113]. Conversely, Type 3, 4 and 5 turbines can provide grid services. According to an industry survey by the European Wind Energy Association, Type 3 and 4 turbines are most common, and were implemented by 62% and 38% of respondents, respectively [67]. While Type 5 turbines have yet to be commercialized, successful operation has been demonstrated via field testing of: (1) a single 0.5 MW Type 5 turbine operating since 2006 amidst a 46 MW wind farm in New Zealand, and (2) eight Type 5 turbines (4 MW) since 2013 in Scotland [114].

Table 8 summarizes the advantages and disadvantages of wind turbine types 3, 4 and 5, in terms of their compatibility with grid integration and ability to offer ancillary services. The information redacted therein forms the basis for the proceeding discussions throughout Section 5.

Table 8. Grid integration challenges for Types 3, 4 and 5 turbines [115].

Grid Integration Challenge	Type 3	Type 4	Type 5
Weak grid operation	Yes, with controls		Yes, no controls needed, tends to make grid stronger Operation at sites with low short-circuit ratio (SCR) yet to be demonstrated
Short circuit current contribution	Limited	No, unless significantly oversized	High, no controls needed
Contribution to system inertia	Inertia-like response using controls, no curtailment	Inertia-like response using controls, with curtailment	Yes, no controls or curtailment needed (for example, a two-pole generator would give four-times real inertia compared to a four-pole generator)
Fast frequency response	Yes, fast response with special controls, curtailment, and/or transient uprating		
Primary frequency response	Yes, fast response with special controls and curtailment		
Participation in frequency regulation	Yes, curtailment needed		Yes, curtailment needed
Independent control of active and reactive power	Yes, with controls		Yes, with controllable automatic voltage regulator (AVR)
Transient performance and ride-through	Yes, with special controls		Yes, same as conventional synchronous generator with AVR
Voltage control	Yes, with special controls		Yes, same as conventional synchronous generator with AVR
GFM operation	Yes, with controls		Yes, no controls (default operation mode)
Black start and islanded operation	Yes, with controls and energy storage		Yes, no controls
Medium-voltage operation	Yes, with step-up transformer; transformerless might be possible in the future		Yes, up to 20 kV with no transformer
Protection impacts	May require adjustment to protection to accommodate lower short-circuit current than synchronous generation (Type 3 has more SCC capability than Type 4)		No change in the existing protection framework
Wind-free voltage support	Yes, with special controls (voltage control only, no inertia)		Yes, with clutch to disconnect generator from gearbox (synchronous condenser mode, provides voltage control and inertia, enhances grid strength)
Brushless operation	Brushes needed	Yes	Yes
Generator	Special design	Special design, dependence on rare-earth minerals for permanent magnet generators	Mass produced, global maintenance network and workforce exists, no dependence on rare-earth minerals
Cybersecurity	Yes	Yes	Fewer controls means fewer targets for external attacks

5.1. Predicting Active Power Demand and Forecasting Generation

The power that must be supplied by the grid is dynamic; it responds to changes in demand. Based on historical data, models of demand can be used to anticipate daily and seasonal fluctuations in load, with a reasonably high level of accuracy. Grid operators leverage these models to plan unit commitments and trades. Since instantaneous demand is less predictable, they also allocate resources to ensure they have appropriate spinning reserves (i.e., unused capacity that is online but not loaded) in the case of unforeseen power shortages [116]. The challenge with using wind energy as the generation source is that its supply is not guaranteed. Instead, grid operators must pair anticipated demand profiles with wind forecasts to make network management decisions. However, accurately forecasting wind energy over multiple time scales is notoriously difficult[117]. Higher degrees of unpredictability necessitate larger costly spinning reserves in order to maintain the same level of grid reliability [116].

Consequently, advances in wind speed forecasting could significantly improve efficiencies in grids relying on wind energy. Numerical weather prediction models, which use data from geographically scattered weather stations, are currently the tool of choice for wind forecasting [118]. These offer valuable predictions at the medium- to long-term scale, but are not suited for short-term modelling due to slow data relay and computational speeds [116]. To overcome these challenges, researchers are looking to leverage artificial intelligence and machine learning for the rapid production of accurate near-term wind speed forecasts [119].

5.2. Frequency Support and Active Power Control

The grid frequency provides an indication as to how well supply and demand are balanced at any given moment. When supply exceeds demand, the grid frequency increases; when demand exceeds supply, the grid frequency decreases. The inertia of the system is inversely related to the rate of frequency change [116]. Since modern Type 3 and 4 wind turbine generators rely on power electronic converters that decouple the turbine's rotational speed from the grid, integration decreases system inertia [117]. Consequently, as wind turbine penetration increases, grids become susceptible to faster frequency variations, potentially resulting in load-shedding, machine damage and blackouts [111].

In order to provide reliable power, grid frequency needs to be narrowly controlled by ensuring that the total power generated is equal to the power consumed by system loads and electrical losses [120]. Active power control is the control of the real power output of a wind turbine or collection of wind turbines in order to assist in balancing total power generated on the grid with total power consumed [120]. **Figure 21** illustrates the forms of active power control that occur at various timescales following a loss-of-supply event.

The **inertial response** is triggered immediately by a deviation in frequency. When a disruption occurs, a conventional synchronous generator will continue to inject the kinetic energy from its rotating masses to the grid. In the case of a loss-of-supply event, this would cause the generator's rotational speed to slow and similarly slow the rate of frequency decline [111]. The opposite is true for a loss-of-load event. In other words, the system inertia will help to reduce the frequency slope immediately following the disruption in **Figure 21**. Ultimately, the purpose of inertial control is to arrest the initial rate of frequency change in order to allow time for the primary frequency response to kick-in.

The **primary frequency control (PFC)** is activated after the inertial response. It seeks to restore the frequency to a steady-state level by increasing or decreasing generation to match load. In synchronous generators, governor controls that adjust power output according to the deviation in frequency are responsible for the primary frequency control. Steady-state is typically achieved within 20 – 30 seconds [111].

Automatic generation control (AGC) or secondary frequency control is active at all times, during normal operation and disruptions. It will restore the frequency to its nominal setpoint by regulating the active power output. Conventionally, centralized system operators will release signals that direct a power plant to adjust its production [111].

Active power control classifications are based on the conventional methods used by synchronous generators to respond to frequency events [120]. However, asynchronous generators are inherently unresponsive to system frequency because their use of power electronic converters prevents them from being synchronized with the frequency of the grid [111]. Consequently, in systems with high levels of wind penetration, the provision of active power control functionalities is necessary to maintain the grid's balance between supply and demand. Moreover, the variability and uncertainty in available wind energy presents unique challenges to providing reliable power since it is not generally considered dispatchable.

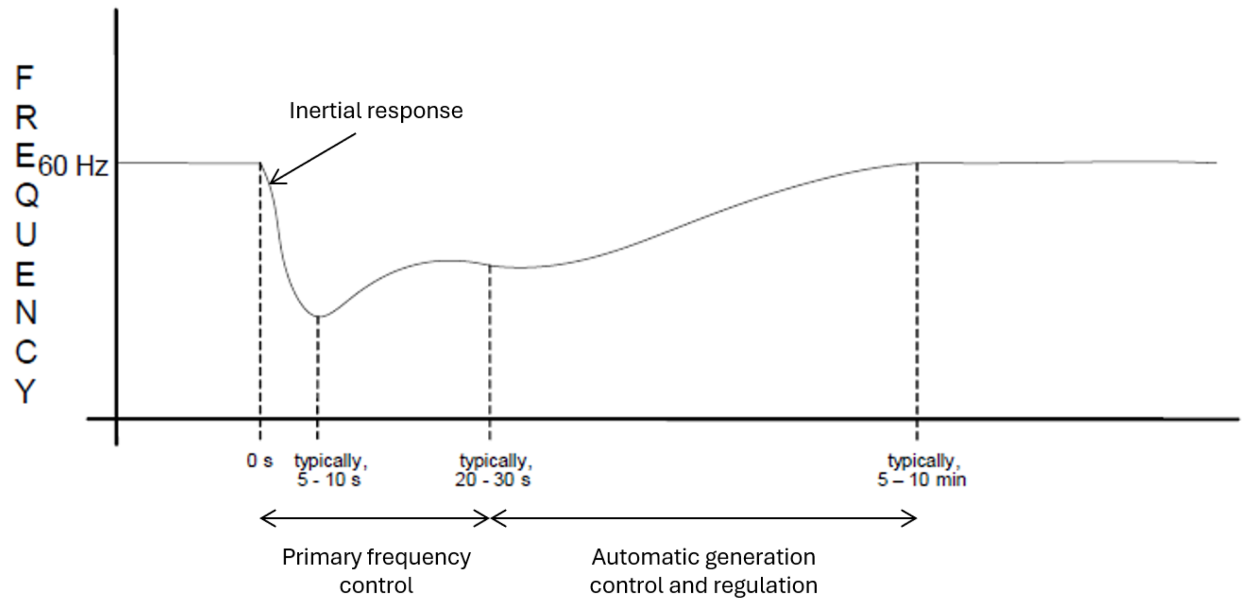


Figure 21. Frequency trace after a loss of supply. The inertial response, primary frequency control and automatic generation control are triggered at different timescales to restore the system frequency. Modified from [111].

To this end, Canadian grid codes contain active power control requirements. Hydro-Québec mandates that wind plants rated above 10 MW have inertial response capabilities (>9 s of >6% overproduction when system frequency deviates by -0.1 to -1.0 Hz) and primary frequency response capabilities (reaction times <500 ms, response times <4 s and damping ratios >0.3) [121]. In fact, Hydro-Québec, a leader of sorts in this regard, has included inertial response emulations for wind turbines in their grid codes since 2006. Their requirements have encouraged grid operators in other Canadian provinces to follow suit, including in Ontario and Saskatchewan. Similar stipulations exist in Spain, China and Europe but they have not yet been adopted in many other jurisdictions, including the U.S.A [111], [122], [123].

A number of strategies have been developed to provide inertial, primary and secondary frequency responses at the individual turbine and power plant levels. An example of a wind farm's active power control scheme is given in **Figure 22**, whereby torque and pitch are controlled to modulate output power according to frequency measurements from the grid and reference commands from the grid operator.

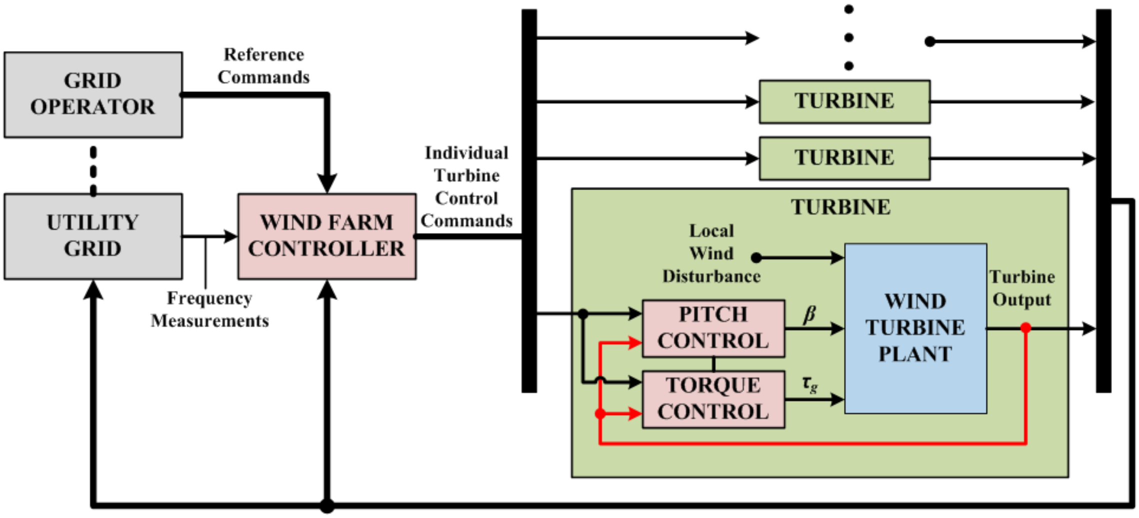


Figure 22: Block diagram depicting the typical interconnection of a wind plant's active power control system with the utility grid and the grid operator [124].

5.2.1. Inertial Response and Primary Frequency Control

While conventional synchronous generators automatically provide inertial control and have governors for primary control, the distinction between inertial and primary responses is less clear for wind turbines that need to implement control loops to execute both types of response [125].

The inertia constant provides a metric for quantifying inertial response performance; it describes the maximum length of time a machine is capable of injecting power at its rated output using only its stored rotational energy. Synchronous generators are a benchmark for comparison and have inertia constants between 2 – 8 seconds [126]. The inertial response may be emulated in a wind turbine by adding a control loop to the power electronic converter that connects the inertia of the rotating turbine directly to the grid [127]. Due to the speed with which power electronics can actuate the torque command signal, wind turbines have the ability of providing more inertial frequency support than conventional generators per unit of spinner inertia [124].

In general, the methods by which inertial and primary response are achieved are proprietary and therefore not outlined in detail. General Electric, Siemens, Vestas and Mitsubishi have all patented their active power control technologies [111]. Nonetheless, active power control of wind turbines is an ongoing area of research [124]. Modellers in academia investigated the combined inertial and primary frequency response achieved in Type 3 turbines by adding either an inertia control loop that mimics the behaviour of synchronous generators via a low-pass filter on the rotor acceleration or a droop control loop that considers the deviation in rotor speed from its setpoint [127]. **Figure 23** plots the frequency trace for each control strategy: an inertial response arrests the initial drop in frequency and a primary frequency control helps the frequency to recover to steady-state after ~20 seconds. Notably, the drop in frequency is less severe with the droop controller than the inertia controller, however its slope is steeper. By implementing this type of control, the Type 3 wind turbines achieved inertia constants in the range of 2 – 6 seconds (i.e., comparable to synchronous machines) [127].

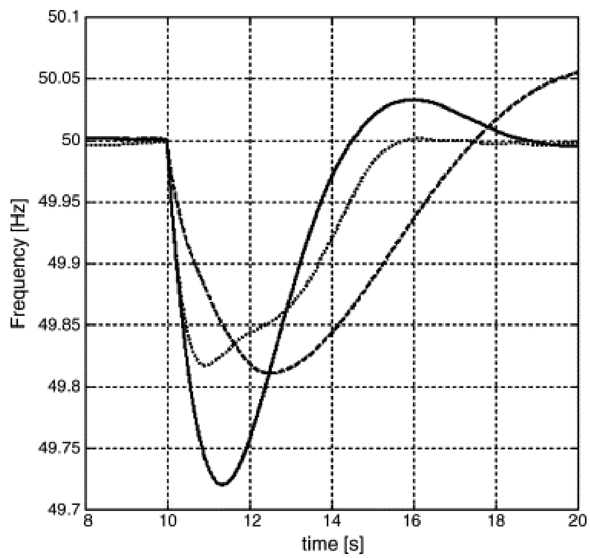


Figure 23. Wind turbine response to a grid frequency disturbance without control (solid line), with inertia control (dashed line) and with droop control (dotted line) [127].

NREL simulated the system frequency response to a large network disturbance to determine how wind turbines with inertial and/or primary frequency control will affect grid stability at various penetration levels [111]. The results are plotted in **Figure 24**. Specific details regarding the control schemes implemented are not provided. The simulation results demonstrate that the active power control of wind power plants can help to significantly arrest sudden drops in frequency. Interestingly, at the highest penetration levels, when wind power plants provide only synthetic inertial response, the frequency nadir (i.e., the lowest frequency point) falls below that of the base case scenario where no active power control is implemented. Therefore, the results suggest that while primary frequency control is more impactful than inertial frequency control alone, the combination of both yields double the benefits. Moreover, as penetration with combined inertial and primary frequency control increases, the nadir increases, suggesting that wind power plants are providing more stability than the synchronous generators on this grid. While the exact control methodologies are not described and their cost cannot be ascertained, the study nonetheless provides confidence that a sufficient level of active power control can be achieved to support high levels of wind turbine penetration.

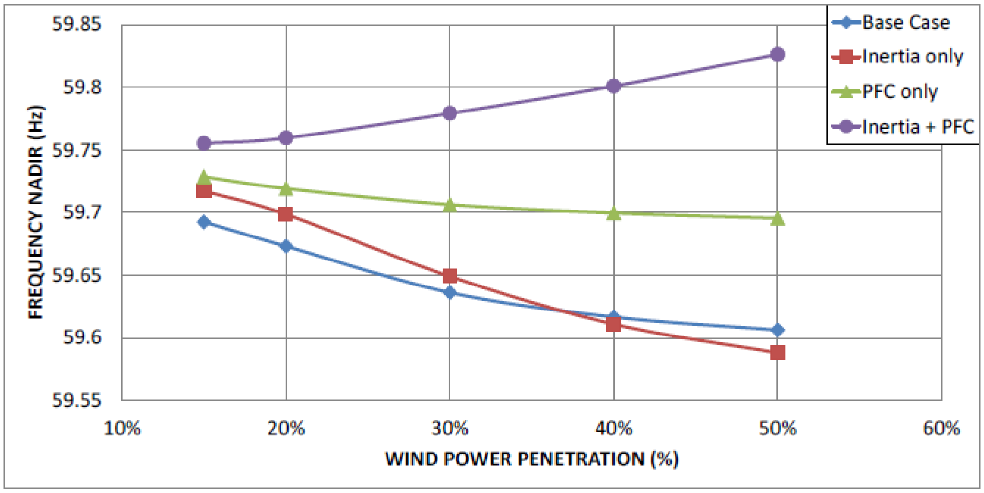


Figure 24. Impact of inertial and primary frequency control (PFC) on the frequency nadir following a major system disturbance for varying levels of wind power penetration. No active power control is implemented in the base case [111].

Unlike synchronous generators, changing wind speeds impact the mechanism by which modern variable-speed wind turbines (i.e., Types 3 and 4) provide inertial control [111]. To illustrate this, **Figure 25** provides the inertial response of a Type 3 turbine to a loss-of-supply event under a) high wind speeds and b) low wind speeds. In the high wind speed scenario, there is sufficient wind power to enable turbine operation at its rated level. Conversely, in the low wind speed scenario the turbine is forced to operate below its rated power level.

In both cases, the controller detects the deviation in frequency almost immediately following the event and enables inertial control for a duration of 15 seconds. It rapidly increases the output power, causing the rotor to decelerate in order to slow the rate of frequency decline. After 15 seconds, the controller disables the inertial response and the primary frequency control returns the turbine to steady-state operating levels. The difference in frequency control between high and low wind speed scenarios lies primarily in the pitch control. Under high wind speeds, the pitch angle is increased to prevent operation above rated levels. Then, when the disturbance occurs, pitch control is disabled (i.e., pitch angle is set to 0°) because the inertial control reduces the speed of the rotor and protection from over-speeding is no longer required. Under low wind speeds, the pitch control is never enabled. Importantly, in higher wind speeds, turbines can control their pitch to tap into additional wind power when a loss-of-supply event occurs, such that they can provide incremental power to the grid. For this reason, normal operation is restored in only 20 seconds for the turbine subjected to higher wind speeds, compared to 35 seconds for its slower wind speeds counterpart [111]. More severe disturbances would require a wind turbine to operate in curtailed mode to provide sufficient reserve for frequency response. This is described in greater detail in Section 5.2.2.

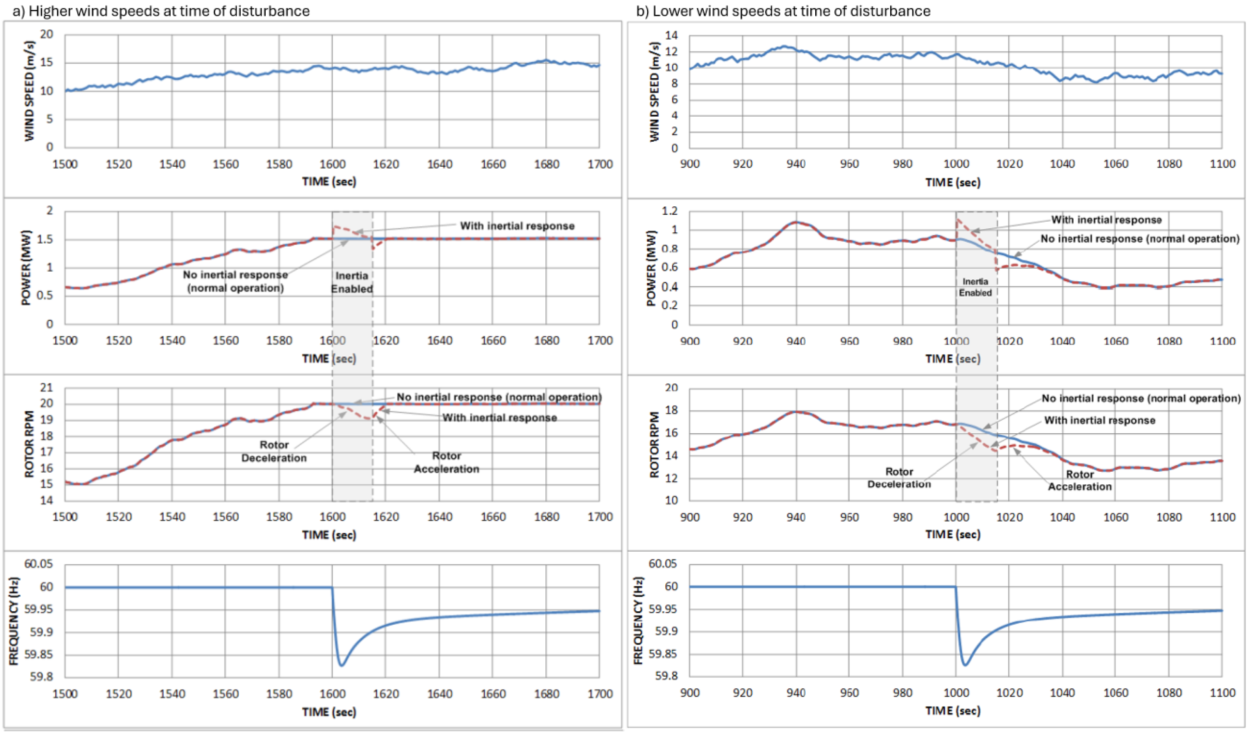


Figure 25. Simulated frequency response of a Type 3 turbine to a loss-of-supply event under a) high and b) low wind speeds at the time of the disturbance [111].

5.2.2. Automatic Generation Control and Curtailment

Wind power plants apply automatic generation control – or regulation – by increasing or decreasing their power outputs in response to grid operator commands. This allows grid operators to dispatch generation resources according to predicted or real demand, and provides flexibility beyond what is afforded by inertial and primary frequency response. For instance, wind generation can often exceed demand, particularly at nighttime when loads are low [128]. To prevent this, wind power is regulated and generation is reduced below the maximum capacity.

On the other hand, generators also need to be able to increase their outputs in response to increased demand. With conventional power plants, this situation is simply handled via commands to increase power outputs. However, wind is considered to be non-dispatchable, and its speeds are variable. Consequently, a common problem arises in that diurnal load peaks tend to intersect with declining wind speeds [128]. To overcome this, wind power plants are set to operate at a level below the maximum available power. This is referred to as commanded de-rating or curtailment. In other words, wind power plants are oversized and their generation is restrained under regular high-wind-speed operation, such that there is sufficient capacity reserve to meet demand (i.e., to ramp up production) even when wind speeds are low. In fact, the grid codes in many countries impose minimum rates at which wind power plants must be able to ramp up or down their active power output [122]. Many grid codes also impose maximum active power ramp rates in order to safeguard their grids from rapid changes in output that could adversely affect stability [122]. Canadian grid codes have yet to set requirements for active power ramping. In part, this leniency is a result of relatively low wind penetration rates and a national reliance on high inertia hydropower [122].

NREL performed field tests to study the ability of a wind turbine to execute automatic generation control under variable wind conditions [111]. As demonstrated in **Figure 26**, generation (P_{gen}) is able to track desired output ($P_{cmd\ Dr+AGC}$) under fluctuating wind conditions by applying a constant 10% de-rating command (i.e., operating at 90% of maximum available power). The controller monitors the available wind power (P_{avail}) based on the estimated wind speed (V_{est}), and continuously applies the de-rating command ($P_{cmd\ Dr}$) to ensure there is sufficient overhead power to accommodate grid operator-commanded automatic generator control. The relatively high frequency fluctuations in **Figure 26** are expected to be smoother when considering an entire wind power plant. Consequently, to improve and build-upon the results, NREL notes that these types of simulations and field tests should be performed at the wind plant control level. There is also interest in studying whether the transition between primary frequency control and automatic generation control is seamless.

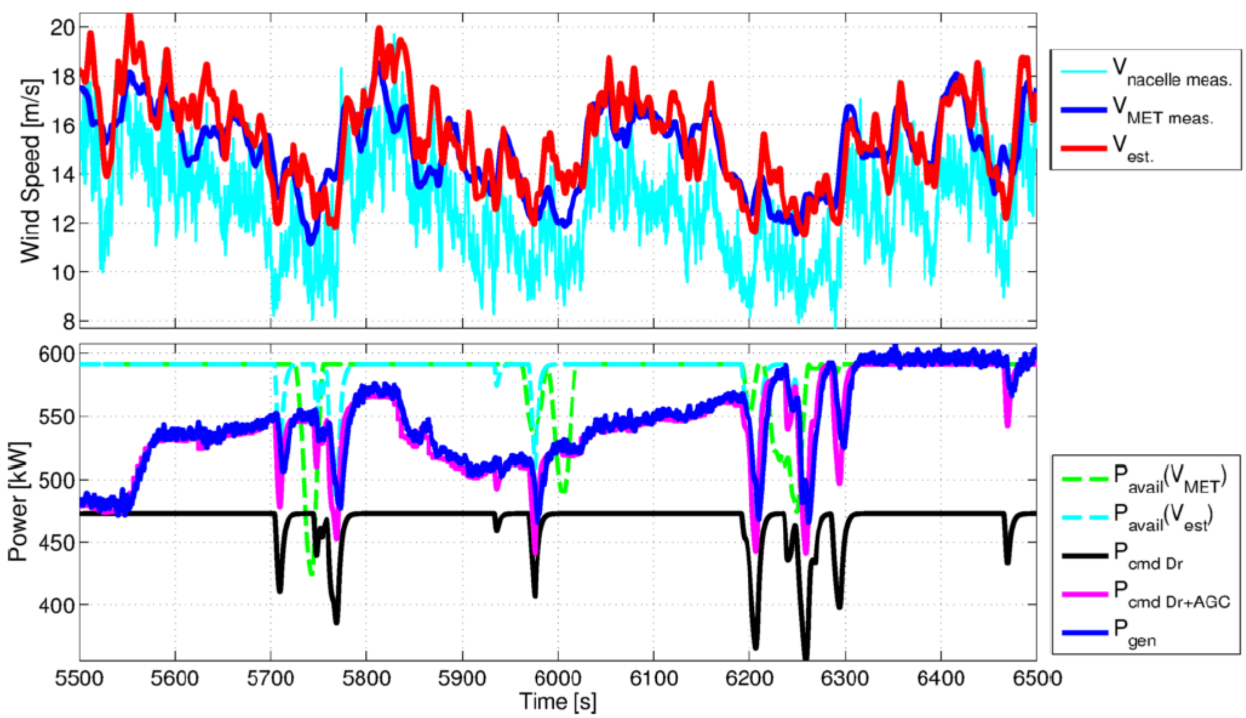


Figure 26. Field test results of the NREL turbine following automatic generation control commands under variable wind speeds [111].

While the automatic generation control capabilities of modern turbines are promising, limitations in transmission infrastructure are expected to result in the excessive curtailment of wind energy due to the inability to transmit power from the generation site to where it is needed [104]. As demonstrated in **Figure 27**, NREL found that modestly increasing the U.S. transmission buildout by adding 4 new lines that reinforce the connections between the Midwest and the West (Transmission Scenario 1), can reduce curtailment by ~50%, compared to the 'business as usual' reference scenario [104]. Additional buildout beyond Transmission Scenario 1 can further reduce curtailment, however there are diminishing returns.

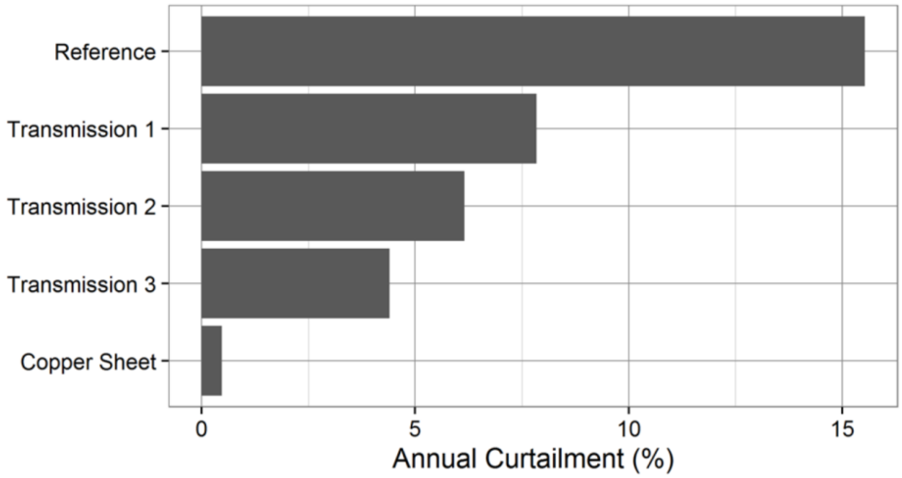


Figure 27. Total annual curtailment of wind energy in the U.S. for various transmission infrastructure buildout scenarios. The Transmission 1, 2 and 3 scenarios add 4, 8 and 9 new lines, respectively, while the Copper Sheet scenario adds an unrestricted level of expansion [104].

Load-generation balancing over large areas will require advancements in grid communication or the implementation of smart grids, capable of monitoring and transmitting load and generation data in real-time [117]. To avoid vulnerabilities to cyber-attacks, the security of the control and communication systems should be carefully considered [117].

While curtailment reduces efficiency, it is crucial for grid reliability. Detailed demand forecasting can help in the economical optimization of curtailment set points. In many situations, it is actually more cost-effective to use less than the maximum amount of available wind power because it allows for dispatch flexibility [111]. Moreover, curtailed power does not need to go to waste; coupling wind energy with energy storage technologies has the potential to improve efficiency and provide increased power reliability. This concept is explored in further detail in Section 5.8.

5.3. Voltage Support and Reactive Power Control

Voltage control is necessary to ensure the reliability of transmission networks. Power network equipment and power consuming equipment are designed to operate within a narrow voltage range; when voltages are too high or too low, equipment fails.

Moreover, the introduction of wind turbine generators to the grid can introduce voltage fluctuations as a result of varying wind speeds [117]. Transmission voltages can be controlled by manipulating a generator's production and absorption of reactive power. Consequently, Canadian grid codes stipulate that wind power plants and distributed systems must satisfy prescribed reactive power capabilities at the point of interconnection. These are often given as power factor design criteria. The power factor quantifies the efficiency of electric power utilization and is defined in Equation 5 as the ratio between active power and apparent power:

$$PF = \frac{P}{\sqrt{P^2 + Q^2}} \tag{5}$$

where PF is the power factor, P is the active power and Q is the reactive power.

Ideally, wind turbines should have power factors equal to 1. However, induction generators tend to absorb large amounts of reactive power from the grid to generate their magnetic fields. This can reduce transmission voltages below acceptable levels and yield power factors less than unity. In Types 1 and 2 turbines, capacitor banks (power factor correction capacitors) are used to minimize voltage changes by maintaining reactive power at a constant set point. Typically, the capacitors are sized to maintain an inductive power factor around 0.98 [110], but this constrains machine speeds inefficiently and necessitates complex switching schemes [129]. Moreover, since reactive power is constant, Type 1 and 2 turbines do not offer voltage control [110].

According to Canadian grid codes, when turbines are generating electricity (i.e., in the absence of faults or disturbances), power factors must be controllable between 0.90 lagging (capacitive) and 0.95 leading (inductive) [128]. As a result, modern turbines opt for systems that offer better control over reactive power.

Wind turbine generators of Types 3, 4 and 5 are capable of voltage control – either directly or indirectly. Indirect control is achieved in Type 3 turbines by manipulating the direct component of the rotor current via power electronics in the voltage-source rotor-side converter. Similarly, Type 4 turbines achieve indirect voltage control by varying the reactive component of current at the line-side converter. Since Type 5 wind turbine generators are synchronous, they employ the automatic voltage regulator (AVR) of conventional power generators, which can be programmed to control reactive power, power factor and voltage directly [110]. Importantly, Type 3, 4 and 5 wind turbine generators can all achieve levels of reactive power control that meet or exceed those set by the power factor design criteria of the Canadian grid codes [110]. Some Type 3, 4 and 5 turbines can even deliver reactive power outside of mechanical operating windows, when the turbine is generating little to no active power. This is referred to as wind-free voltage support.

Direct voltage control can also be achieved in the grid forming operation of Type 3, 4 and 5 wind turbine generators.

5.3.1. Grid Following versus Grid Forming Operation

Conventional synchronous generators 'form' the grid. In other words, they act in grid forming (GFM) mode as voltage sources to ensure that the magnitude of voltages and the frequency at various nodes remain within tolerable limits. These will stay synchronized with the grid during small disturbances. Conversely, inverter-based resources, including traditional wind turbine generators, operate in grid following (GFL) mode. These generators adjust their active power output by controlling injected current and depend on the grid to provide a stable voltage and frequency reference. However, as the penetration of inverter-based resources increases, the ability of the grid to provide this stable reference is compromised. Consequently, the lack of stability offered by GFL operation will inhibit the deep penetration of inverter-based resources [130]. Various studies have sought to quantify the maximum penetration of GFL turbines, however, the methods are highly sensitive to the topology of the simulated network used for the case study, the wind speed variability and the measured factors selected to constrain stability. Nonetheless, wind turbine penetration limits around 30% have been postulated [131], [132], [133].

Therefore, it is imperative that modern wind turbine generators be equipped with the appropriate controls to enable GFM operation. This can be achieved by embedding software into Type 3 and 4 systems – no additional mechanical components are required [115]. Alternatively, Type 5 turbines, though not yet commercially available, do not require additional controls as they are synchronous and thus inherently GFM [115]. Conversely, Type 1 and 2 turbines are not suited for GFM operation.

In the GFL operation of Type 3 and 4 turbines, the converter controls the level of injected current according to the active and reactive power set points. The controller determines these set points by monitoring the reference current and using a phase-locked loop (PLL) to measure the phase angle of the grid voltage at the point of interconnection [115]. However, in GFM operation, the PLL is unnecessary because the converter directly controls the voltage at the point of interconnection. In both GFL and GFM mode, outer loops on the rotor-side converter enable active and reactive power control for frequency and voltage response. The difference, however, is that grid services are provided by controlling voltage in GFM mode and current in GFL mode [115].

The outer control loops on the rotor-side converter of a Type 3 turbine operating in a) GFL and b) GFM mode are given in **Figure 28**. In the GFL operation mode, the output currents of the generator are synchronized with the grid voltage via the PLL. The PLL outputs, θ_{PLL} and ω_{PLL}, are used to compute the reference angle (θ_r) and frequency (ω_{r}) for vector control of the rotor-side converter. These inform the reactive (Q_{ref}) and active power set points (P_{ref}), and the rotor current ($i_{rq,ref}$ and $i_{rd,ref}$) required to achieve them. GFM control is significantly more complex. Therein, the key difference is that the reactive and active power control loops generate reference values for the magnitude ($v_{m,ref}$) and frequency ($\omega_{\mathrm{s,ref}}$) of voltage at the stator terminal, rather than the rotor current. The $\omega_{\mathrm{s,ref}}$ is then used to obtain θ_r and ω_{r} for the vector control of the rotor-side converter. Thus, another important difference is that PLL is not used to derive θ_r or ω_{r} under GFM operation.

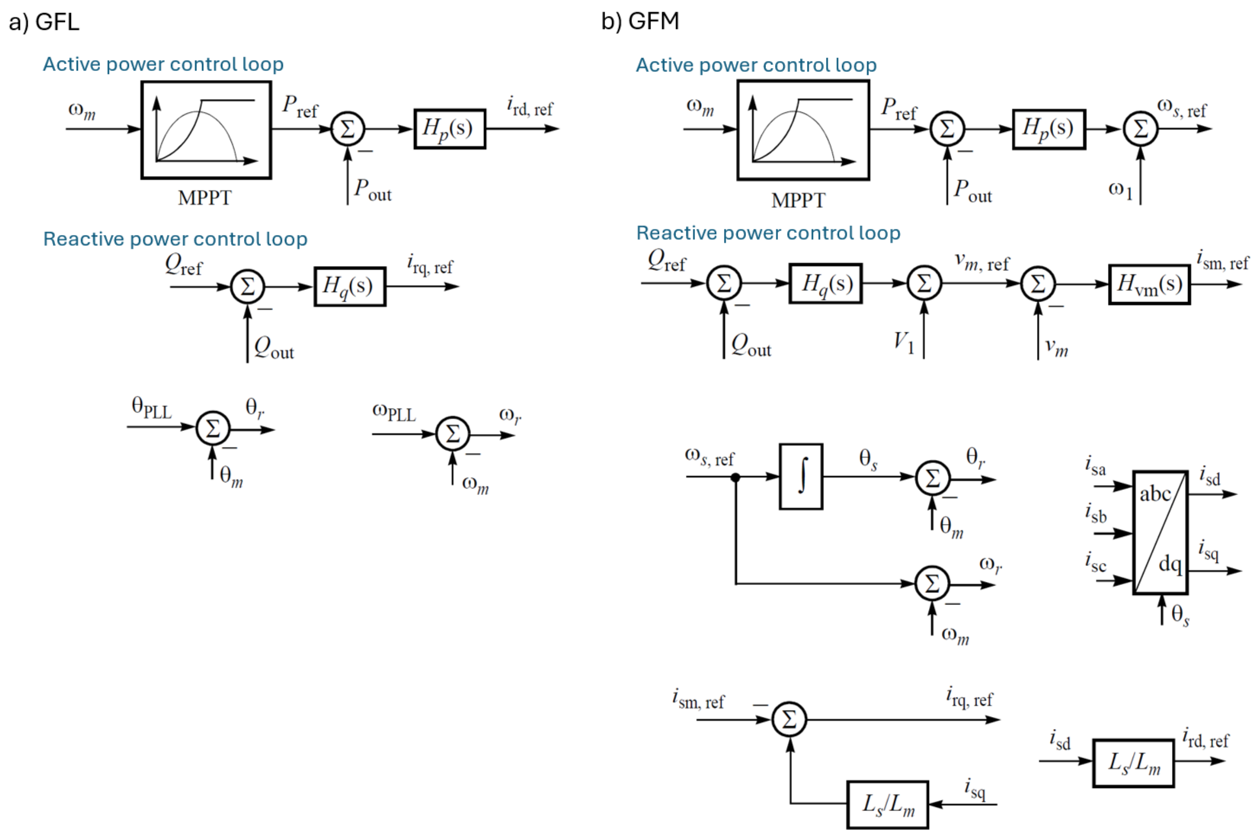


Figure 28. GFL and GFM control loops of the rotor side converter in a Type 3 wind turbine generator for a) GFL and b) GFM operation [134].

Unlike Type 3 turbines, which have induction generators that are connected directly to the grid, Type 4 turbines employ a full-scale power converter that decouples the generator from the grid. Consequently, the GFM controls are significantly more complex for Type 3 generators [134]. The general control scheme of a Type-4 turbine operating in GFM mode is given in **Figure 29Error! Reference source not found.**. The GFM control of Type 4 turbines can be achieved by modifications to the grid-side or rotor-side converter. In **Figure 29**, the grid-side converter controls the DC-link voltage.

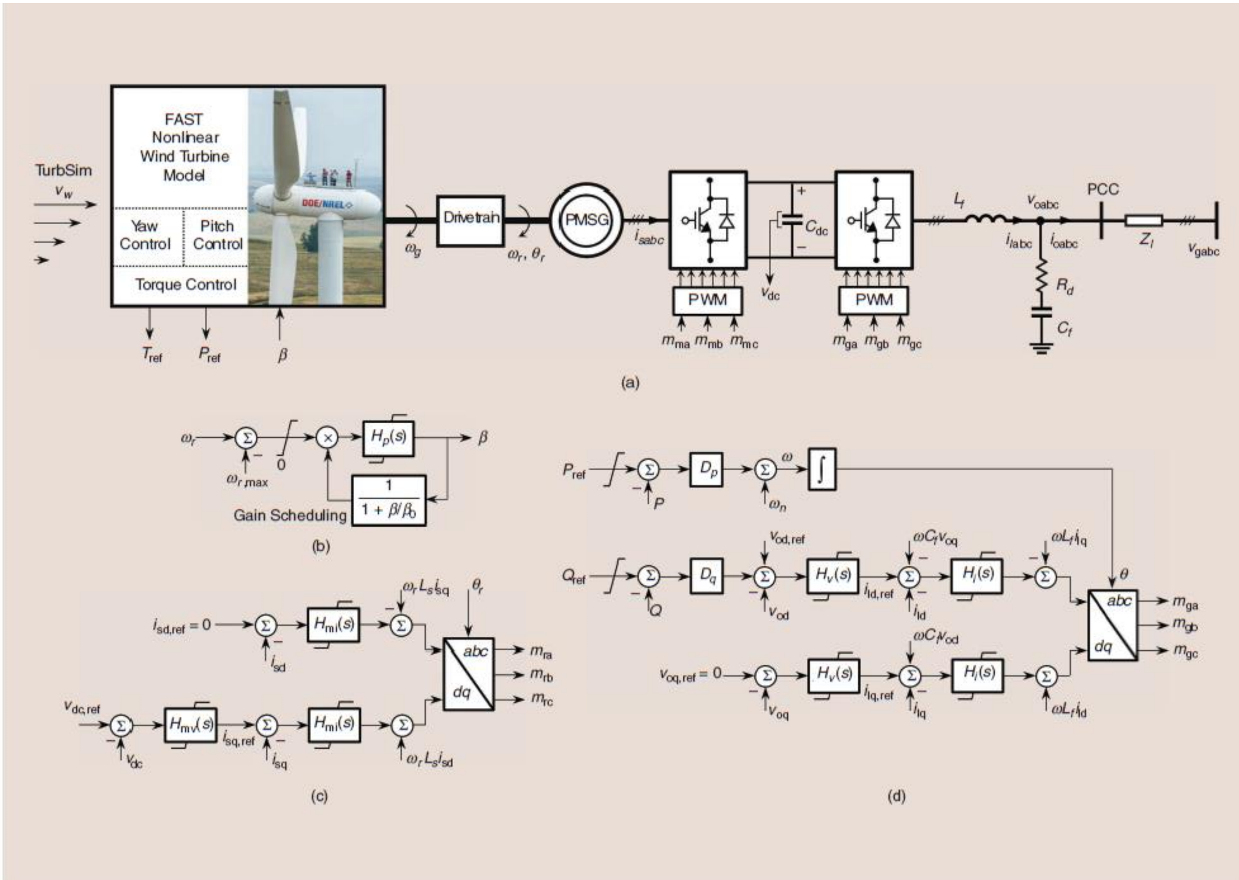


Figure 29. The GFM control for a Type-4 wind turbine generator, including: (a) the circuit diagram of the GFM-controlled Type-4 generator; (b) the turbine patch control; (c) the rotor-side converter control, and; (d) the grid-side converter control [115]

GFM operation presents many advantages. Firstly, it decreases the likelihood of experiencing problems due to sub-synchronous oscillations [134]. When a generator resonates at a sub-synchronous frequency that matches a natural resonant frequency of the electrical system, energy is exchanged between each source. This can lead to torsional stress on the generator shaft and severe damage. GFM operation also permits stable operation in weak grids. This phenomenon is further elucidated in Section 5.6. A final advantage of GFM turbines is that they can operate stably in stand-alone or islanded mode and supply local loads [134]. This is discussed in Section 5.5.

Nonetheless, disadvantages with GFM do exist. Namely, it is more costly and complex. GFM can also result in compromised performance under variable wind speeds. **Figure 30** provides the simulated response of a 2.5 MW Type 3 turbine operating in GFL and GFM mode to a sudden increase in wind speeds from 5 to 12 m/s at t = 10 seconds. In both operating modes, the turbine responds to the change in wind speed by increasing its active power output from 0.4 MW to 2.5 MW (i.e., its rated power). However, the reaction is substantially faster and overshoot is minimized in GFL operation, compared to GFM operation. The observation is explained by the difference in control mechanisms: in GFL mode, current is used to control active power directly, while in GFM mode, the frequency of the stator voltage is indirectly used to modulate active power. Consequently, the response speed for active power control is slower in GFM mode. This also has important implications on the magnitude of mechanical stress to which the turbine will be subjected. Since active power output increases more slowly under GFM operation, the difference between the available wind power and the power generated by the turbine ($P_{wind} - P_{out}$) reaches a larger value, causing the rotor speed to increase more rapidly. Once the rated speed is reached, pitch control is activated. Importantly, the rapid increase in rotor speed subjects the GFM turbine to added mechanical stress. Further research is required to determine the degree to which this might adversely affect turbine lifetimes. Moreover, the implementation of sophisticated pitch control schemes capable of responding to large $P_{wind} - P_{out}$ discrepancies in order to reduce mechanical stress should be investigated.

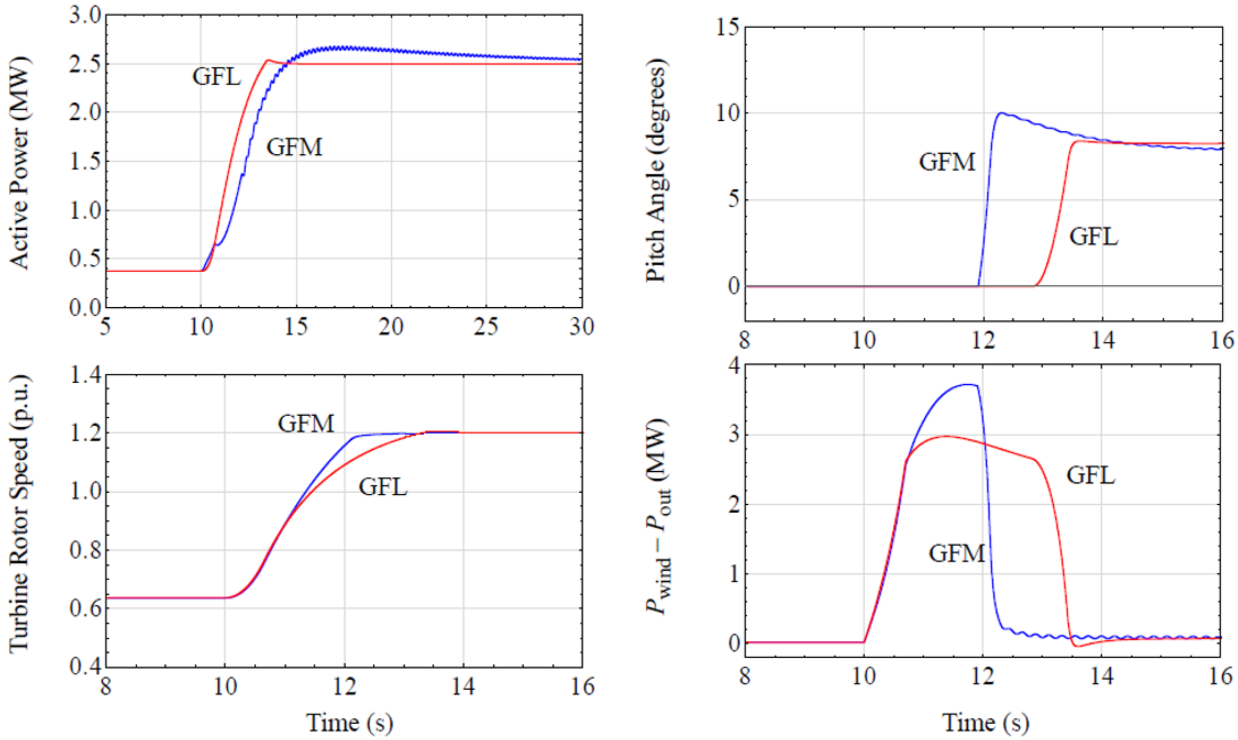
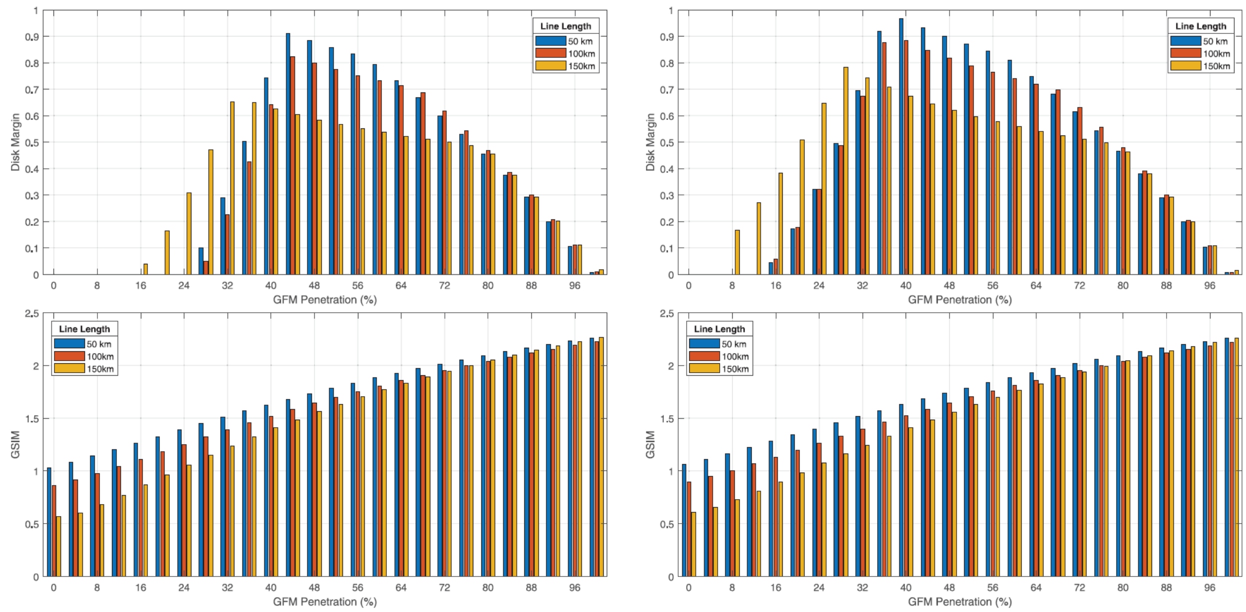


Figure 30. Response of a 2.5 MW Type 3 wind turbine generator operating in GFL and GFM mode to a sudden increase in wind speed from 5 to 12 m/s at t = 10 s [134].

Currently, wind turbine generators are predominantly GFL. However, GFM technologies are on the horizon. Siemens Gamesa has already demonstrated the small-scale operation of several 3.2 MW Type IV turbines in GFM mode [135]. Recently, NREL also performed the first-ever successful demonstration of a Type 3 turbine operating with GFM controls [136].

The share of GFM versus GFL turbines that will ensure system stability remains an important question. A recent study simulated an offshore wind farm made up of 25 turbines to determine the optimal GFM penetration [137]. The analysis relied on two metrics to assess system stability: (1) the grid-strength system impedance (GSIM), where low GSIM indicates that the system has poor damping and is more prone to voltage perturbations, and (2) the disk margin, where low disk margin suggests the system is vulnerable to gain and phase perturbations. The results, given in **Figure 28**, reveal the critical GFM penetration (i.e., the minimum number of GFM turbines required to stabilise the system, such that the disk margin is greater than zero), the optimal GFM penetration (i.e., the penetration that provides the largest robustness or disk margin), and the maximum GFM penetration (i.e., the point after which the disk margin begins to decay rapidly).



(a) 0.5 p.u. active power

(b) 0 p.u. active power

Figure 31. Disk margin and grid-strength impedance metric (GSIM) at increasing GFM penetration levels for an offshore wind farm with 25 turbines and export cable lengths of 50, 100 and 150 km at a) 0.5 p.u. and b) 0 p.u active power [137].

These penetration levels are tabulated in **Table 9** and vary according to active power output and export cable length between 8 – 28% for the critical GFM penetration, 28 – 44% for the optimal GFM penetration, and 68 – 84% for the maximum GFM penetration.

Table 9. Critical, optimal and maximum penetration of GFM turbines according to active power output and export cable length for an offshore wind farm composed of 25 turbines. Tabulated from [137].

Active Power Output (p.u.)	Export Cable Length (km)	Critical Penetration (%)	Optimal Penetration (%)	Maximum Penetration (%)
0.5	50	28	44	68
	100	28	44	72
	150	16	32	80
0	50	16	40	72
	100	16	40	80
	150	8	28	84

5.3.2. Fault Ride-Through

Thus far, this section has dealt with steady state reactive power support; however, transient support is equally important. The intrinsic connection of system voltage to demand can lead to faults in cases of erratic demand behaviour or system failure. For instance, when demand for system power increases suddenly, generators are unable to increase supply instantaneously. As a result, it can trigger the grid voltage to decrease, if even for brief periods of time, until the supply is corrected. Similarly, voltage can increase if demand suddenly drops. These periods of low or high voltage, called faults, are dangerous in that they can damage the electrical components of wind turbines, including the inverters, pitch actuators and controllers. However, disconnection to protect electrical equipment is not always an option. System disturbances cause surges in reactive power demand. Therefore, it is important that generators have some ability to stay connected to the grid when temporary faults occur in order to prevent the widespread loss of generation (i.e., blackouts) and to facilitate voltage recovery by providing reactive power support [117]. Fault ride-through (FRT) refers to the ability of wind turbine generators to remain connected to the grid at voltages lower or higher than the nominal value.

To ensure the resilience of the transmission system, grid codes stipulate requirements for FRT. Since low voltage events are more common and difficult to manage, many grid codes only have requirements for low voltage ride-through (LVRT). Grid code requirements for fault ride-through in Quebec and Alberta are given as examples in **Figure 32**. In particular, wind turbine generators must remain in service for a minimum of 0.15 seconds when the voltage drops to 0% of the rated value in both provinces [121], [138].

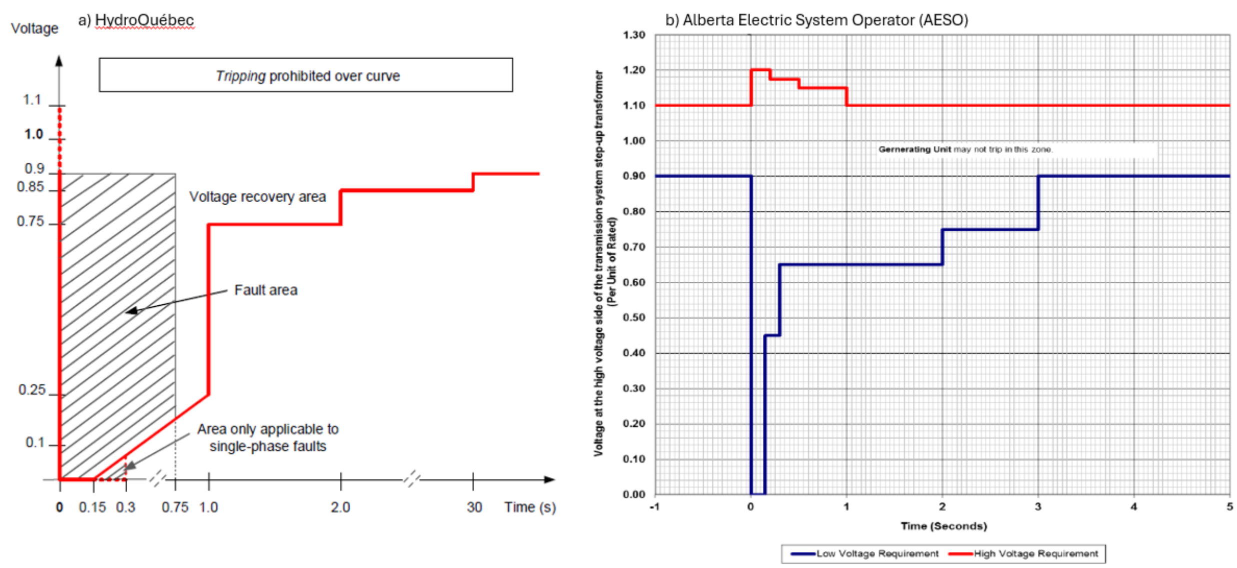


Figure 32. Fault ride-through requirements for wind turbine generators as per the a) HydroQuébec and b) Alberta Electric System Operator (AESO) grid codes [121], [138].

FRT is more challenging for Type 3 turbines than for Type 4 turbines [139]. When faults occur, they can excite high rotor currents in Type 3 turbines, resulting in DC-link overvoltage and failure of the rotor-side converter [139]. To preclude this, self-protective mechanisms are immediately triggered that disconnect the turbine from the grid, inhibiting many of the control functionalities of Type 3 turbines, including reactive power support. Importantly, it also renders the turbine noncompliant to grid codes [139]. In order for a Type 3 turbine to successfully ride through a fault, sequential control objectives are to: (1) restrain the inrush of high rotor current at the onset of the fault; (2) increase the injection of reactive power after the voltage has reached a stable low-point, and; (3) activate voltage control to restore the voltage to its pre-fault nominal value [140].

To accomplish the FRT objectives in Type 3 turbines, several solutions have been proposed, as summarized in **Figure 33**.

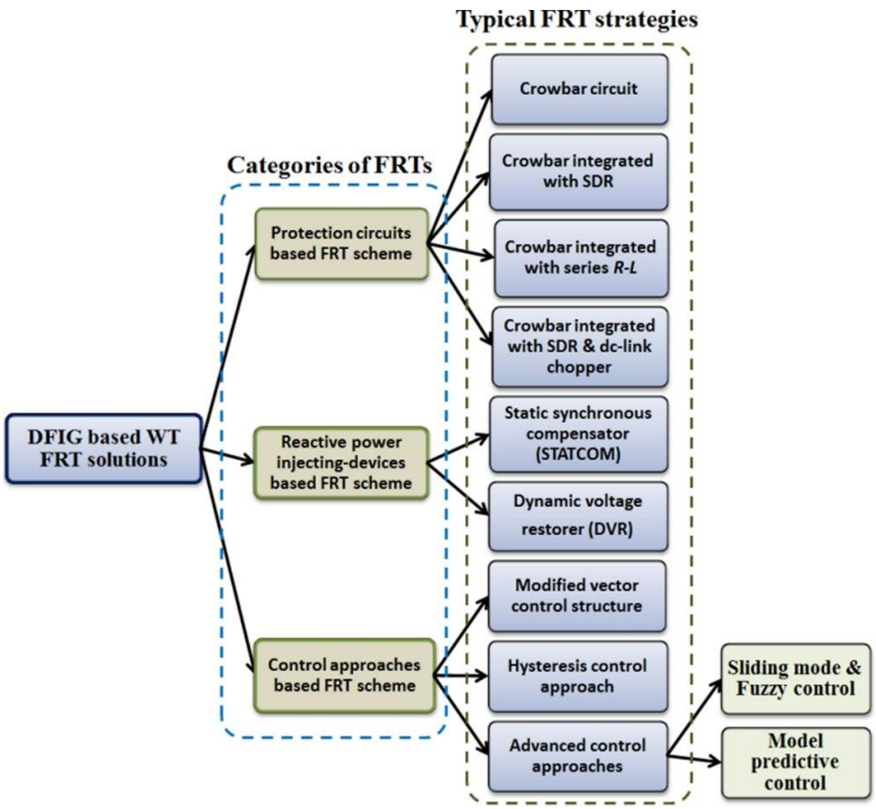


Figure 33. Proposed solutions for achieving fault ride-through with Type 3 wind turbine generators [140].

Crowbar protection constitutes the most commonly applied control scheme for preventing the rotor-side converter from experiencing overcurrent [140]. It allows for the rotor-side converter to be bypassed during voltage sag, but simultaneously disables active and reactive power control, causing large absorption of reactive power and delayed recovery. Recent advancements have incorporated series dynamic resistors (SDR), series R-L circuits and DC-link chopper circuits to limit the time that crowbar protection is activated [140]. However, these additions increase cost and complexity.

To increase reactive power injection following a drop in voltage, external devices are installed at the point of interconnection [140]. Flexible AC Transmission Systems (FACTS) are a group of power electronic semiconductor devices that may be added as auxiliary units on the power line to better support the grid. By employing thyristor valves (older technology) or voltage source converters (newer technology), they can provide rapid control over active and reactive power by manipulating nodal voltage magnitudes and angles, and line reactance [139]. While the VSC-based technology is generally preferred for its faster control, wider operating ranges and smaller size, they are considerably more expensive than their thyristor-based counterparts [139]. Importantly, since FACTS devices are external to the wind turbine generator, they can be used to retrofit existing wind farms that are rendered noncompliant to increasingly stringent grid codes. A study of a Type 3 wind turbine farm found that inclusion of a FACTS static compensator (STATCOM) made voltage restoration faster and reduced associated overshoot and oscillations [141]. Moreover, the STATCOM rating is proportional to the level of support [142].

Finally, significant efforts have focused on improving control strategies to promote ride-through and enhance recovery after a fault has occurred. This is often preferred since it negates the need for additional hardware. Most turbines rely on GFL vector control for regulating power. However, vector control is typically optimized for steady-state operation; additional considerations are required to provide compliant fault ride-through capabilities [140]. For instance, feed-forward transient compensation controls have been introduced to conventional rotor-side converter current regulators such that the rotor output voltage is appropriately aligned with the fault voltage, minimizing the need for crowbar protection [143]. **Figure 34** compares the experimental response to a three-phase fault of a Type 3 turbine that implements feed-forward transient compensation control with one that does not. It demonstrates that under conventional control, crowbar protection is activated (i.e., rotor-side current, I_{RSC}, drops to zero) when the stator voltage, V_s, sags. The crowbar then fails to turn off once the stator voltage has recovered because the inrush of stator current induces overcurrent in the rotor-side converter. This subsynchronous operation absorbs large amounts of active (P_s) and reactive power (Q_s) from the grid, hindering recovery. Contrastingly, the turbine with feed-forward transient compensation control, the magnitude of rotor current overshoots are minimized at the beginning and end of the fault (points E and F). Consequently, crowbar protection is not activated, and the generator is able to successfully ride through the fault and continues to supply active power. It should be noted, however, that the DC-bus voltage drops during the fault. Under more severe voltage sags, crowbar protection may need to be activated to maintain the DC-bus voltage.

More advanced control strategies have been recently proposed, including those that implement nonlinear controllers, model predictive control, and artificial intelligence [144]. However, these come at the expense of increased computational load and make implementation less practical. Therefore, research is ongoing to develop a feasible strategy to support the FRT compliance of Type 3 turbines.

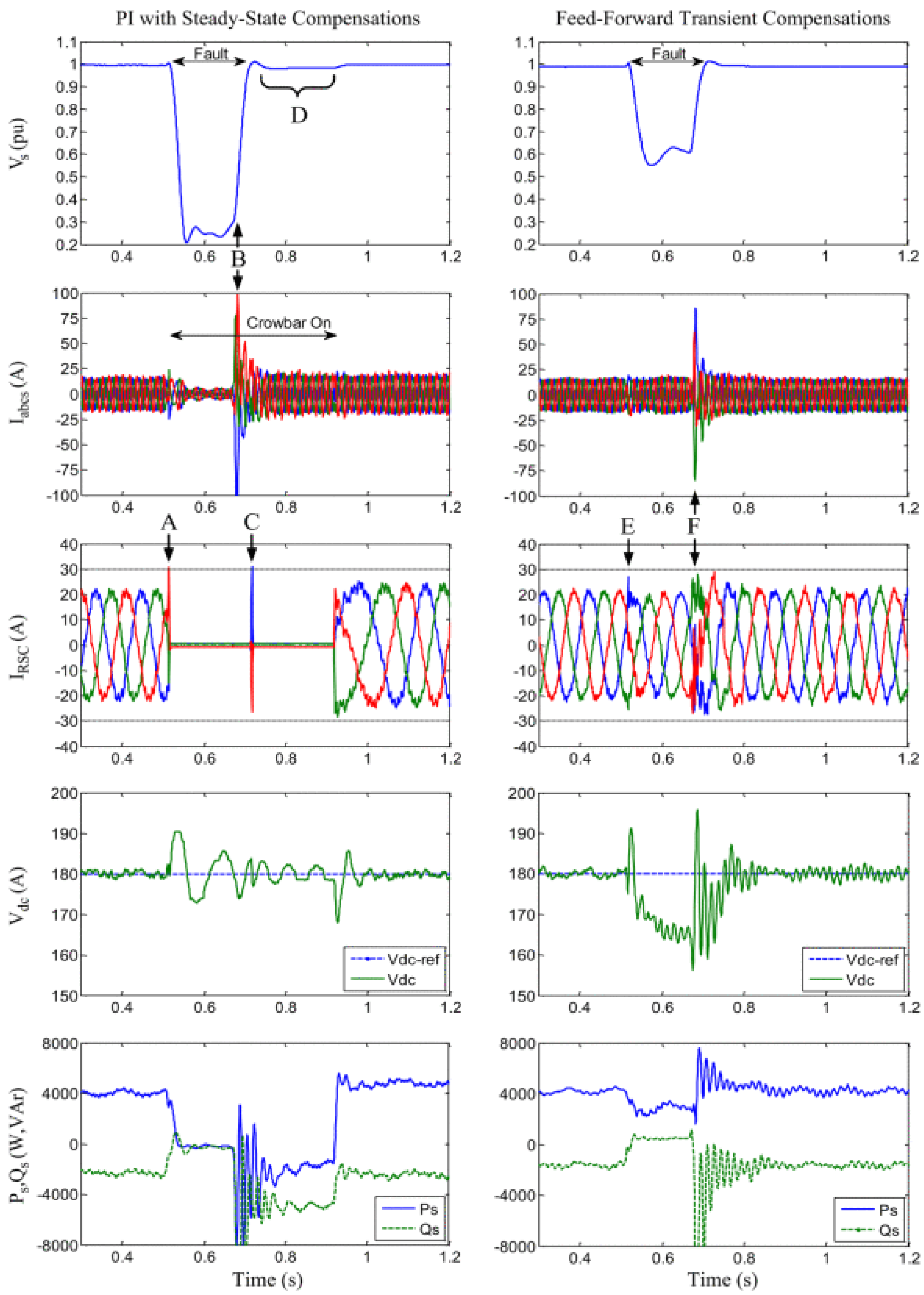


Figure 34. Experimental response of a Type 3 turbine during a three-phase fault, implementing standard vector control or vector control enhanced with feed-forward transient compensations [143].

While high rotor-side converter overcurrent makes Type 3 turbines prone to significant FRT challenges, Type 4 are generally better equipped for FRT. When a fault occurs and the voltage at the point of interconnection decreases, the grid-side converter of a Type 4 turbine will respond by increasing its current to inject more power into the grid. When the drop in voltage is significant, the grid-side converter will reach its upper threshold of current and its ability to inject power becomes limited. Meanwhile, the rotor-side converter will continue to transmit active power to the DC-link capacitor resulting in saturation and stress [145].

The hardware and software-based strategies proposed in **Figure 33** to enhance the FRT capabilities of Type 3 turbines have similarly been applied to Type 4 turbines [145]. However, FRT control strategies for Type 4 turbines have focused more on dissipating excessive energy in the DC-link, rather than on managing rotor-side converter overcurrent. To this end, superconducting fault current limiters (SFCLs) have been applied to minimize the mismatch in power between the grid- and rotor-side converters, thereby reducing the DC-link overvoltage [146]. **Figure 35** demonstrates that implementation of the SFCL significantly reduces the DC-link capacitance voltage, allowing for successful ride-through of a three phase fault. Other researchers have connected energy storage systems to the DC-link capacitor to absorb the excess energy during faults; once the fault is resolved, the stored energy is transferred to the grid, boosting recovery [145]. FACTS devices, braking choppers and crowbar circuits have also been applied [145]. The aforementioned strategies constitute hardware-based solutions, necessitating procurement and increased system costs. Conversely, software-based solutions that minimize the power imbalance between the rotor- and grid-side converters have received significant attention; while they increase system complexity, they have little impact on cost [147].

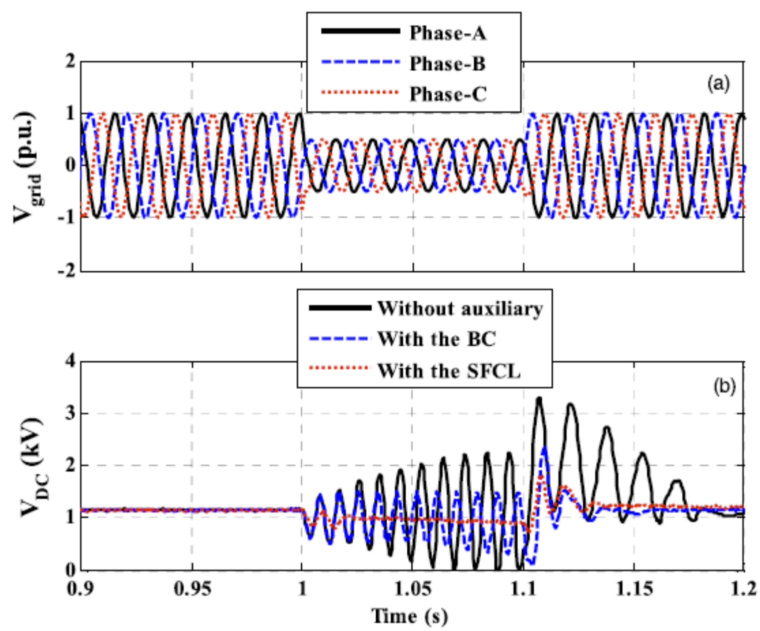


Figure 35. a) Grid voltage and b) DC-link capacitance voltage of a Type 4 wind turbine generator subject to a three phase fault under various FRT enhancement schemes, including braking choppers (BC) and superconducting fault current limiters (SFCL) [146].

5.3.2.1 Short Circuit Contributions

Short-circuiting constitutes the most common type of power system failures [117]. When a generator responds to a fault by contributing large amounts of current, fault ride-through is more challenging. Moreover, it is critical to understand the short circuit contribution of a wind power plant so that its cables and high-voltage switchgears can be appropriately sized and its protection equipment set-points can be defined. Similarly, the thermal short circuit current will dictate the design of electrical lines and protection equipment outside of the wind farm [148]. However, determining the short circuit contributions of wind turbine topologies that use power converters is significantly more complex than for synchronous generators because a constant transient/internal voltage cannot be assumed [148].

To simplify the design process, the IEC released an updated standard (IEC-60909-0) in 2016 that provides a formula for calculating the short circuit contributions of Type 3 and 4 wind turbines. The challenge is that the formulas use input parameters that are based on the proprietary control algorithms of the power converters. These are neither sufficiently understood nor publicly available [148]. To help streamline the wind power plant design process, researchers are using novel approaches to estimate the short circuit parameters required by the IEC guidelines [148].

Type 1 turbines contribute significant short circuit current [109]. The same is true for Type 2 turbines operating below rated slip. However, for variable speed Type 2 turbines, short circuit current is inversely related to rotor resistance; contributions are lower and damping coefficients are higher for higher rotor resistance [109]. Type 3 turbines are capable of controlling their post-fault power system oscillations because their use of power converters decouples the rotor speed from the synchronous speed. However, converter controllability during faults is often compromised, particularly when the fault occurs close to the generator terminals. Error! Reference source not found. a) gives the typical short circuit current contributions of Type 3 turbines when the generator is shorted at its terminals. It demonstrates that Type 3 turbines exhibit large overcurrent outputs (up to 3 p.u. for a three-phase fault) that decay over time [109]. Type 4 turbines are better equipped to handle faults since their power converter separates their generator from the grid. By controlling their current directly, Type 4 turbines can continue to operate in normal mode and can output balanced and symmetrical current (although reduced active power will be delivered as a result of the reduction in system voltage in the event of a fault) [109]. This behaviour is demonstrated for all fault types in Error! Reference source not found. b), where, by design, the short circuit current contribution is limited to 110% of the rated value [109]. Type 5 turbines inject higher levels of fault current than Type 3 and 4 turbines because of the natural response of the synchronous generator [105].

Three-phase faults illicit the largest short circuit currents from all wind turbine types. Therefore, these contributions are used in the design of protection systems.

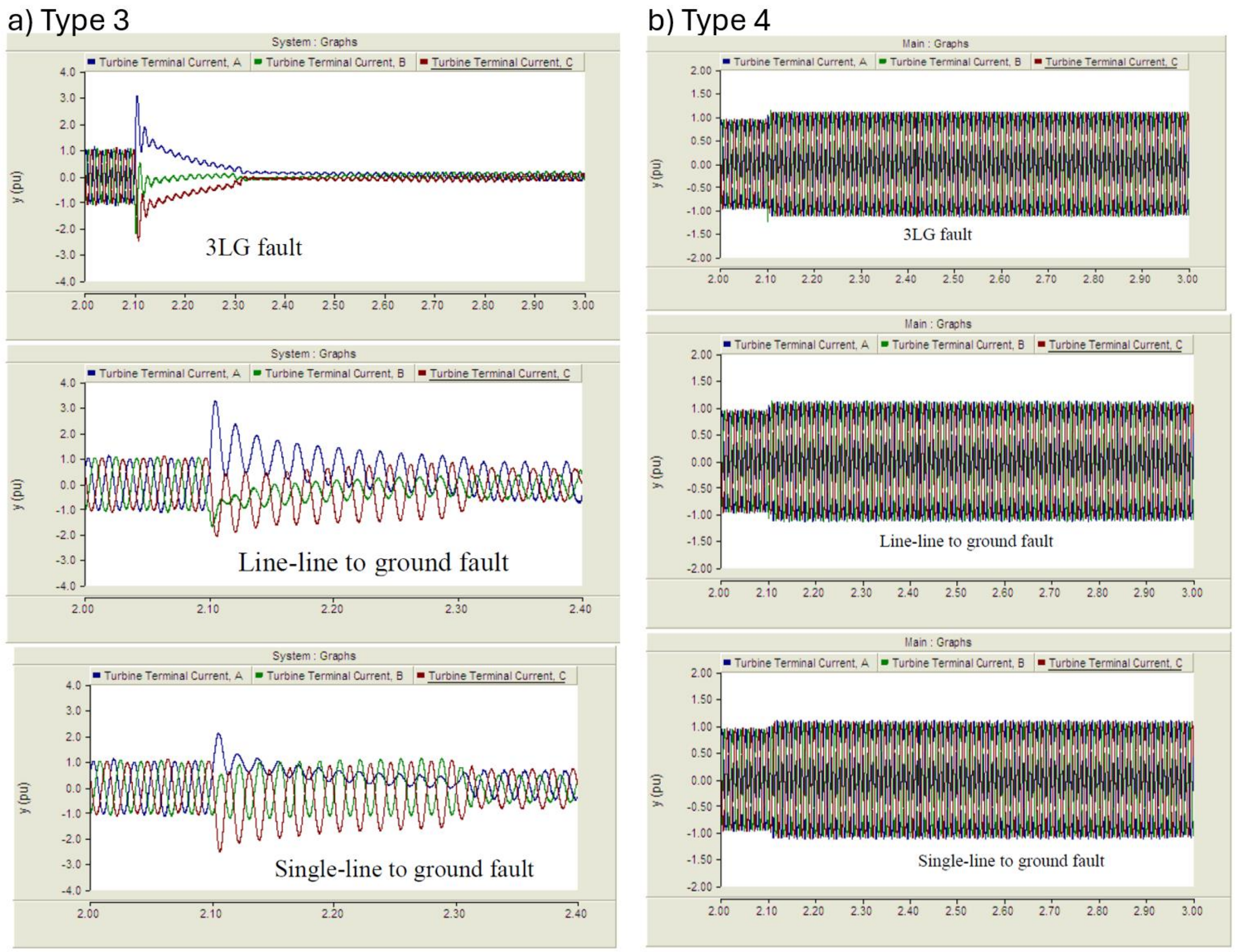


Figure 36. Short circuit current contributions of a) Type 3 and b) Type 4 wind turbine generators to three-phase (3LG), line-line to ground and single-line to ground faults at the generator terminals [109].

Recent real-world disturbances in high-inverter based resource grids have led to important takeaways with regards to the fault ride-through capabilities of asynchronous generators. The 2021 grid failure in Texas, Odessa, resulting from a single-line-to-ground fault on a step-up transformer at a combustion power plant has received particular attention [149]. Prior to the disturbance, wind and solar PV resources comprised 34% (15,952 MW) and 9% (4,533 MW) of the ERCOT generation mix, respectively. While the fault did not directly affect these resources, a severe reduction in inverter-based active power output was observed due to inverter-level tripping or control system behaviours within the asynchronous generators. Solar PV was affected predominantly: its output power was reduced by 1,112 MW. Comparatively, wind output power was only reduced by 36 MW. The loss of power was mainly attributed to perturbations in system voltages and phase angles which caused inverter-based resources to disconnect from the bulk power system. All affected wind turbine generators were Type 3. In response to this major disturbance, NERC has recommended fault ride through guidelines to replace the existing PRC-024-3 standard which outlines the frequency and voltage protection settings for generating resources.

5.4. Power Oscillation Damping

The angular stability of a power system describes the ability of the machines it connects to remain synchronized in spite of disturbances and to maintain or restore the equilibrium between electromagnetic torque and mechanical torque [108]. Angular stability may become compromised under severe disturbances and under minor changes in load or generation. The former is referred to as transient stability and was described in the preceding Section 5.3.2, and the latter is referred to as small signal stability. Due to a lack of synchronizing torque (i.e., related to rotor angle perturbations) or damping torque (i.e., related to speed deviations), small signal instability may arise, resulting in non-oscillatory or oscillatory responses, respectively [108]. In general, the non-oscillatory response has been solved by incorporating automatic voltage regulators in the generators [108]. In contrast, small-signal oscillations can stem from the power system and the generator and must be mitigated with damping control [108].

Since wind turbines are connected asynchronously to the grid or decoupled from the grid via power electronic converters, they do not induce new low frequency oscillation modes into the power system [108]. It is important to note that while this applies to Type 1 – 4 turbines, Type 5 turbines may foreseeably contribute to and be affected by power system oscillations.

Due to challenges associated with active and reactive power control, deep wind energy penetration has the potential to hinder angular stability. Synchronous generators may be forced to carry the burden of providing inertia and damping torque on behalf of the inertia-less grid connected wind turbine generators, resulting in mechanical stress and compromised stability overall. However, modern turbines and appropriate control measures, such as those described herein, can be implemented to mitigate this issue. For instance, since rotor oscillations are visible from the grid frequency signal, wind turbines equipped with appropriate frequency controls can help to enhance damping of the oscillatory modes [108]. Similarly, sophisticated voltage control (e.g., GFM control) can slow active power response and hinder damping control.

While power system oscillations are of less concern with asynchronous wind turbine generators, they are still subject to inner torsional oscillations. These can be induced by the interaction of rotating elements and electrical drives in wind turbines. In modern Type 3 and 4 wind turbines, the drive-train and power converter can contribute to inner oscillations. Drive-train oscillations are somewhat damped by the generator under normal operation. However, variations in wind speed and electrical disturbances near the point of interconnection may incite torsional drive-train oscillations [108].

In order to control inner oscillations, mechanical or converted-based regulation may be applied. In mechanical regulation, oscillations are mechanically damped by regulating the turbine blades via pitch control, by including mechanical dampers in the drive-train or with the use of FACTS devices. Conversely, various torque controllers, including a PID controller that applies a band-pass filter to damp desires frequencies, have been proposed to provide faster oscillatory response [108].

5.5. Black Start and Islanded Operation

Black start refers to the ability of a power plant to self energize in order to restore a power system from a blackout. Hence, black start capabilities are critical for the resilience of electric grids [150].

Currently, black start capabilities reside in conventional power plants that employ synchronous machines with a firm hydro or gas energy supply [150]. While reliable, black start via conventional power plants is slow and fossil-fuel reliant [151]. Presently, inverter-based resources do not participate in the restoration of power grids [150]. However, thanks to their use of controllers, wind turbine generators have the potential to enable comparatively fast and environmentally friendly grid restoration [151]. Further, incorporating black start capabilities in inverter-based resources is a requisite for deep penetration.

Since blackouts are relatively common, wind turbines are generally equipped with an internal energy storage device capable of supplying power to critical components such as safety lights, controllers and switchgears for up to an hour [151]. However, when a wind turbine is without power for an extended period of time, it becomes vulnerable to moisture damage, icing, vibrations at the natural frequency, loss of hydraulic pressure and deformation in the bearings [151]. Consequently, external power supplies are used to periodically activate and energize wind turbine components in order to prevent damage [151]. Additionally, for offshore wind farms, a diesel generator is typically installed at the offshore substation to power auxiliary substation components, permit substation start-up and provide power to the turbines in the case of a prolonged outage [151]. While diesel generators are inexpensive, they pose a threat to oceanic environments and marine wildlife. Preferably, wind turbines could harness the available wind energy to sustain themselves and their substations during blackouts. This is referred to as the islanded operation of a wind turbine and is beneficial for reducing or eliminating reliance on auxiliary power supplies. In fact, any instance where 100% of the load is met by power supplied from the wind farm is considered islanded operation. Therefore, the islanded operation and black start capabilities of wind turbines can also support the operation of remote microgrids or islanded power systems that do not contain any conventional generators.

In order to provide black start and islanded operation capabilities, a wind turbine generator must be (1) equipped with internal power supplies capable of energizing the controllers and converters, measuring wind speed and direction, and powering the yaw mechanism and pitch system, as required for start-up; (2) capable of balancing production under its own variable auxiliary loads (1 – 5 % of rated power, for heaters, pumps, etc.), offshore substation loads and variable wind speeds, and; (3) capable of operating in harmony with up to a few hundred other turbines in order to permit synchronized operation and load-sharing [151].

Many of the patented methods for black start involve the use of a local power source, such as a diesel generator, to start one or a few turbines, such that the energized turbines can then supply the start-up power for the remaining turbines in the farm [152], [153], [154]. A controller in the wind power plant is used to communicate with the turbines and facilitate the coordinated start-up. Following the energization of the initial turbines, the diesel generator is disconnected, enabling the farm to operate as an island. Building on this strategy, other black start and islanded operation patents have eliminated the use of an external generator by relying, instead, on internal energy storage of the wind turbine [155], [156]. Specifically, the use of electrical batteries connected directly to the pitch control system that can enable a turbine to enter into self-sustaining mode within 5 seconds of a loss of grid supply or a period with no wind has been proposed [156].

A key challenge exists in how to synchronize operation between turbines that are not connected to the grid. Early patents proposed that islanded wind power plants rely on the voltage of a single turbine in the farm and synchronize all other turbines to follow this reference turbine [151]. However, the reliability of the proposed methodology is questionable. Grid forming control can endow a wind turbine generator with superior black start and islanded operation capabilities, by enabling it to form the islanded voltage [150]. As described in Section 5.3.1, Type 3 and 4 turbines can be operated in GFM mode by modifying their software and control schemes; no modifications to Type 5 turbines are required.

While several patents have outlined control schemes for enabling black start and islanded operation, many challenges still need to be addressed. For instance, controlling active power outputs at 1 – 5% of rated levels necessitates excessive pitch action and imposes severe mechanical stress on the drivetrain and tower. Alternatively, the use of chopper circuits to limit generation is costly. The trade-off between price and mechanical impact needs to be studied [151]. Challenges associated with active power control in GFM mode, such as those described in Section 5.3.1 (i.e., slower response and added mechanical stress), also remain. This is important in the case where the wind power plant must respond to step changes in load as auxiliary turbine systems and substations are connected and disconnected from islanded operation [151]. Additional challenges include a lack of control strategies for re-energizing transmission lines, maintaining synchronism among turbines during severe transients and surviving low-wind-speed scenarios to prevent a second blackout [150].

The islanded operation of a microgrid resembles transmission system scenarios with deep wind energy penetration. Both face difficulties associated with supplying stable and reliable power. As such, the control strategies described throughout Section 5 for offering frequency support, voltage support, fault ride-through, etc. under high levels of wind penetration and variable wind speeds are also applicable to the operation of islanded microgrids.

Grid codes have yet to mandate that wind turbine generators have black start capabilities. However, as the share of inverter-based resources increases and the number of power plants capable of participating in black start decreases, exigencies are likely to emerge. The European Network of Transmission System Operators for Electricity has already set requirements that power-generating facility owners must provide a quotation for enhancing their generators with black start capabilities at the request of the relevant grid operator [151]. Consequently, significant work is required to advance the black start capabilities and islanded operation of wind turbine generators.

5.6. Connection to Weak Grids

The short circuit ratio (SCR) quantifies the strength of the grid at the point of common coupling (PCC) and is defined as:

$$SCR = \frac{SCMVA\ at\ PCC}{Wind\ farm\ capacity} \tag{6}$$

where SCMVA is the apparent short circuit power, which is defined as the product of the voltage and current before and after a fault, respectively.

High SCRs indicate that the grid is resilient to turbine generator problems because the power generated by the wind farm is not significant compared to the total amount of power available at the PCC. Conversely, low SCRs (i.e., ≤ 3 [157]) indicate that voltage at the PCC will be seriously impacted by the active and reactive power of the generator, resulting in increased susceptibility to voltage fluctuations, flicker and harmonic emissions.

Turbine installation is prioritized in locations where wind resources are favourable and vacant space is abundant. Therefore, preferred sites are often remote or offshore – areas where the grid tends to be weak (i.e., short circuit power is limited). Consequently, wind farms often suffer from low short circuit ratio connections, necessitating either reduced active power generation or enhanced reactive power control [139], [158]. To promote efficient operation and cost-recovery, improving reactive power control is prioritized.

Under strong grid connections, Type 3 and 4 turbines are considered to offer sufficient steady state reactive power control (as per the current grid codes). However, the reactive power support of Type 3 turbines may be inadequate in weaker grids [159]. Since these are currently the most commonly deployed turbines, mitigation measures in the form of external support are required to ensure grid stability. The deployment of FACTS devices and the implementation of GFM control have been proposed as potential solutions.

NREL studied the impact of grid strength on a Type 3 turbine operating in GFM mode during a variation in wind speeds [134]. **Figure 37** gives the turbine's active power output under a) a weak grid with SCR = 4 and b) a strong grid with SCR = 8 when the wind speed increases rapidly at t = 30 seconds. The simulation results demonstrate that stable operation is supported by the GFM turbine in the weak grid. This is a major advantage of GFM operation, particularly as inverter-based resource penetration increases and grids are rendered weaker. Conversely, the GFM turbine operates unstably in the strong grid. This behaviour is attributed to the voltage-source nature of GFM turbines, which requires sufficient impedance between the wind plant and the grid [134]. GFM instability in very high strength grids can therefore be mitigated by using reactors or high-impedance transformers to maintain sufficient grid impedance [134].

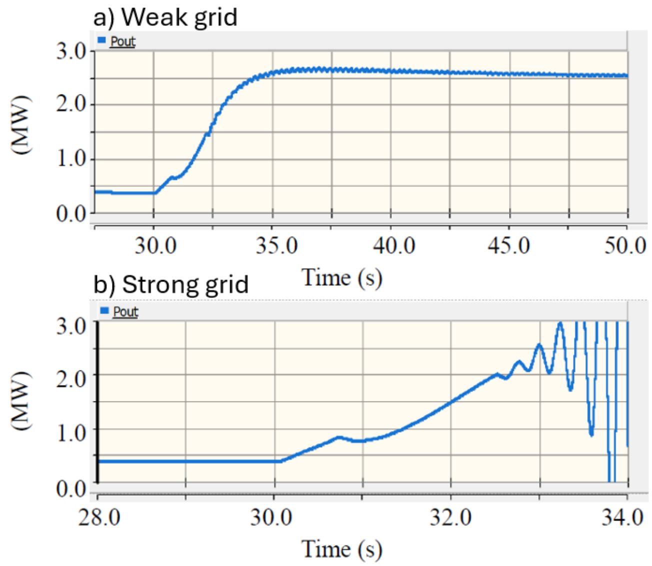


Figure 37. Active power output of a Type 3 wind turbine generator operating in GFM mode during a sudden increase in wind speeds at t = 30 s under a) a weak grid with SCR = 4 and b) a strong grid with SCR = 8 [134].

5.7. Transmission Infrastructure for Offshore Wind Integration

To take advantage of the faster wind speeds and nearly unbounded available space that can support larger capacities, offshore wind farms are pushing the envelope towards increasingly long-distance transmission. Consequently, advanced power transmission technologies are required to prevent losses over long distances while ensuring stable connections. Presently, there are three candidate transmission technologies.

1. **High voltage alternating current (HVAC)** transmission is popular because it is mature and cost-effective. A converter matches the variable frequency of the AC current output by the wind turbine generator to the synchronous frequency of the grid. The current is transmitted onshore through submarine cables and passed through a step-up transformer to increase its voltage. However, the high capacitance of the HVAC cables generates reactive current, resulting in power losses that are proportional to distance. **Figure 38** plots the relationship between transmitted power and distance for HVAC cables and demonstrates the severity of power losses that increase dramatically with distance. Consequently, as wind farms are built further and further offshore, HVAC transmission power losses become increasingly significant and may no longer be a viable option [160].

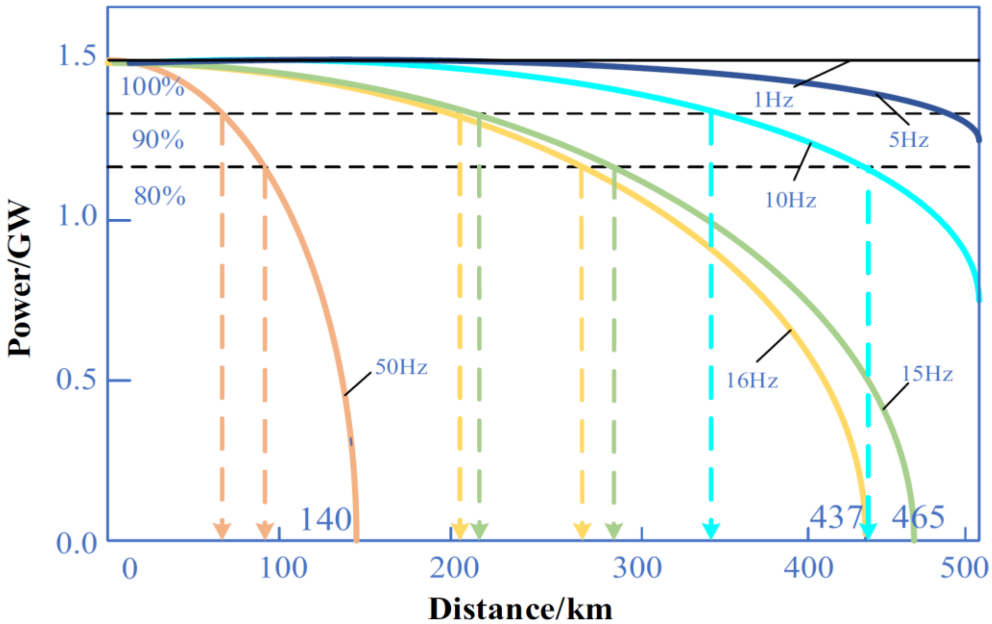


Figure 38. Maximum amount of active power that can be transmitted by HVAC cables as a function of transmission distance and frequency [160].

2. **High voltage direct current (HVDC)** transmission is more efficient than HVAC transmission (since it does not fall victim to capacitance effects), and consequently becomes more cost-effective at large transmission distances. However, HVDC transmission is inherently more complex as it requires offshore converter stations [160]. Voltage source converter HVDC (VSC-HVDC) transmission is applied to connect most of the large offshore wind farms across the world. Importantly, its use of power electronics supports black start (unlike some other HVDC topologies). The biggest challenge with HVDC transmission is the difficulty of building and servicing large offshore stations.
3. **Low-frequency alternating current (LFAC)** or fractional frequency alternating current (FFAC) transmission is a novel take on HVAC transmission technology that reduces the power frequency to one-third of its original value. As a result, it limits system complexity while improving the transmission capacity. An onshore back-to-back converter converts the low frequency to the frequency of the grid. However, LFAC transmission has yet to be commercially deployed for offshore wind farms [160].

Transmission distance is the main factor that influences the selection of integration technologies. **Figure 39** demonstrates that for transmission distances less than 60 km, HVAC technologies should be applied; above 80 km, HVDC is more cost-effective [160]. LFAC demonstrates great potential to support transmission at distances between 60 and 200 km, however field testing is required to ascertain its suitability [160].

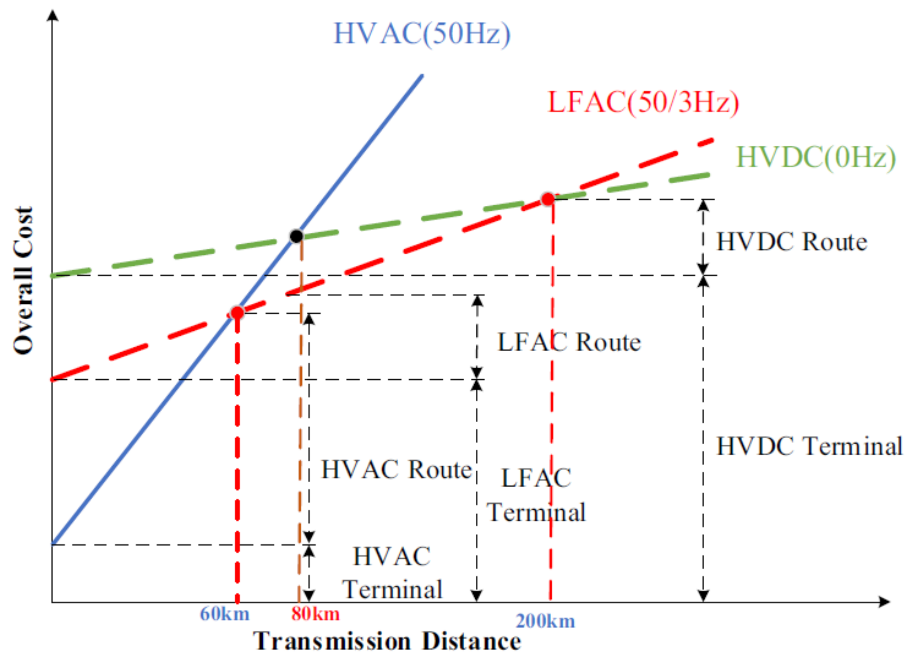


Figure 39. Cost of offshore wind farm transmission technologies as a function of transmission distance [160].

The inclusion of FACTS devices such as a STATCOM is also beneficial for Type 3 offshore turbines requiring long distance connections (>100 km) [139].

5.8. Energy Storage Systems

The inherent intermittency and variability of wind energy poses a challenge to large-scale grid integration and the provision of ancillary services. However, the application of energy storage systems (ESS) has the potential to solve many of the outstanding reliability issues [161].

The principal objective of a power system is to maintain the balance between electricity generation and load. Currently, grid operators reserve a margin of their thermal (i.e., coal and gas) and hydro generation to account for the variation in renewable energy resources. In future net-zero grids, active power curtailment will be required to provide ramping flexibility. To avoid inefficiencies and make curtailments more economical, ESSs should be applied complementarily. When available wind power is in excess of demand, ESS can be charged. In this way, stored energy can be used to supplement active power when wind speeds are low or loads are high, minimizing the level of constant de-rating required. Consequently, ESS can help with frequency regulation and dispatchability.

ESSs are either high capacity, wherein power is discharged over long periods of time, or high power, wherein power is discharged rapidly. From a wind energy grid integration perspective, the rapid response characteristics and improved cyclability of high power ESSs are more attractive for addressing the frequent short-term fluctuations of the power system [162]. Examples of high power ESSs include flywheels, certain batteries, supercapacitors and superconducting magnets [162]. Conversely, high capacity ESSs should be applied for long-term energy management, such as for time-shifting and non-spinning reserve supply [163]. These include pumped hydroelectric storage, compressed air power plants, fuel cells, and certain batteries [162]. **Table 10** summarizes the grid integration applications according to ESS types.

Table 10. Grid integration applications of energy storage systems. Modified from [163].

Application	Time scale	Examples of Suitable ESSs
Energy arbitrage, load leveling	Hours – days	• Pumped hydro storage • NaS batteries • Compressed air energy storage • Fuel cells
Frequency regulation	Seconds – minutes	• Li-ion batteries • NaS batteries • Flywheels • Fuel cells
Oscillation damping, voltage support, LVRT	<1 second	• Lead acid batteries • NaS batteries • Flywheels • Fuel cells • Superconducting magnets
Primary reserves	~10 minutes	• Pumped hydro storage • Flywheels • Batteries
Secondary reserves	Minutes – hours	• Pumped hydro storage
Emergency power supply, black start	Minutes – hours	• Lead acid batteries

To facilitate electricity arbitrage, an ESS can be charged during off-peak generation and discharged during on-peak generation, so as to flatten loads and balance energy costs [163]. Similarly, researchers are investigating the use of curtailed power from renewables for the production of green hydrogen [164].

ESSs can help to provide frequency regulation by supplying active power according to droop controls or commands. Without an ESS, frequency regulation is possible provided that energy is curtailed constantly to permit ramping. By applying an ESS, the amount of curtailed energy can be reduced since stored energy can be used for ramping. The use of an ESS to coordinate frequency control across multiple wind turbines is presented in **Figure 40**. The simulation results demonstrate superior frequency control under the energy storage configuration for geographically distributed wind turbines exposed to varying wind speeds (as per the turbine output power) [165].

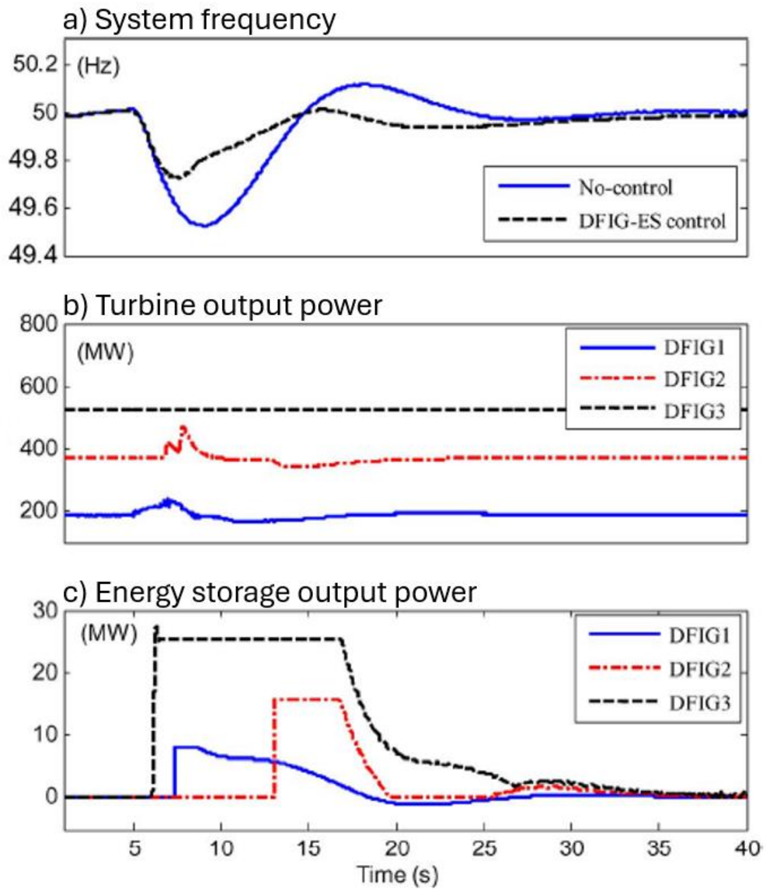


Figure 40. Coordination of active power control across three Type 3 wind turbine generators using energy storage [165].

ESSs can also be used for low voltage ride-through, as briefly described in Section 5.3.2. For Type 4 turbines, subject to DC-link overvoltage, an ESS can be applied to absorb the excess power, permitting successful fault ride-through. This is the case for the simulated turbine in **Figure 41** after experiencing a severe voltage dip of 70% [166]. In particular, by harnessing a supercapacitor energy storage system, the DC-link voltage experience only a small oscillation at the onset and end of the fault. **Figure 41** also demonstrates the mechanism by which this occurs: the power transferred from the generator to the grid is set to a maximum permissible value, according to converter constraints, and the remaining excess power is used to charge the supercapacitor.

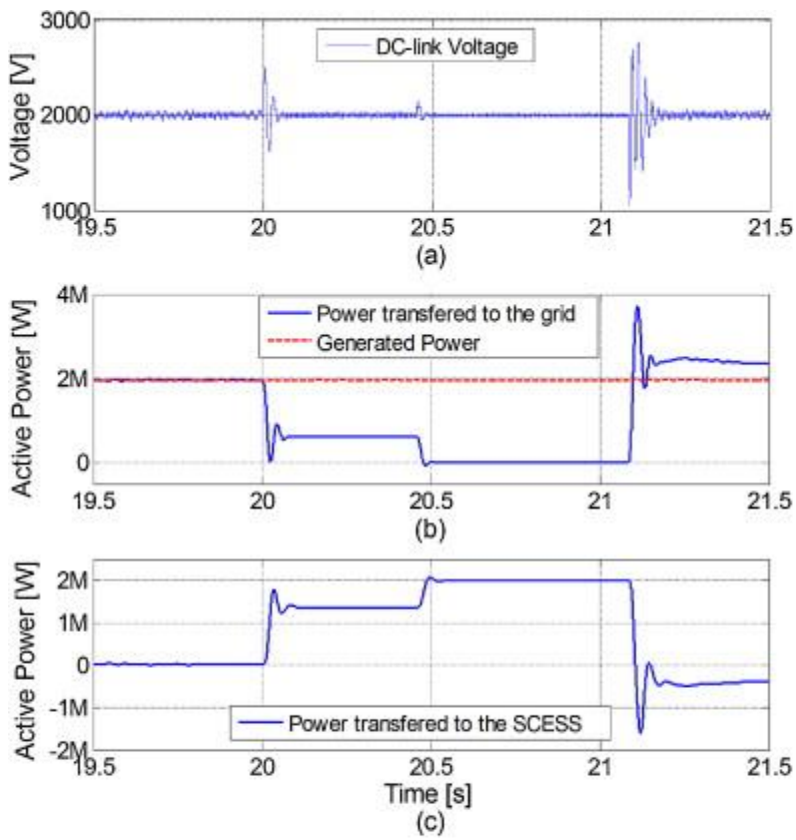


Figure 41. Fault ride-through capability of a Type 4 turbine enhanced using a supercapacitor energy storage system (SCESS) to prevent DC-link overvoltage [166].

Reserves are stores of energy that can be accessed at time scales from minutes to hours to meet power demands in cases of emergency. Due to the significant forecast error associated with wind energy, reserves can help to increase power reliability.

ESSs can also serve as emergency power supplies for the black start of wind turbine generators, as previously described in Section 5.5. Importantly, advancement of energy storage systems in this regard can help to displace the diesel generators used more conventionally. This is particularly important as offshore wind deployment increases.

Many challenges remain in harnessing ESSs to facilitate the grid integration of wind turbine generators. Namely, the ESS often costs as much as the turbine [161]. Consequently, adoption will require a very strong use-case or the emergence of more cost-effective ESSs. To keep costs at a minimum, many studies have investigated the optimal sizing of ESSs for wind farms. Typically, these have been performed for battery technologies. Findings suggest that the ESS should be sized at 15 – 25% of the wind farm's rated capacity in order to smooth fluctuating wind power and provide effective dispatchability [163]. In this case, it is more economical to curtail some wind energy than to oversize the ESS to store surplus energy [167].

5.9. Passive Systems

Distributed wind energy conversion systems are receiving significant attention for their potential to support autonomous energy production and electrification in remote communities where the cost of utility grid connection is prohibitive. Optimization of wind turbine generators for these applications aims to maximize energy harvesting and reduce costs. Power electronic converters and sophisticated algorithms enable maximum power point tracking under variable wind speeds in conventional grid-connected turbines. However, power electronics are both costly and prone to failure. Consequently, researchers are looking into the implementation of passive wind turbine generators that negate the need for converters and other electrical control devices. Permanent magnet synchronous generators, such as those used in Type 4 wind turbines are popular for small-scale wind generators as a result of their simplicity and high power density [168]. They are adapted for passive operation and connected directly to DC loads or batteries via passive diode rectifiers [168], [169], [170], [171]. Importantly, maximum power point tracking and efficiencies similar to conventional generators were achieved with the optimized passive systems [168].

6. Outlook and Recommendations

In general, wind turbine technologies have evolved to meet the grid support functionalities required by the grid codes that have jurisdiction over them. However, whether current grid codes are sufficiently stringent to support the deep penetration of inverter-based resources required in the future net-zero grid is an important question. For instance, today's wind turbines allow for a certain quality of voltage support, frequency support, fault ride-through, etc. However, the contributions of the quality of these individual services to permissible penetration levels remains unclear. Elucidating which grid services are limiting deep penetration could help to efficiently guide future research and development. Consequently, leveraging advanced transient modelling tools to study the effects of wind energy deployment on system-wide stability is crucial. The level of penetration that would be supported by turbines complying with current Canadian grid codes is also unclear. Analyses to this effect could help to inform whether the realization of Canada's net-zero future will necessitate a revision of grid codes or advancements in turbine control technologies. Moreover, it could help to set reasonable penetration constraints in the capacity expansion energy models used for policymaking.

But power system simulations with wind turbine generators are not straightforward. In order to obtain useful results, the mechanical, aerodynamic and control aspects of the wind turbine generator, as well as wind speed variations need to be included in the model. Importantly, this type of simulation could provide additional insight into how the intermittency of wind energy is expected to affect grid stability under deep penetration scenarios. However, the types of expertise required for these sophisticated simulations are not frequently found in one individual. Consequently, the formation of multidisciplinary work units is likely required.

Moreover, this review revealed several key gaps in the literature that should be bridged in the near-term to facilitate further grid integration. Firstly, the majority of the stability studies conducted to-date focus on the grid support provided by a single wind turbine generator. Extrapolation is then used to draw grid-level conclusions. While this type of study forms a crucial starting point for analysis, there is a clear need to perform stability studies at the wind farm-level, rather than the turbine level.

Similarly, the interactions between several wind farms, other inverter-based generators, like photovoltaics, energy storage systems and the grid should be thoroughly investigated. Secondly, most grid stability analyses are conducted in the virtual domain – field tests are extremely limited. Therefore, there is a need to validate simulation results by conducting real-world experiments.

Additionally, the expansion and coordination of transmission networks is expected to be important in efficiently accommodating wind energy generators. Notably, if generators are spread across increasingly large areas, and are all connected via coordinated transmission networks, the impacts of wind variability are expected to be reduced, according to the principles of geographical averaging. Transmission network considerations are equally important for the integration of offshore wind turbines. As a result, optimization of the transmission infrastructure in Canada will permit significantly more efficient use of available resources.

Controls and hardware must be added to modern Type 3 and 4 wind turbine generators such that they can provide appropriate levels of grid services. However, the feasibility of performing large-scale retrofits has not been assessed. Replacing the existing turbines with Type 5 turbines constitutes another potential solution. The logistical and economical aspects of both scenarios should be compared.

In addition to the conclusions drawn with regards to grid services, this review revealed several other considerations that may impact grid integration. Firstly, a lack of resources exists for promoting distributed wind, including limited access to applicable data and models. Furthermore, as the end-of-life of the first-ever installed turbines looms, net-zero options for decommissioning need to be reviewed. While recycling is often a preferrable option, transportation of large blades to recycling facilities can offset emission benefits. Therefore, the feasibility of recycling wind turbine blades in Canada should be evaluated from a cost and environmental perspective. Moreover, it was noted that several of the materials required in the construction of wind turbines are vulnerable to supply chain disruptions. It is important to review the availability of these critical materials from a Canadian context and to bolster the security of high-risk supply chains such that net-zero target relying on increased wind turbine deployment are not jeopardized. Finally, global warming is anticipated to yield increasingly severe weather events, higher sea levels, changes in the migratory behaviour of wildlife, etc. Consequently, the expected impact of climate change on wind turbines in Canada should be studied and appropriate mitigation measures should be established to ensure resiliency.

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8. Appendix A – Wind Turbine Manufacturers

Table 11. Summary of wind turbine manufacturers, models and deployment locations in Canada [41].

Manufacturer	Model	Deployment Location
Acciona	AW-3000/116	Nova Scotia
Acciona Wind Power	AW-1500/77	New Brunswick
Acciona Wind Power	AW116/3000	Prince Edward Island
Bonus	AN 150/30	Alberta
Bonus	B23/150	Yukon
DeWind	DeWind 9.2	Prince Edward Island
Enercon	E-40/600, E-70/2300, E-70 E4, etc.	Alberta, British Columbia, Northwest Territories, Nova Scotia, Ontario, Quebec, Saskatchewan
EWT	DW52, DW54	Nova Scotia
Gamesa	G90/2000	Alberta, Ontario
GE	GE 1.5SLE, GE 1.6-100, GE 1.6 XLE ,etc	Alberta, British Columbia, Nova Scotia, Ontario, Quebec,
Lagerwey	LW750-52, LW52	Alberta, Ontario
Leitwind	LTW77-1500	British Columbia
Nordex	N60/1300	Alberta
NEG Micon	NM48/750	Quebec
Northwind	100B	Newfoundland and Labrador
Pfleiderer	PWE 650	Ontario
Samsung Renewable Energy	25xc	Ontario
Senvion	3.2 M114, MM92, MM82	British Columbia, Ontario, Quebec
Siemens	SWT-2.3-101, SWT-2.3-93, SWT-2.3-113	Alberta, Manitoba, Ontario, Quebec, Saskatchewan
Suzlon	S97/2100	Nova Scotia
Tacke	TW 600	Ontario
Turbowinds	T600-48	Nova Scotia

Vensys	V62, V77	Nova Scotia
Vestas	V44/600, V90/3000, V80/1800, etc.	Alberta, British Columbia, Manitoba, New Brunswick, Newfoundland and Labrador, Nova Scotia, Ontario, Prince Edward Island, Quebec, Saskatchewan, Yukon
Windmatic	WM15S	Newfoundland and Labrador

9. Appendix B – Research Questions

Table 12. Research questions identified in completing this literature review. Urgency is defined on a scale from 0 – 10, where 10 indicates that the concern is presently impacting the grid and 0 indicates that a concern will not foreseeably impact the grid. Importance is defined on a scale from 0 – 10, where 0 10 indicates that the issue threatens the normal operation of the entire grid and 0 indicates that it poses no threat to any portion of the grid or is out of scope of the SRES project. Effort is defined on a scale from 0 – 10, where 10 indicates that answering the question would require a significant amount of effort and 0 indicates that no effort is required,

Service/Concern	Research Questions	Urgency	Importance	Effort	Priority (U&I)	Priority (U&I&E)
Grid Forming Operation	What share of GFL or GFM turbines can support power system stability? What are the ramifications of GFM operation with regards to frequency response/active power control?	7	9	5	79.4%	72.3%
Frequency Regulation and Reserve	What reserve requirements keep active power and frequency within acceptable bounds? (i.e., commanded de-rating, curtailment) Under these levels of reduced output, how can efficiency be maximized? (energy storage, H2 production, etc.) How much spinning/non-spinning reserve does a system need in the presence of Type 3, 4 and 5 (GFL and GFM) turbines?	9	9	7	90.0%	68.7%
Retrofits for Grid Services	What is the feasibility of retrofitting existing Type 3 and 4 wind turbines with controls that enable them to provide grid services?	6	9	6	73.5%	64.6%
Emissions	To what extent are a wind turbine's life cycle emissions impacted when it is equipped with controls for providing grid services? How is required maintenance impacted? How does this impact LCOE?	8	7	7	74.8%	60.7%
Wind Speed Variability	How is the variability of wind speeds expected to impact grid stability? How can forecasting, reserves, energy storage and curtailment help to mitigate this? Are different controls/measures needed to support a stable grid in areas of low/high variability?	8	8	8	80.0%	57.7%

Penetration Levels	Given the current wind turbine technologies, what level of penetration could be supported while maintaining a stable grid? What penetration levels are supported for GFM vs. GFL. vs. Type 3, 4 or 5 turbines? Which grid services (FRT, frequency support, etc.) are limiting penetration?	9	10	9	94.9%	56.5%
Islanded Operation	Are turbines capable of switching between grid-connected and islanded operation modes? How is stability maintained during islanded operation?	6	7	7	64.8%	55.2%
Impacts to LCOE	How are capital and operating costs of turbines impacted by the addition of controls? How is life span impacted? What does this do to LCOE? Does the technology remain competitive?	8	9	9	84.9%	52.4%
Type 5 Wind Turbine Generators	When are Type 5 turbines expected to enter the market? What technological limitations are currently preventing commercialization? What will be the cost? How does Type 5 turbine penetration enhance grid stability? What are the minimum levels of Type 5 turbines in stable, all-IBR grids?	5	7	7	59.2%	51.9%
Energy Storage	How should energy storage systems be sized to accomodate ramping and black start capabilities? How does wind speed variability impact the size of energy storage required?	9	5	9	67.1%	44.8%
Offshore Wind	How are grid services provided by offshore wind turbines? Are there any limitations in providing grid services caused by the geographic location (or other factors) of offshore wind turbines?	6	7	9	64.8%	43.8%
Turbine vs. Farm Control & Interactions	How do wind turbines in a farm interact during voltage and frequency disruptions? How is support provided at the farm-level vs. the individual turbine level?	8	9	10	84.9%	41.6%
Black Start Capabilities	In high-IBR grids, are wind turbines expected to provide sufficient black start capabilities? How can they supply the transformer, cold-load and other inrush current needed? Given their low over-current apability, will theybe able to withstand the inrush of current? What size/type of energy storage is required? How is black start affected by variable wind speeds?	9	7	10	79.4%	39.8%

Coordinated Control	How is do controls differ at the turbine level versus the farm level? To what extent are auxillary FACTS devices required? How is control coordinated between all of these?	6	8	10	69.3%	36.3%
Grid Codes	Are current grid codes sufficiently stringent to support the deep penetration of IBRs? How are grid codes expected to evolve? Will wind turbine technologies be capable of meeting future grid code demands?	7	3	9	45.8%	34.8%
Monetization of Grid Services	What is the potential for monetizing the ancillary services provided by wind turbine generators? Is monetization required to drive manufacturers to enhance controls? Is policy required?	6	6	10	60.0%	33.0%
Climate Change	What is the expected impact of climate change on wind turbines in Canada? Can existing turbines be retrofitted to withstand climate changes? What mitigation measures need to be established to ensure resiliency of turbine components and transmission infrastructure?	5	1	7	22.4%	27.1%
Recycling	What is the feasibility of recycling wind turbines in Canada in terms of logistics and cost? Are the net associated emissions positive or negative?	8	0	7	0.0%	0.0%
Critical Materials	Is the availability of critical materials for wind turbine manufacturing expected to be a barrier to net-zero emissions in Canada, by preventing deployment?	2	0	5	0.0%	0.0%

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