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Yukon Development Corporation-

Putting Next Generation Hydro in Context: Other Solutions to Meet Yukon's Long Term Energy Future

Submitted By: Midgard Consulting Incorporated

Date: 13 November, 2015

Executive Summary

The Yukon Development Corporation ("**YDC**") has hired Midgard Consulting Incorporated ("**Midgard**") to complete the report *Putting Next Generation Hydro in Context: Other Solutions to Meet Yukon's Long Term Energy Future*. The report is intended to help inform the public regarding the types of decisions and tradeoffs necessary to fulfill the Yukon's need for new electricity sources and to support the Yukon's continued economic growth and development based on meeting the following objectives:

1) Provide a context for Next Generation Hydro ("**NGH**") projects, by presenting impacts and tradeoffs of a variety of alternative supply options
2) Promote a fact-based conversation around the potential solutions and alternatives
3) Provide a consistent, apples-to-apples comparison between NGH and alternative energy supply options.

To inform the tradeoffs and decisions facing the Yukon as it meets its growing electricity needs, a multi-step process was followed to:

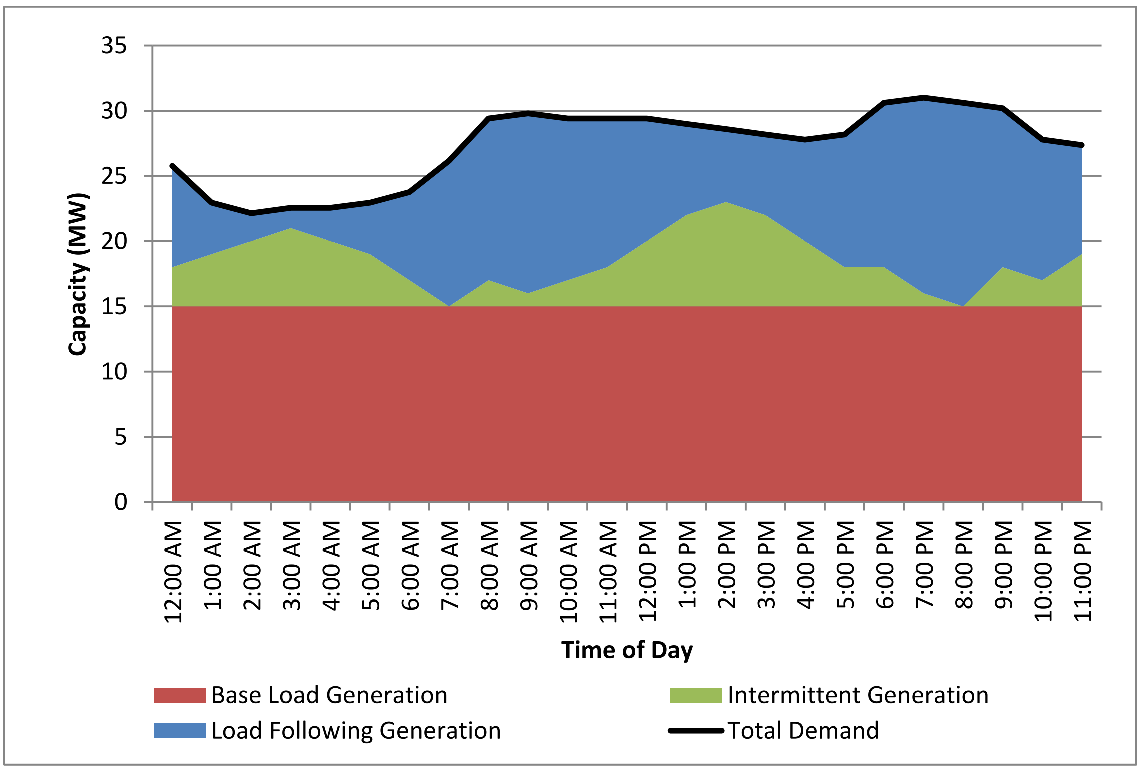
1) Define the electricity need (Figure 2 & Table 1)
2) Define the factors of interest and evaluation criteria (Figure 3).
3) Compare the resource options (Table 2).
4) Create energy development scenarios (Table 4)
5) Summarize the scenario results (Table 5)

After evaluating the scenarios on the basis of the evaluation criteria, Table 5 shows that all of the generation scenarios have the potential to meet the forecast average energy and capacity needs of the Yukon in a socially acceptable manner. However, all of the generation scenarios also have certain advantages and disadvantages that make the decision about which generation types to pursue a selection among tradeoffs. Therefore, after evaluating the scenarios Next Generation Hydro remains a viable candidate for further consideration because NGH has similar economic cost when compared to other generation options, zero Greenhouse Gas ("GHG") emissions from electricity generation, and it meets the Yukon's need for electrical winter energy and capacity from 2035 to 2065.

It is important to state and emphasize that this review is not a utility resource plan and it does not, in any way, restrict the utility resource planning necessary to "keep the lights on" and ensure that there is a reliable electrical grid for the Yukon. Rather, this report is a discussion of the different supply options available in the Yukon and their tradeoffs in terms of high level economics, usage, and environmental and social acceptability.

Electric generation assets are often grouped by their attributes with respect to capacity and energy. Assets that have dependable capacity (also called "firm" or "dispatchable" energy) are those assets that can be called on at any time to generate power (e.g. hydroelectricity with storage, natural gas, and diesel). Assets that generate power only when their fuel supply is available, and not necessarily when the energy is required by the load, are called intermittent generators because they typically rely on less predictable natural resources to provide fuel for generation (e.g. wind turbines, solar panels and run-of-river hydro assets). Since electrical system operators must constantly match the instantaneous demand for electricity with the supply of electricity, intermittent resources are more difficult to work with because they cannot be counted on to provide energy as required (and may also provide excess energy when it is not wanted). Therefore, dispatchable generators (e.g. base load & load following) play an important role in helping system operators match electricity generation to remain in step with the rise and fall of both intermittent generation and electricity demand as shown in Figure 1.

Figure 1: Typical Base Load, Intermittent and Load Following Generation



When viewed on a monthly basis, the energy gap forecast (see Figure 2) shows a larger need for energy during the colder weather months of November through April, and a much smaller need for energy during the warmer months of May through October. Therefore, the fundamental energy challenge that new generation in the Yukon must address is the demand for winter energy and instantaneous peak winter capacity as summarized in Table 1.

Figure 2: Yukon Baseline Case Monthly Electrical Energy Gap (2035, 2045, 2055 & 2065)

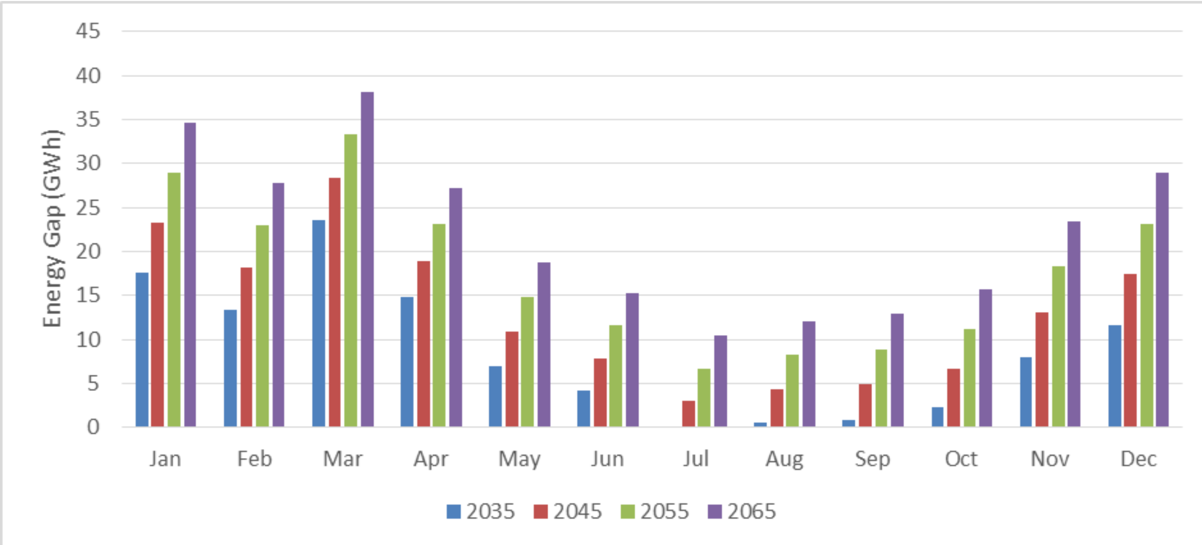


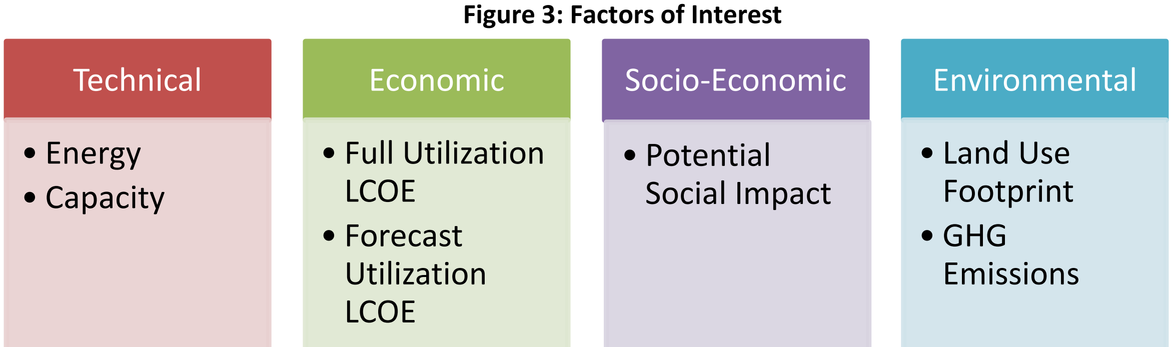
Table 1: Yukon Baseline Case Annual Electrical Energy & Peak Capacity Gaps for 2035 & 2065

	Annual Energy Gap		Peak Capacity Gap	
	2035	**2065**	**2035**	**2065**
Forecast Gap	103 GWh/Year	265 GWh/Year	21 MW	53MW

In Table 1 the annual energy gap is the forecast total annual energy gap measured in GWh/year[1] whereas peak capacity is the once a year instantaneous peak electrical demand that typically occurs in the winter and is measured in MW (Megawatts).

The future energy supply options available for use in meeting the Yukon's needs were compared in terms of four areas of interest: Technical, Economic, Social, and Environmental. The areas are detailed in Figure 3 below.

Figure 3: Factors of Interest



[1] Energy = Power x Time. Therefore, 1 MWh (Megawatt hour) is 1 MW (Megawatt) x 1 hour. 1 GWh (Gigawatt hour) is equal to 1,000MWh.

The four areas of interest are explained further below:

1) Technical:
    a. **Energy:** A measure of electricity used over time. For example, 1 MW of load for one hour (h) requires 1 MWh of energy.
    b. **Installed Capacity:** Installed capacity measures the maximum ability of an electrical generator to produce electricity in a given moment, typically measured in watts ("W"), kilowatts ("kW"), or megawatts ("MW").
    c. **Firm Capacity**: Firm capacity measures the dependable (or reliable) ability of a generator to produce electricity when called upon in times of greatest need (e.g. to dependably generate electricity during peak winter demand).
2) Economic:
    a. The **Full Utilization Levelized Cost of Energy** ("Full Utilization **LCOE**") compares the cost of different energy supply options, and is calculated by dividing the total lifetime project cost by the *maximum electrical energy that can be produced by the project*. It is assumed that a project is built at its full size and capacity, that the projects generate at their maximum potential, and that all of the generated energy is consumed. LCOE is typically expressed in $/MWh (dollars per megawatt-hour).
    b. The **Forecast Utilization Levelized Cost of Energy** ("Forecast Utilization **LCOE**") provides an apples-to-apples way to compare the cost of different energy supply options. Forecast LCOE is calculated by dividing the total lifetime cost of the project by the *electrical energy it provides to Yukon loads*. LCOE is typically expressed in $/MWh (dollars per megawatt-hour).
3) Social:
    a. For the purposes of this report, the **Potential Social Impact** has been simplified to assume that projects are potentially socially acceptable assuming that stakeholder concerns and issues are addressed. As a result, Social Acceptance is not a criterion that is assessed further.
4) Environmental:
    a. **Land-Use Footprint** refers to the area which is directly affected or occupied by the energy supply project.
    b. **Greenhouse Gas** ("**GHG**") **Emissions** include Carbon Dioxide (CO_2) and Methane (CH_4). GHG emissions were evaluated on the basis of electricity generation only. A full life-cycle GHG emissions estimate, including upstream fuel processing and component manufacturing, transportation, construction and decommissioning has not been considered.

The energy supply options available in the Yukon are summarized, by factor, in Table 2 below:

Table 2: Yukon Resource Type Summary

	Technical			Economic	Socio-Economic	Environmental	
Resource	**Max. 2065 Energy (GWh)**	**Max. 2065 Installed Capacity (MW)**	**Max. 2065 Firm Capacity (MW)**	**Full Utilization LCOE ($/MWh)**	**Social Impact**	**Land-Use Footprint (ha/MW)**	**Production GHG Emissions[2] ($kgCO_2e/MWh$)**
Wind	65	21	0	157	Potentially Acceptable	36 ± 22	0
Wind + Battery Storage	88	28	0	192	Potentially Acceptable	36 ± 22	0
Solar	13	14	0	192	Potentially Acceptable	0 - 3.5	0
Next Generation Hydro[3]	557	57	57	92	Potentially Acceptable	313 (Range: 187 – 545)	0
Run-of-River Hydro	Unlimited (@23.4GWh / project)	Unlimited (@4.7MW / project)	0.6MW / project	116+	Potentially Acceptable	≈11	0
Small Hydro with Storage	Unlimited (@43.6GWh / project)	Unlimited (@6.5MW / project)	4.2MW / project	126+	Potentially Acceptable	390 (Median)	0
Pumped Storage Hydro	-10* *PS does not produce energy	20	20	183	Potentially Acceptable	145	0
Natural Gas	710	Unlimited	141	229	Potentially Acceptable	0.28-0.42	708

As an electrical island without a connection to its neighbours, the Yukon must at all times match electricity self-supply and electricity demand in order to keep the electricity grid from blacking out. Moreover, electrical energy needs must be met over the longer term (e.g.: energy on a monthly basis) and the shorter term (e.g.: capacity to meet daily and winter peak demands). To fulfill these requirements, a series of

[2] GHG emissions are based on the energy production phase only and are not full life-cycle emissions.

[3] The reported values (Energy, Installed Capacity, Firm Capacity, Full Utilization LCOE, Land Use Footprint, and GHG Emissions) for Next Generation Hydro are the average of the respective values for Granite Canyon, Fraser Falls, Two Mile Canyon and Detour Canyon. It is assumed only one Next Generation Hydro project will be constructed and installed capacity is expandable up to 90-107MW if required.

scenarios was evaluated on their ability to meet the forecast 2065 energy and capacity gaps identified in the Baseline Scenario of the *Yukon Electrical Energy and Capacity Need Forecast*. Table 3 is a summary of the ability of different energy supply options to meet the forecast Yukon electricity needs.

Table 3: Yukon Resource Types – Ability to Meet Forecast Electricity Needs on a Standalone Basis

Resource	Standalone Resource	Rationale
Wind[4]	No	The integration limit for wind (plus utility battery support) is 28 MW[5] in 2065 (20% of installed capacity), and this is insufficient to meet the Yukon's forecast energy and capacity needs. Must be combined with other generation types.
Solar	No	The integration limit for solar is 14MW in 2065 (10% of installed capacity), and this is insufficient to meet the Yukon's forecast energy and capacity needs. Must be combined with other renewable generation types.
Next Generation Hydro	Yes	Next Generation Hydro provides sufficient dependable winter energy and capacity (57MW expandable up to 90-107MW as required) to meet the Yukon's forecast energy and capacity needs.
Run-of-River Hydro	No	Practical limits on easily developed Run-of-River projects limit the winter energy and capacity economically available from this resource type. On a standalone basis, over 80 Run-of-River projects would be required to meet the winter energy and capacity needs in 2065. Hence, Run-of-River hydro is an expensive source of winter energy and capacity.
Small Hydro with Storage	No	Small Hydro Storage energy shape limits the winter energy and capacity economically available from this resource type. On a standalone basis, approximately 14 projects would be required to meet winter energy and capacity needs in 2065. To reduce the overall costs Small Hydro Storage will likely be combined with other generation types and is preferred over Run-of-River as a source of small hydro winter energy and capacity.
Pumped Storage Hydro	No	This 20MW resource is a net energy consumer; therefore it must be combined with other generation types as part of a generation portfolio.
Natural Gas	Yes	Natural Gas Generation provides sufficient dependable winter energy and capacity.

As shown in Table 3 above, only Natural Gas Generation and Next Generation Hydro can meet the Yukon's forecast electricity needs on a standalone basis. The other generation types must be combined together to potentially meet the Yukon's forecasted needs. As a result, four energy supply scenarios were considered:

[4] Wind integration is supported by a utility scale battery.

[5] Wind resources are added in 7.2 MW (4 X 1.8 MW turbines) steps for the purposes of scenario development.

Natural Gas, Next Generation Hydro, Renewables Portfolio (with No Pumped Storage), and Renewables Portfolio (with Pumped Storage). The portfolios are detailed below in Table 4.

Table 4: Yukon Energy Development Scenarios

Scenario	Description	Resources Included
Scenario 1 – Natural Gas	Build out natural gas generation	Natural Gas
Scenario 2 – Next-Generation Hydro	Build a single Next-Generation Hydro project	Next Generation Hydro
Scenario 3 – Renewables Portfolio (No Pumped Storage)	Build a combination of renewable generation resources (excluding pumped storage hydro) to satisfy energy needs. If required to satisfy residual capacity needs, add natural gas generation	Wind (with utility scale battery), solar, run-of-river hydro, small hydro with storage and natural gas (capacity only)
Scenario 4 – Renewables Portfolio with Pumped Storage	Build a combination of renewable generation resources including pumped storage hydro to satisfy energy needs. If required to satisfy residual capacity needs, add natural gas generation.	Wind (with utility scale battery), solar, run-of-river hydro, small hydro with storage, pumped storage, and natural gas (capacity only)

The four energy development scenarios were compared according to the following parameters:

1) Technical: Energy – Annual energy measured in GWh
2) Technical: Capacity – Installed capacity measured in MW
3) Economic: Forecast LCOE measured in $/MWh.
4) Environmental: Land-use footprint measured in hectares (ha).
5) Environmental: GHG emissions measured in tonnes of CO_2 equivalent (CO_2e) per year.

After evaluating the scenarios on the basis of the evaluation criteria, Table 5 shows that all of the generation scenarios have the potential to meet the forecast average energy and capacity needs of the Yukon in a socially acceptable manner. However, all of the generation scenarios also have certain advantages and disadvantages that make the decision about which generation types to pursue a selection among tradeoffs.

Table 5: Yukon Scenario Summary Matrix

	Technical		Economic	Socio-Economic	Environmental	
Scenario	**Meets Yukon Energy Needs?**	**Meets Yukon Capacity Needs?**	**Forecast Utilization LCOE ($/MWh)**	**Social Impact**	**2065 Land-Use Footprint (hectares)[6]**	**2065 GHG Emissions (tonnes CO_2e)**
Scenario 1 – Natural Gas	Yes	Yes	250	Potentially Acceptable	22	190,000
Scenario 2 – Next-Generation Hydro	Yes	Yes	240	Potentially Acceptable	18,000	0
Scenario 3 – Renewables	Yes	Yes (with Natural Gas capacity)	360	Potentially Acceptable	29,000	≈0
Scenario 4 – Renewables with Pumped Storage	Yes	Yes (with Natural Gas capacity)	270	Potentially Acceptable	20,000	≈0

The results in Table 5 contain findings that deserve additional explanation as follows:

1) **Meeting Yukon Capacity Needs:** Both renewables scenarios (#3 & #4) use natural gas generation in the years leading up to 2065 to meet winter peak electricity demands because natural gas generation is currently the least cost method of providing capacity in the Yukon. Although the Yukon's capacity needs could theoretically be met with renewables (e.g. with additional small hydro storage projects), the cost would be prohibitive compared to using natural gas generation. See Figure 4 and Figure 5 for a breakdown of energy and capacity for Scenario 3 and Scenario 4 respectively.
2) **Forecast Utilization LCOE:** The Scenario #3 Forecast Utilization LCOE is highest because fully closing the winter energy gap with renewables results in low utilization factors for the last few renewable assets added to the scenario (thus driving up the cost of this option). The addition of pumped storage in Scenario 4 provides winter energy that reduces the number of small hydro storage projects needed to meet winter energy needs, thus reducing the cost for Scenario #4.

[6] When comparing the scenario footprints it must be recognized that the impact of the different footprints are different for the different project types. For example, the majority of the Next Generation Hydro footprint is general land use and creating a new lake / water storage reservoir where a river previously existed, whereas the renewable portfolios (Scenarios 3 & 4) are a combination of new lakes / water storage reservoirs, modifying existing lakes, and general land use. Therefore, land use impacts cannot be directly compared without evaluating the types of impacts as well as the footprint.

3) **Land Use Footprint:** When comparing the scenario footprints it must be recognized that the impact of the different footprints are different for the different project types. For example, the majority of the Next Generation Hydro footprint is general land use and creating a new lake / water storage reservoir where a river previously existed, whereas the renewable portfolios (Scenarios 3 & 4) are a combination of new lakes / water storage reservoirs, modifying existing lakes, and general land use. Therefore, land use impacts cannot be directly compared without evaluating the types of impacts as well as the footprint. Additionally, the land use footprints for the renewable scenarios are large because the small hydro storage projects in the Yukon typically impact lakes which result in large area impacts.
4) **Greenhouse Gas Emissions:** Although, Scenario 3 and Scenario 4 fill the forecast capacity gap in 2035 and the energy gaps up to 2065, they fail in practice to meet the capacity needs in 2065 and as a result will need thermal generation (natural gas, diesel) to meet the Yukon's capacity needs, and therefore the direct generation GHG emissions will be low, but not actually zero in practice.

The energy and *installed* capacities required for each scenario to meet the Yukon's forecasted energy and *firm* capacity requirements in 2065 are listed in the Table 6 below.

Table 6: Yukon Scenario Summary – Energy and Capacity in 2065

Scenario	Energy (2065)	Installed Capacity (2065)
Scenario 1: Natural Gas	444 GWh Existing Hydro 265 GWh Natural Gas **= 710 GWh**	92 MW Existing Hydro 53 MW Natural Gas **= 145 MW**
Scenario 2: Next-Generation Hydro	444 GWh Existing Hydro 265 GWh NGH **= 710 GWh**	92 MW Existing Hydro 57 MW NGH **= 149 MW**
Scenario 3: Renewables Portfolio (with No Pumped Storage)	444 GWh Existing Hydro 88 GWh Wind 5 GWh of Solar 172 GWh Small Hydro Storage **= 710 GWh**	92 MW Existing Hydro 29 MW Wind with Battery Integration (7.5MW) 5 MW Solar 72 MW Small Hydro Storage 8.8 MW Natural Gas **= 207 MW**

Scenario	Energy (2065)	Installed Capacity (2065)
Scenario 4: Renewables Portfolio (with Pumped Storage)	444 GWh Existing Hydro 88 GWh Wind 5 GWh Solar 180 GWh Small Hydro -8 GWh Pumped Storage **= 710 GWh**	92 MW Existing Hydro 29 MW Wind with Battery Integration (7.5MW) 5 MW Solar 39 MW Small Hydro 20 MW Pumped Storage 8.8 MW Natural Gas **= 194 MW**

Figure 4 and Figure 5 below graphically show the quantities of energy and *installed* capacity needed for each scenario in 2035 and 2065 (Note: Existing Hydro has been removed from the graphics so that the relative generation additions can be seen more easily).

Figure 4: Scenario Energy Addition Comparison Charts – 2035 & 2065

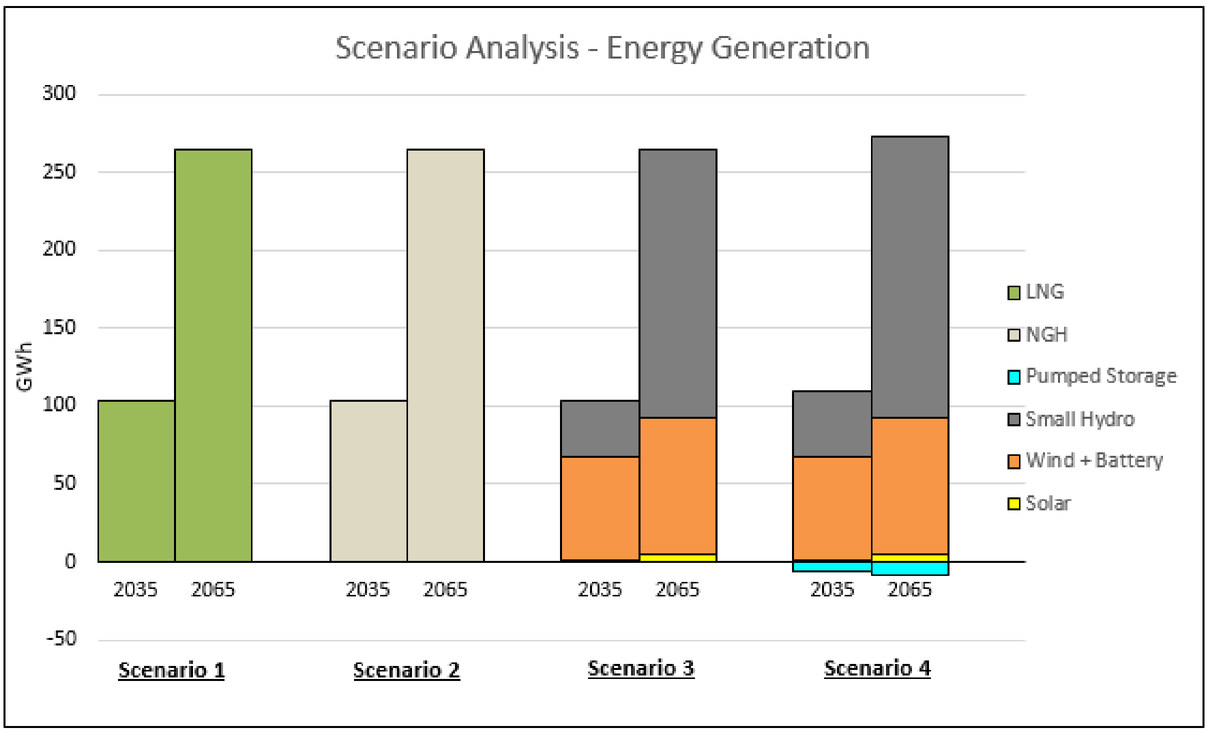


Figure 5: Scenario Installed Capacity Comparison Charts –2035 & 2065

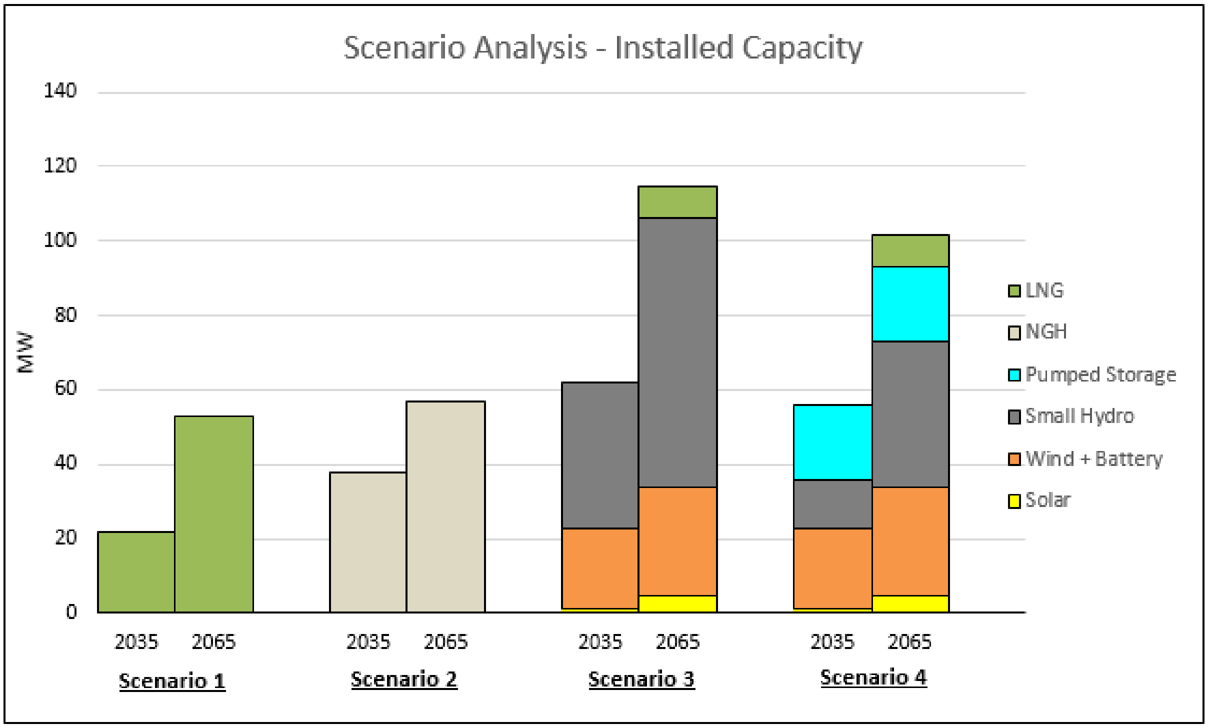


Table 7 below summarizes the pros and cons of each scenario.

Table 7: Pros and Cons of Generation Proposed Generation Scenarios

Scenario	Pros	Cons
Scenario 1: Natural Gas	▪ Similar economic cost when compared to Scenarios 2 & 4. ▪ Dispatchable (as in, can be turned on and off) as required ▪ Can reliably supply power during winter months ▪ Meets Yukon electricity needs throughout the planning period ▪ Has the smallest land use footprint of all the energy supply scenarios	▪ Highest GHG emissions of all the energy supply scenarios
Scenario 2: Next-Generation Hydro	▪ Similar economic cost when compared to Scenarios 1 & 4. ▪ Zero GHG emissions ▪ Dispatchable (as in, can be turned on and off) as required ▪ Meets Yukon electricity needs throughout the planning period	▪ Similar land use footprint when compared to Scenario 4.

Scenario	Pros	Cons
Scenario 3: Renewables Portfolio (with No Pumped Storage)	▪ Zero GHG emissions Note: In practice thermal (natural gas) generation is needed to provide dependable winter capacity to support the intermittency, or variability, of the renewables generation assets.	▪ Highest cost option ▪ Fails to meet the forecasted capacity gap in 2065 and will require additional capacity resources (e.g. natural gas or diesel generation). ▪ Larger footprint and transmission line infrastructure requirements compared to the other renewables scenario (Scenario 4).
Scenario 4: Renewables Portfolio (with Pumped Storage)	▪ Similar economic cost when compared to Scenarios 1 & 2. ▪ Zero GHG emissions Note: In practice thermal (natural gas) generation is needed to provide dependable winter capacity to support the intermittency, or variability, of the renewables generation assets.	▪ Fails to meet the forecasted capacity gap in 2065 and will require additional capacity resources (e.g. natural gas or diesel generation). ▪ Similar land use footprint when compared to Scenario 2.

In summary, after evaluating the scenarios on the basis of the evaluation criteria, Table 5 shows that all of the generation scenarios have the potential to meet the forecast average energy and capacity needs of the Yukon in a potentially socially acceptable manner. However, all of the generation scenarios also have certain advantages and disadvantages that make the decision about which generation types to pursue a selection among tradeoffs (see Table 7). Therefore, after evaluating the scenarios Next Generation Hydro remains a viable candidate for further consideration because NGH has similar economic cost when compared to other generation options, zero Greenhouse Gas (“GHG”) emissions from electricity generation, and it meets the Yukon’s need for electrical winter energy and capacity from 2035 to 2065.

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LIST OF ACRONYMS

ROR	Run-of-River
LNG	Liquefied Natural Gas
MAD	Mean Annual Discharge
NGH	Next Generation Hydro
PSH	Pumped Storage Hydro
LCOE	Levelized Cost of Electricity
YDC	Yukon Development Corporation
YEC	Yukon Energy Corporation
GHG	Greenhouse Gas

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1 Overview

The Yukon Development Corporation ("**YDC**") has commissioned Midgard Consulting Incorporated ("**Midgard**") to complete the *Alternatives to Next Generation Hydro Report*. This overview discussion is intended to help inform the public regarding the types of decisions and tradeoffs necessary to fill the Yukon's need for new electricity sources and to support the Yukon's continued economic growth and development.

The Yukon is facing challenging decisions about how it will meet a growing forecast energy and capacity gap, and consequently new generation projects within the territory are required to support the Yukon's continued growth and development. Generation investments will help address the Yukon's unique challenges including, but not limited to: being an islanded grid, the uncertainty of increased industrial (e.g. mining) loads, and the need for winter energy and peaking capacity, while simultaneously minimizing environmental, cultural and socio-economic impacts.

Midgard has prepared this review of energy development scenarios for the Yukon based on YDC's identified need to meet the following objectives:

1) Provide a context for *Next Generation Hydro* ("**NGH**")projects, by presenting impacts and tradeoffs of a variety of energy development scenarios
2) Promote a fact-based conversation around these potential solutions and alternatives
3) Provide a consistent framework with which to compare NGH and other potential energy developments.

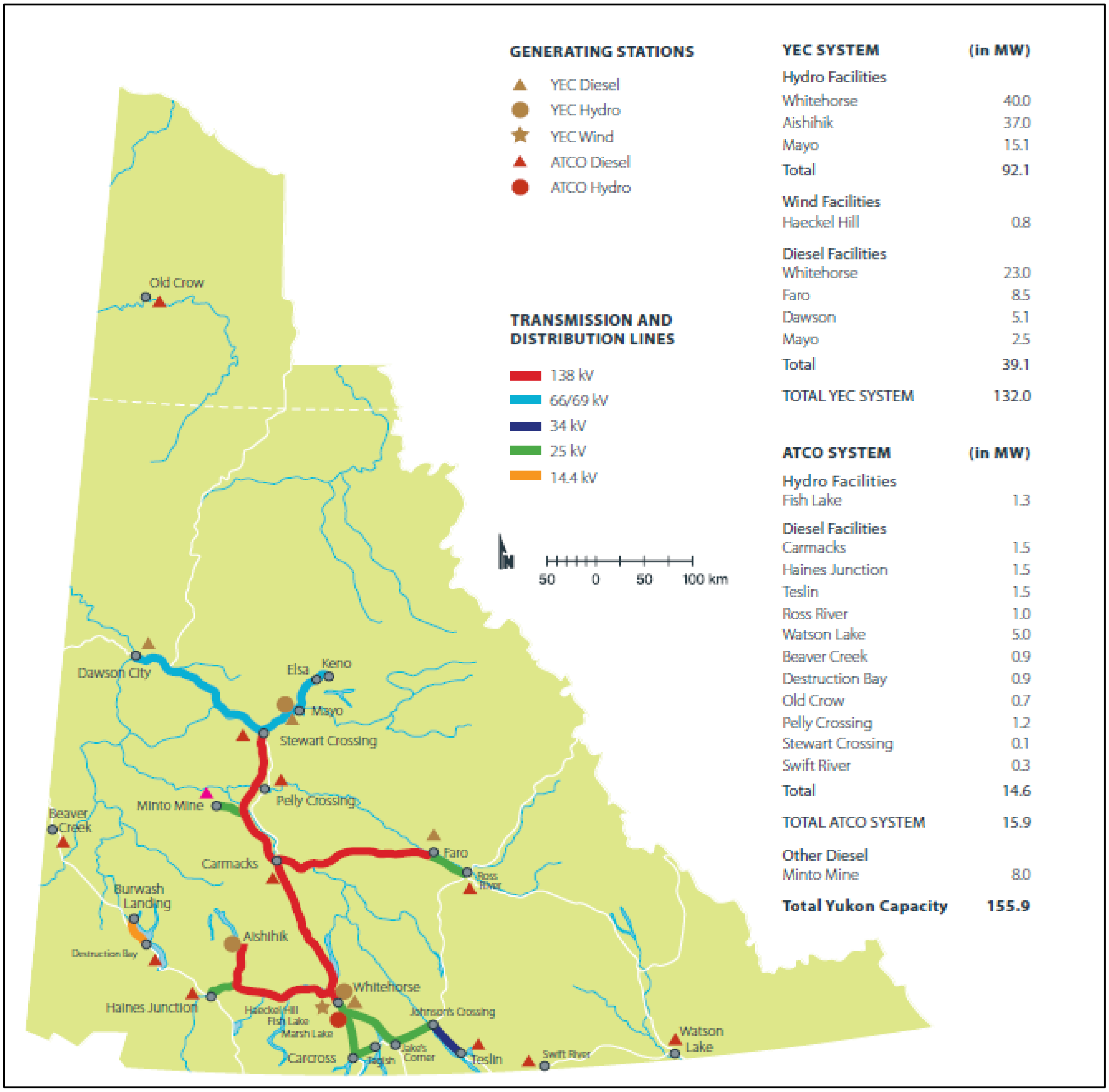
It is important to state and emphasize that this review is not a utility resource plan and does not in any way restrict the utility resource planning necessary to "keep the lights on" and ensure that there is a reliable electrical grid for the Yukon. Rather, this report is a discussion of the different generic generation technologies available in the Yukon and the tradeoffs that are inherent in each of these generic technologies in the Yukon context.

1.1 The Yukon Electrical Grid

The Yukon interconnected grid currently has 132MW of installed capacity as follows:

- 92MW Hydroelectric: Whitehorse (40MW), Aishihik (37MW), and Mayo (15MW).[7]
- 39MW Thermal Generation: Diesel and Natural Gas
- 0.8MW Wind: Two wind turbines on Haeckel Hill[8]

Figure 6: Map of Yukon and its Electrical Infrastructure[9]



[7] The 1.3 MW Fish Lake hydro scheme is not a YEC facility and is not included in this report.

[8] The existing turbines on Haeckel Hill will have reached the end of their service life by 2035 and are not included as resources in the 2035-2065 energy development scenarios.

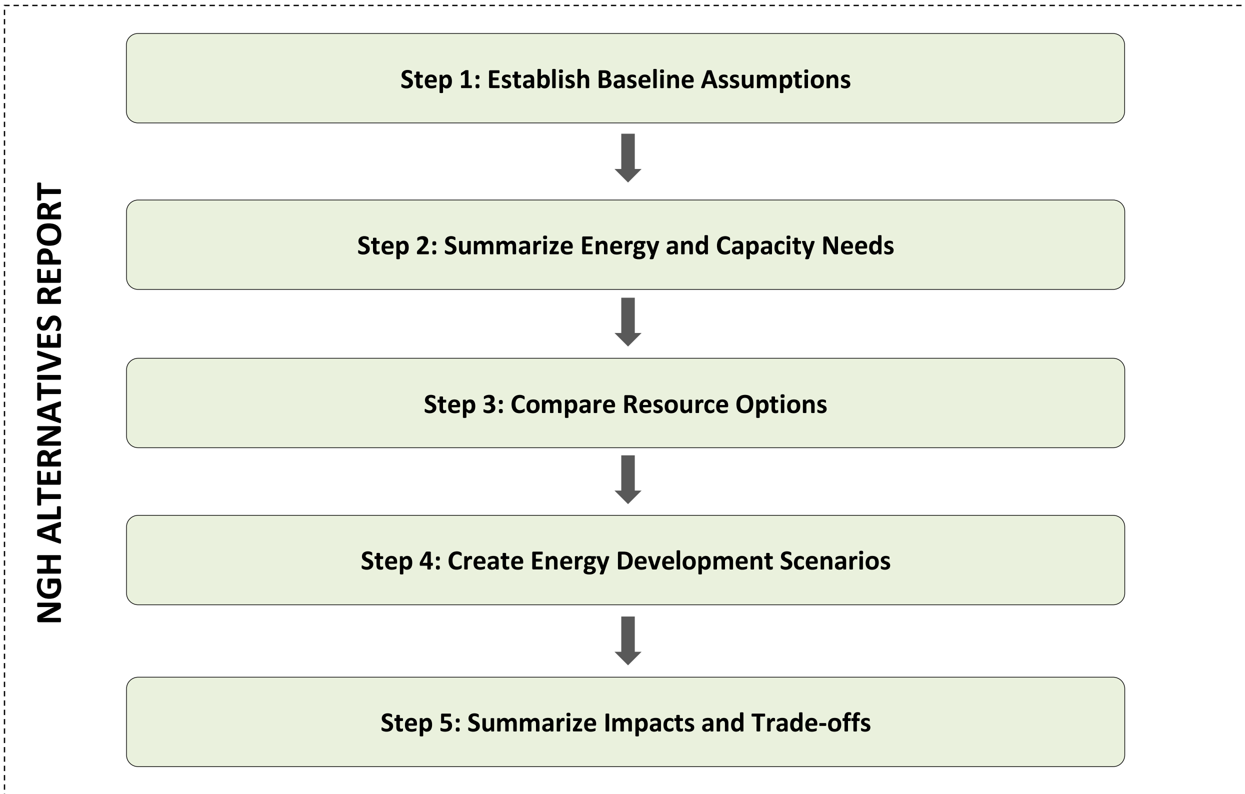
[9] Map courtesy of Yukon Energy Corporation.

2 Methodology

2.1 Midgard Approach

Midgard undertook the work assignment with a multi-step approach as shown in Figure 7:

Figure 7: Methodology



The steps are described as follows:

1. **Establish Baseline Assumptions:** Review of initial assumptions and analytic approaches to establish a set of assumptions that are consistent with long term planning objectives. A summary of Midgard's assumptions can be found in Appendix A:.
2. **Summarize Energy and Capacity Needs:** From the *Yukon Electrical Energy and Capacity Need Forecast,* extract the forecast energy and capacity gaps based on the Baseline 2065 scenario.
3. **Resource Options:** Identify generation resource options available in the Yukon and where available use Yukon based data to develop generic resource options for Wind, Solar, Small Hydro (with and without water storage), Natural Gas, Pumped Storage and a representative Next Generation Hydro project.
4. **Energy Development Scenarios:** Identify different energy and capacity gap closure approaches that could be followed such as developing thermal (natural gas) generation only, Next Generation Hydro,

or mixed generation portfolios that include wind, solar, and smaller hydro, plus additional resources needed to address the remaining gap after these renewable resources have reached natural, technical or economic limits.

5. **Summarize Impacts & Tradeoffs:** A matrix summarizing the results of the work.

The future energy resources available for use in meeting the Yukon's needs were compared in terms of four primary factors:

Figure 8: Factors of Interest

Technical	Economic	Socio-Economic	Environmental
• Energy • Capacity	• Full Utilization LCOE • Forecast Utilization LCOE	• Potential Social Impact	• Land Use Footprint • GHG Emissions

2.2 Technical Factors

2.2.1 Energy and Capacity

Electricity generation is measured via two related but different measures: energy and capacity. Capacity is a measure of the instantaneous ability of a given generator to produce power, typically measured in watts ("W"), kilowatts ("kW"), or megawatts ("MW"). Energy is a measure of power used over time and represents the work that is done by the electricity. A 1 MW plant that operates for 1 hour is said to have produced 1 megawatt-hour ("MWh") of energy. The difference between energy and capacity is important to understand and key to thinking about the requirements of a utility.

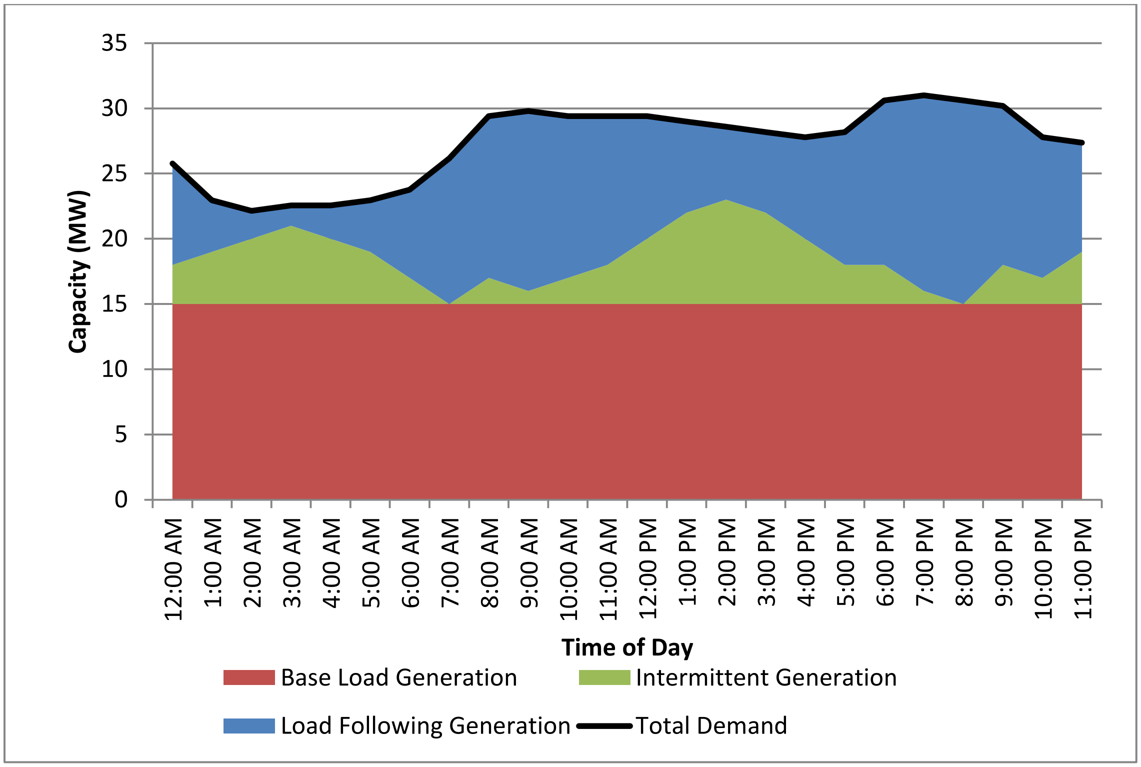
Electric generation assets are often grouped by their attributes with respect to capacity and energy. Assets that have dependable capacity (also called "firm" or "dispatchable" energy) are those assets that can be called on at any time to generate power. Assets that generate power only when their fuel supply is available and not necessarily when the energy is required by the load are called intermittent generators. Therefore, the critical difference between a generation resource being firm and dispatchable versus being intermittent is the generator's ability to call on its fuel supply as, and when, needed.

Intermittent resources typically rely on less predictable natural resources to provide fuel for generation. Examples of intermittent resources include wind turbines, solar panels and run-of-river hydro assets. Although the amount of energy that intermittent resources will generate in the long term (e.g. annually) is often predictable, instantaneous capacity or short-term energy generation can be unpredictable. In general, the variability of intermittent generation sources, including wind and solar, must be "firmed" by another generation source which is able to quickly respond to changing levels of generation. This capacity firming is provided by generation which is online and ready to be connected to the grid at a moment's notice. At present, the only practical technologies which can meet this need are hydro with storage (including pumped storage) and thermal (natural gas or diesel) generation.

Another important characteristic to consider when comparing different generation options is the speed at which various generators are able to turn on and off, and to change generation levels (e.g. ramp up and ramp down). Generation assets that run at a constant output (or slowly varying output levels) are run to meet "base loads", which is to say they are operated at constant output levels. Other generation options, such as storage hydro, diesel generators, or natural gas reciprocating engines, can be dispatched quickly as required to meet short term changes in demand for power. These variable types of generators have "load following" capability and change their output levels in response to short term (e.g. second by second, minute by minute, or hourly) changes in demand.

As previously mentioned, intermittent resources will generate as, and when, their fuel supplies are available. Since electrical system operators must constantly match the instantaneous demand for electricity with the supply of electricity, intermittent resources are more difficult to work with because they cannot be counted on to provide energy as required (and may also provide excess energy when it is not wanted). Therefore, load following generators play an important role in helping system operators match electricity generation to remain in step with the rise and fall of both intermittent generation and electricity demand.

Figure 9: Typical Base Load, Intermittent and Load Following Generation



2.3 Economic Factors

Calculating a unit cost of energy, or a "Levelized Cost of Energy" (LCOE), provides a consistent means of economically comparing generation projects. The LCOE calculation accounts for both the energy generated, and the total capital and operating costs, for a generation facility over its expected lifetime.

Several inputs are required to calculate Levelized Cost of Energy, including annual energy production, costs (in the form of capital costs, fuel costs, and operating costs), and economic assumptions (discount rate and project lifetime). These inputs are applied in the following LCOE equation:

$$LCOE = \frac{Total\ Present\ Value\ of\ Costs}{Total\ Present\ Value\ of\ Energy\ Output}$$

2.3.1 Full Utilization LCOE

The full utilization LCOE, expressed in $/MWh, is calculated assuming that a project is built at its full size and capacity, that the projects generate at their maximum potential, and that all of the generated energy is consumed.

The full utilization LCOE is therefore calculated as follows:

$$Full\ Utilization\ LCOE = \frac{Total\ Present\ Value\ of\ Costs}{Total\ Present\ Value\ of\ \textbf{Full Utilization Energy}}$$

Because the Yukon is an islanded grid with no ability to export surplus energy, it is not practical that all generation assets on the Yukon grid will be able to fully utilize their generation output. Therefore, although the full utilization LCOE is an indicator of economic cost, it is more suited for comparing resource options on a generic basis, rather than as part of a full resource mix.

Full utilization LCOE is used when summarizing generic generation resources (as in Section 4); the purpose of full utilization LCOE is to discuss resources individually without the context provided by a complete generation scenario. Full utilization LCOE therefore describes the cost of energy assuming ideal resource usage without taking into account the role a generation resource plays when working in combination with other generation resources.

2.3.2 Forecast LCOE

The forecast LCOE does not assume that the entire energy output from any generation source is fully consumed, but rather that the generation asset fulfills a role as part of a larger Yukon generation supply scenario. For example, some Yukon generation must be kept in reserve to meet peaks in electricity demand and therefore does not always produce at its full output. Similarly, at certain times of year the Yukon has more generation potential than is consumed in the Yukon (e.g. in the summer), and generation assets are under-utilized. As a result, the forecast LCOE will typically be higher than the full utilization LCOE, as it accounts for the actual cost of operating the entire generation mix.

The forecast utilization LCOE is calculated as shown below:

$$Forecast\ Utilization\ LCOE = \frac{Total\ Present\ Value\ of\ Costs}{Total\ Present\ Value\ of\ \textbf{Forecast Utilization Energy}}$$

In this report the emphasis will be on the Full Utilization LCOE, but it should be understood that for an islanded grid such as the Yukon without the opportunity to trade surplus energy to its neighbours, the actual cost of generation in the Yukon is higher than the Full Utilization LCOE and is represented by the Forecast Utilization LCOE.

2.4 Socio-Economic Factors

For the purposes of this report, the socio-economic factors have been simplified to simply indicate whether or not a project might potentially be socially acceptable, assuming that stakeholder concerns and issues could be addressed satisfactorily. Because this report is discussing “generic” generation projects rather than specific projects, it does not attempt to assess social acceptance, but rather indicate whether or not it might be possible that a project could be socially acceptable.

For example, coal fired generation and nuclear generation were considered to be socially unacceptable due to the typically high social barriers to adoption of these resources. However, a wind farm, solar farm or hydroelectric generation could possibly be acceptable given an appropriate project and accommodations. Therefore, the following projects types were considered to be potentially acceptable assuming concerns and negative impacts are adequately mitigated or offset by positive benefits:

1) Wind
2) Solar
3) Hydroelectric (Run Of River, Storage and Pumped Storage)
4) Natural Gas
5) Diesel

2.5 Environmental Factors

2.5.1 Land-Use Footprint

Land-use footprint refers to the area of land which is directly affected or occupied by the generation resource. For the purposes of this report, land-use impacts were estimated on the basis of the direct footprint associated with generation activities only. Indirect land-use impacts for items such as construction (e.g. transportation, laydown areas, component manufacturing etc.), offsite management (e.g. head office), and public facilities (e.g. road improvements, other public infrastructure, etc.) were not considered. Additionally, secondary impacts such as the cumulative impact of land fragmentation were not considered.

2.5.2 GHG Emissions

Greenhouse gases (GHGs) include Carbon Dioxide (CO_2) and Methane (CH_4), which are commonly produced by the extraction and burning of fossil fuels. Project GHG emissions were evaluated on the basis of electricity generation only. A full life-cycle GHG emissions estimate, including upstream fuel processing and component manufacturing, transportation, construction and decommissioning has not been considered. For this reason, generation resources such as wind, solar and hydro are considered to have zero GHG emissions for generation purposes, although it is recognized there are GHG emissions associated with these generation resources over their full life cycle. Fossil fuel resources such as natural gas generation and diesel generation are similarly evaluated on the basis of GHG production resulting from fuel combustion only, and not the GHG impacts of fuel production and delivery.

The Yukon's current GHG emissions from all sources, including heating, transportation and industrial emissions (including electricity generation) are approximately 400,000 tons of CO_2e per year[10].

[10] Carbon Dioxide Equivalent (CO_2e) based on 2013 emissions. Source: *National Inventory Report 1990-2013: Greenhouse gas Sources and Sinks in Canada,* Environment Canada, 2015.

3 Yukon Energy and Capacity Needs

3.1 Energy Need Forecast – Baseline Scenario

Yukon is an islanded grid that must self-supply all its own electrical energy and capacity. The need for electrical energy and capacity is growing, and is expected to continue growing through to the end of 2065 and beyond.

As part of the *Next Generation Hydro* study, Midgard has forecast the supply and demand of electricity in the Yukon for the period 2035-2065 as part of its *Yukon Electrical Energy and Capacity Need Forecast*. For the purposes of this report, the Baseline scenario energy and capacity gap was selected as the scenario to evaluate for the 2035 to 2065 window. The forecast gap between currently available generation (hydroelectric) supply and future energy demand grows continuously over the period 2035-2065 and is summarized in Figure 10. The total forecast energy demands in the Baseline scenario are tabulated in Table 8.

Figure 10: Baseline Case Electrical Energy Demand and Supply Forecast (2035-B, 2045-B, 2055-B & 2065-B)

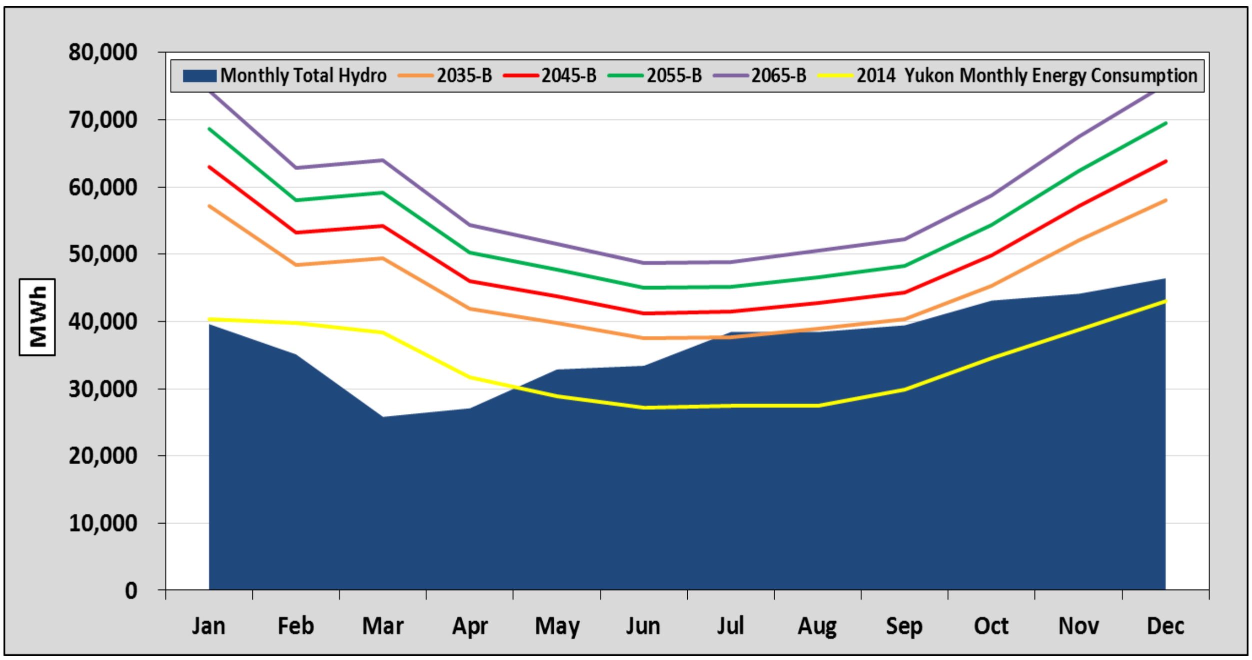


Table 8: Table of Baseline Case Monthly Electrical Energy Demand Forecast for 2035, 2045, 2055 & 2065

Month	2035 (MWh/Month)	2045 (MWh/Month)	2055 (MWh/Month)	2065 (MWh/Month)
Jan	57,200	62,900	68,600	74,300
Feb	48,500	53,300	58,100	62,900
Mar	49,300	54,200	59,100	64,000
Apr	41,900	46,000	50,200	54,300
May	39,800	43,700	47,600	51,600

Month	2035 (MWh/Month)	2045 (MWh/Month)	2055 (MWh/Month)	2065 (MWh/Month)
Jun	37,500	41,200	45,000	48,700
Jul	37,700	41,400	45,200	48,900
Aug	38,900	42,800	46,600	50,500
Sep	40,300	44,300	48,300	52,300
Oct	45,300	49,800	54,300	58,800
Nov	52,100	57,200	62,400	67,500
Dec	58,100	63,800	69,600	75,300
Total	546,600	600,600	655,000	709,100

When viewed on a monthly basis, the energy gap forecast (see Figure 11 and Table 9) shows a larger need for energy during the colder weather months of November through April, and a much smaller need for energy during the warmer months of May through October. Therefore, the fundamental energy challenge that new generation in the Yukon must address is the demand for winter energy and capacity.

Figure 11: Baseline Case Monthly Electrical Energy Gap (2035-B, 2045-B, 2055-B & 2065-B)

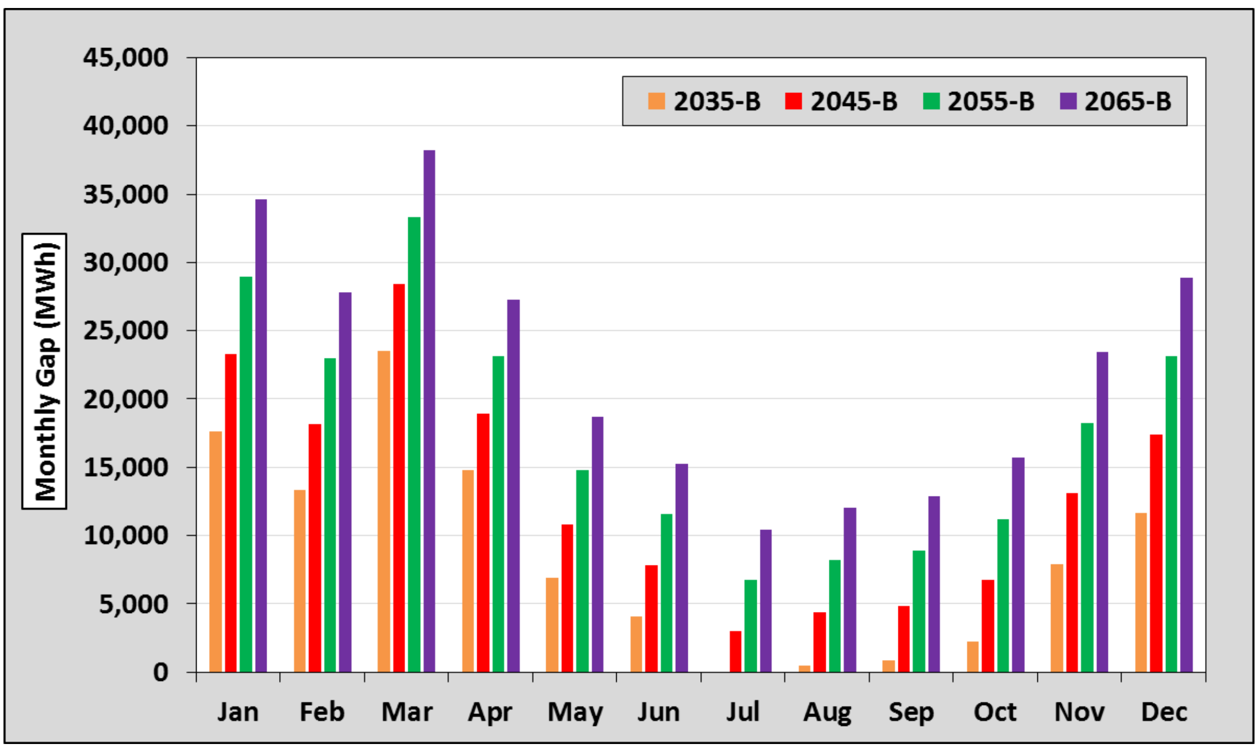


Table 9: Table of Baseline Case Monthly Electrical Energy Gaps for 2035, 2045, 2055 & 2065

Month	2035 (MWh/Month)	2045 (MWh/Month)	2055 (MWh/Month)	2065 (MWh/Month)
Jan	17,635	23,312	28,978	34,655
Feb	13,362	18,168	22,965	27,771
Mar	23,524	28,416	33,299	38,192
Apr	14,801	18,954	23,100	27,254
May	6,892	10,834	14,769	18,711
Jun	4,110	7,831	11,545	15,265
Jul	-	2,991	6,721	10,458
Aug	498	4,358	8,210	12,070
Sep	878	4,876	8,866	12,863
Oct	2,221	6,715	11,202	15,697
Nov	7,934	13,095	18,248	23,409
Dec	11,639	17,397	23,144	28,902
Total	103,494	156,947	211,047	265,247

3.2 Capacity Need Forecast – Baseline Scenario

Along with a need for energy there is a need for sufficient capacity on the Yukon grid to meet peak electricity demand (e.g. cold winter days). Sufficient generation capacity is required on the Yukon grid so that when electricity demand peaks occur, there is sufficient generation to meet that need (otherwise the Yukon grid will black out). Figure 12 and Table 10 show the growing forecast Baseline capacity gap from 2035 to 2065.

Figure 12: Yukon Baseline Winter Capacity Gap

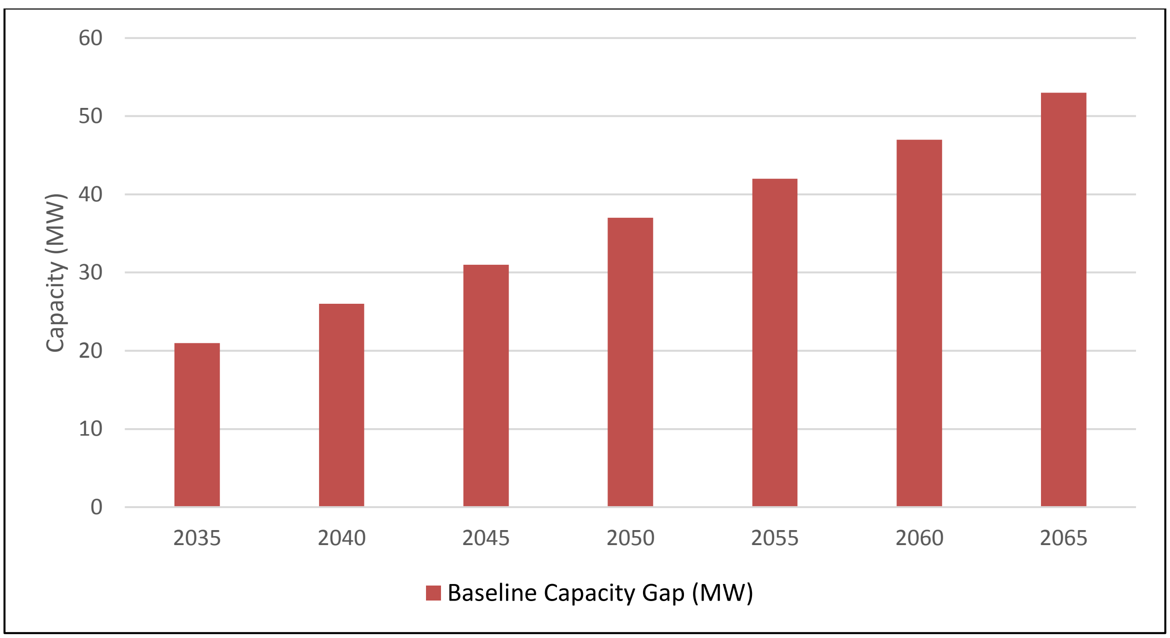
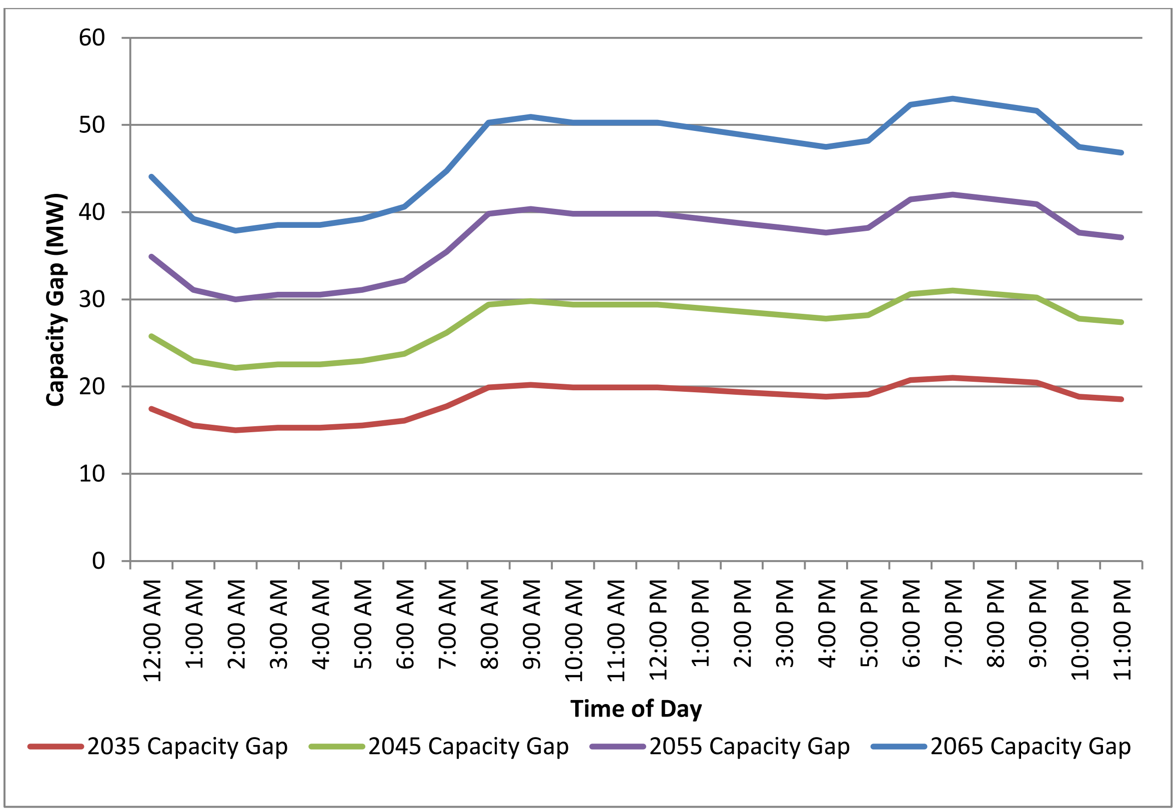


Table 10: Baseline Winter Capacity Gap, 2035-2065

Year	Capacity Gap (MW)
2035	21
2040	26
2045	31
2050	37
2055	42
2060	47
2065	53

Capacity needs change as consumer demands increase and decrease in response to changing activities over the day. Energy demand is typically lowest during the night (when people are asleep), and begins to ramp up as people wake up and use energy for heating, cooking and lighting. The peak demand period is typically early evening when people return from work and increase their energy usage for heating, cooking, lighting, chores, and entertainment. A sample demand curve for the Yukon, scaled to the 2035-2065 capacity forecast gaps is shown in Figure 13.

Figure 13: Sample Yukon Winter Capacity Demand Gap 2035-2065



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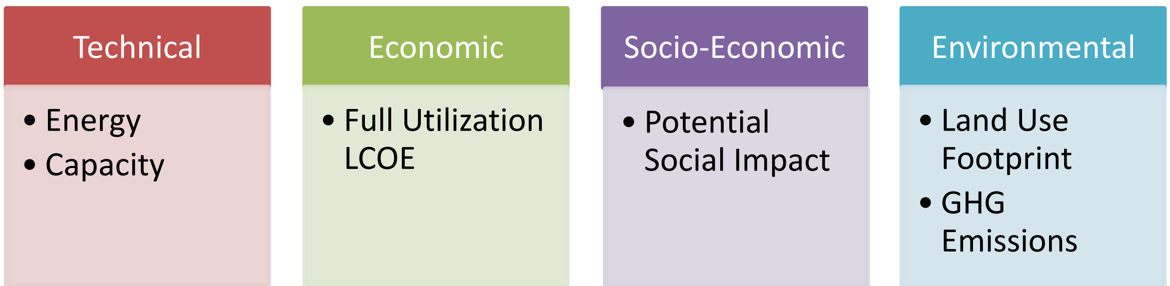
4 Generation Resources

The energy resources available for use in meeting the Yukon's needs were compared in terms of four factors:

Figure 14: Factors of Interest



4.1 Wind Generation

Wind-driven electric generation converts the kinetic energy of wind into electrical energy, and this conversion is most commonly done using a wind turbine. The blades of a turbine are forced to spin by the wind, the drivetrain transfers the rotational energy to an electric generator, and the electric generator generates electricity. Wind energy resources are characterized as non-firm (intermittent) resources because electrical energy is only generated when the wind blows within a suitable range of speeds (not too fast and not too slow).

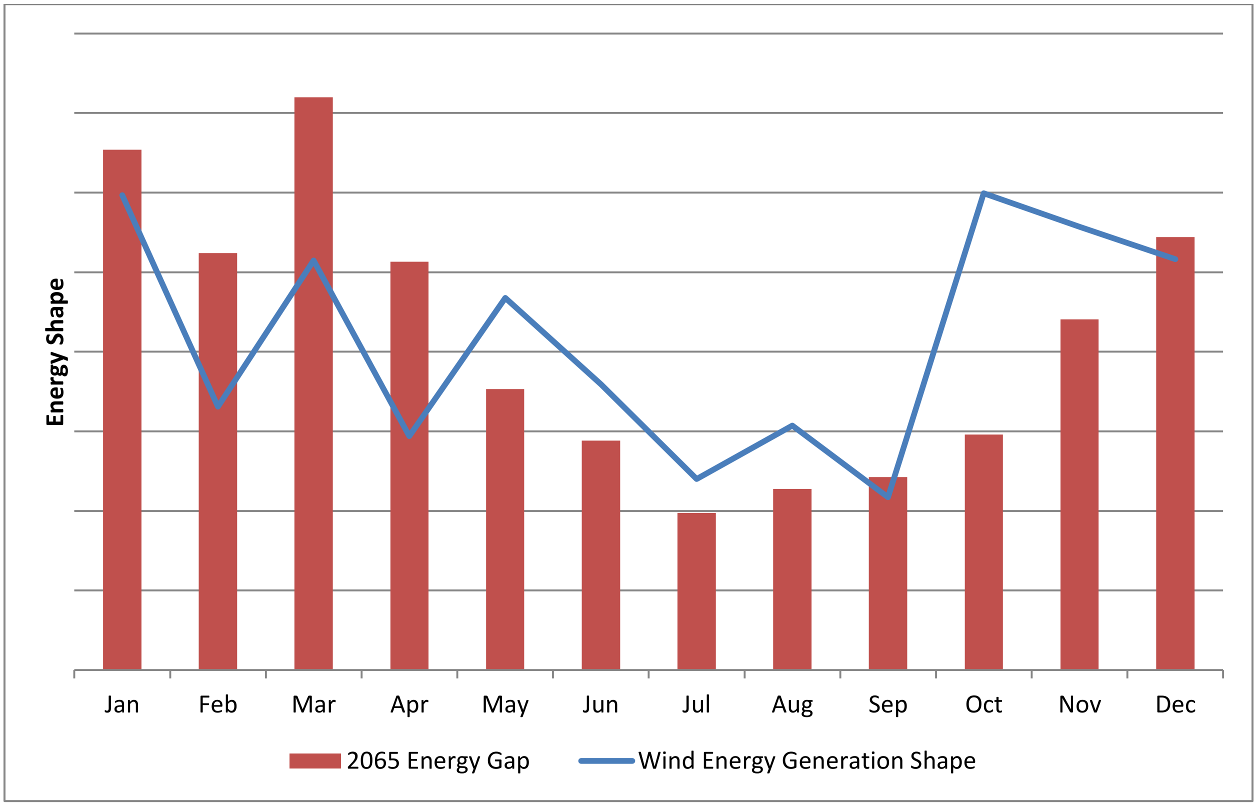
Figure 15: Wind Turbines on Haeckel Hill[11]

[11] Image Source*:* Yukon Development Corporation/Yukon Energy Corporation.

4.1.1 Wind - Technical Factors

Figure 16 compares the typical trend of wind power availability in the Yukon as compared to the forecast future energy needs on a month-by-month basis. The trend or "shape" of wind energy availability in the Yukon is a reasonably good match for the shape of the forecast future energy gap, with more energy generated in the winter and less energy generated in the summer.

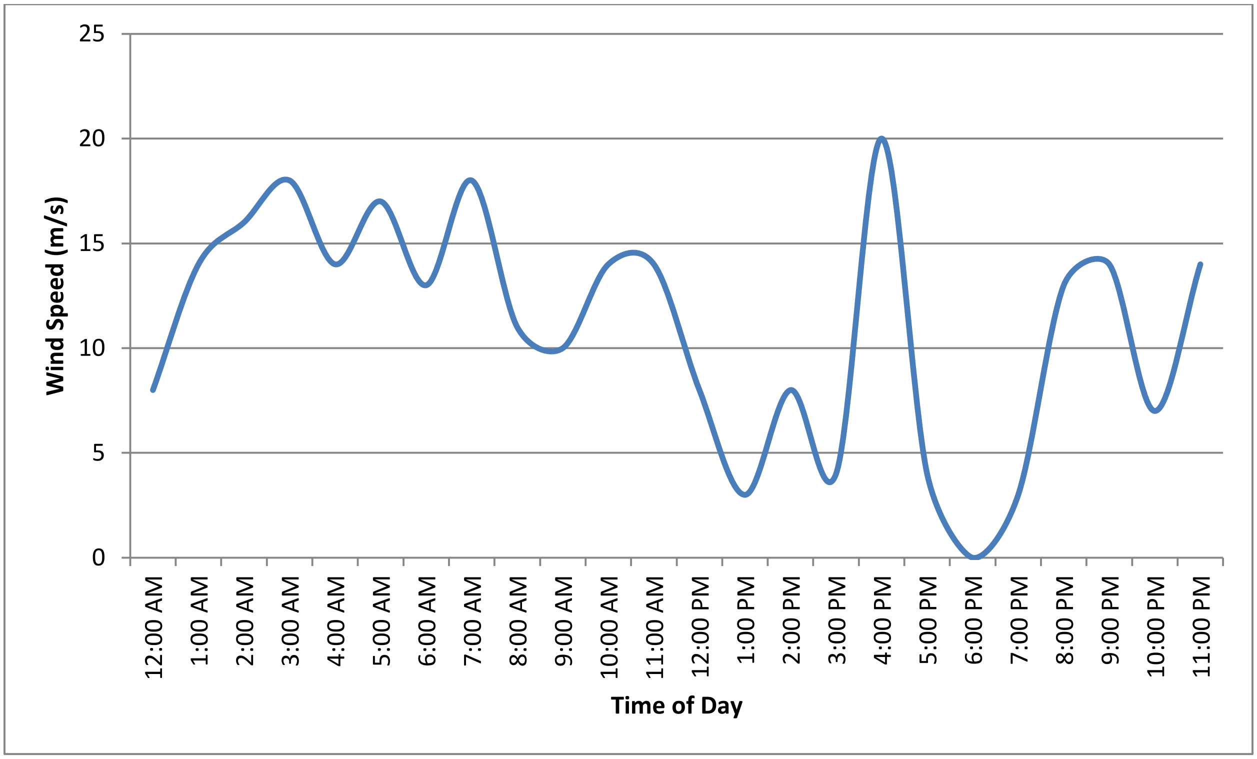
Figure 16: Wind Energy Generation Shape vs. Forecast Demand Gap



Unfortunately, the maximum contribution of wind energy to the Yukon grid is limited by the ability of the Yukon grid to integrate (or accommodate) wind generation. Beyond a certain point, installing more wind generation onto the Yukon grid is not technically practical because the system will not be able to handle short term fluctuations in wind generation output without causing stability problems. An example of the variation in wind speed at the Whitehorse Airport is shown in Figure 17[12].

[12] It is acknowledged that the wind speed at the Whitehorse airport may not accurately reflect, and potentially overstate, wind speed variability for actual wind farm locations in the Yukon, but sub-hourly data for sites under active consideration by YEC is not publicly available at this time.

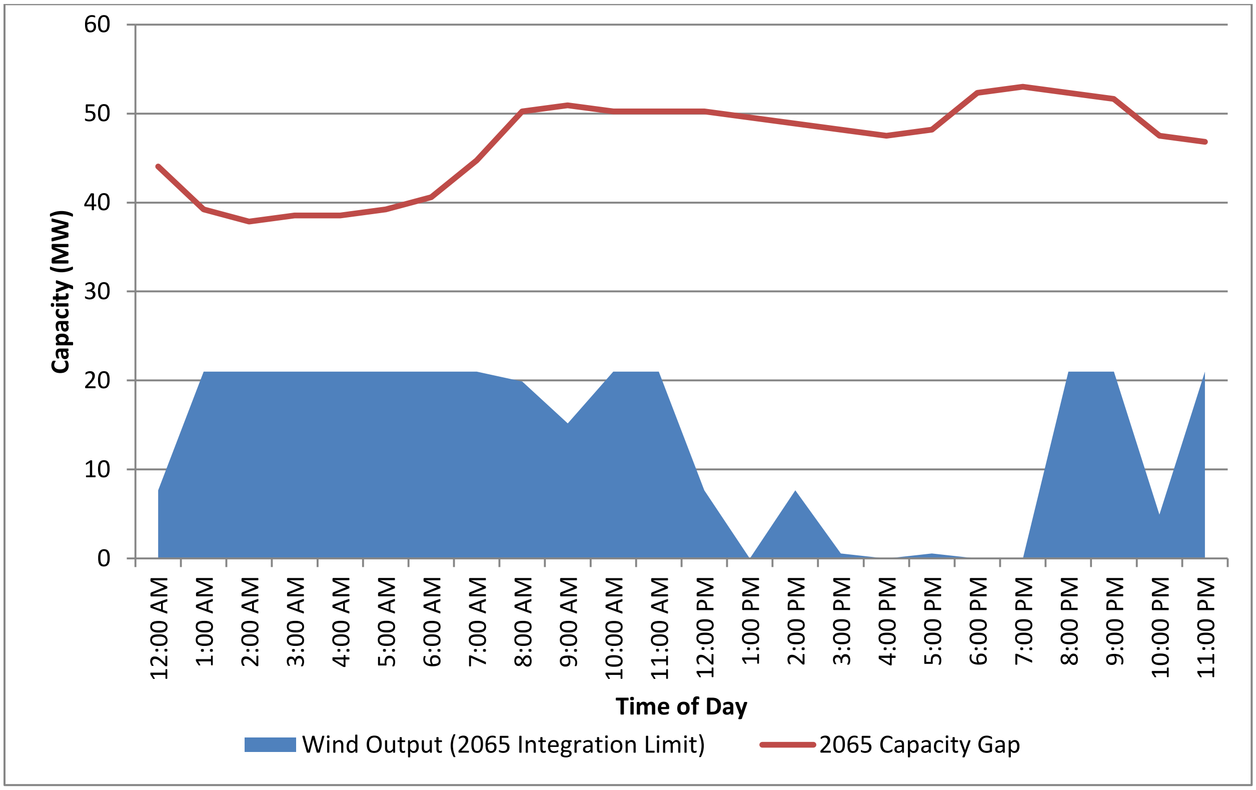
Figure 17: Whitehorse Airport Wind Speed Sample[13]



Wind generation from one or two project sites (as would be the case in the Yukon) is variable and depends on localized changes in wind speeds and conditions. Although fluctuations in wind output on a minute-by-minute or hour-by-hour basis may be mitigated by technologies such as grid scale battery storage, longer periods without wind would cause the output of a wind farm to drop to zero. As a result of this variability and lack of geographic diversity, wind power does not have the ability to meet the Yukon's firm capacity needs. An example of a daily wind energy pattern, assuming maximum wind integration in 2065, is shown in Figure 18. The available capacity varies throughout the day as the wind picks up and dies down.

[13] For July 15, 2015. Source: Environment Canada, 2015

Figure 18: Wind Daily Capacity - Example[14]



Extending the limits on wind integration is an area of active research and development, particularly in the area of utility scale battery installations. As a result, although current wind integration limits are estimated at 10%-15% of installed capacity for an islanded grid, for the purposes of this report the integration limit for wind has been increased to 20% through the addition of emerging grid scale battery storage technologies that make wind easier to integrate into the grid (see Table 11 for a summary, and Appendix B: and Appendix H: for additional details).

Table 11: Assumed Maximum Wind Integration with Battery Support

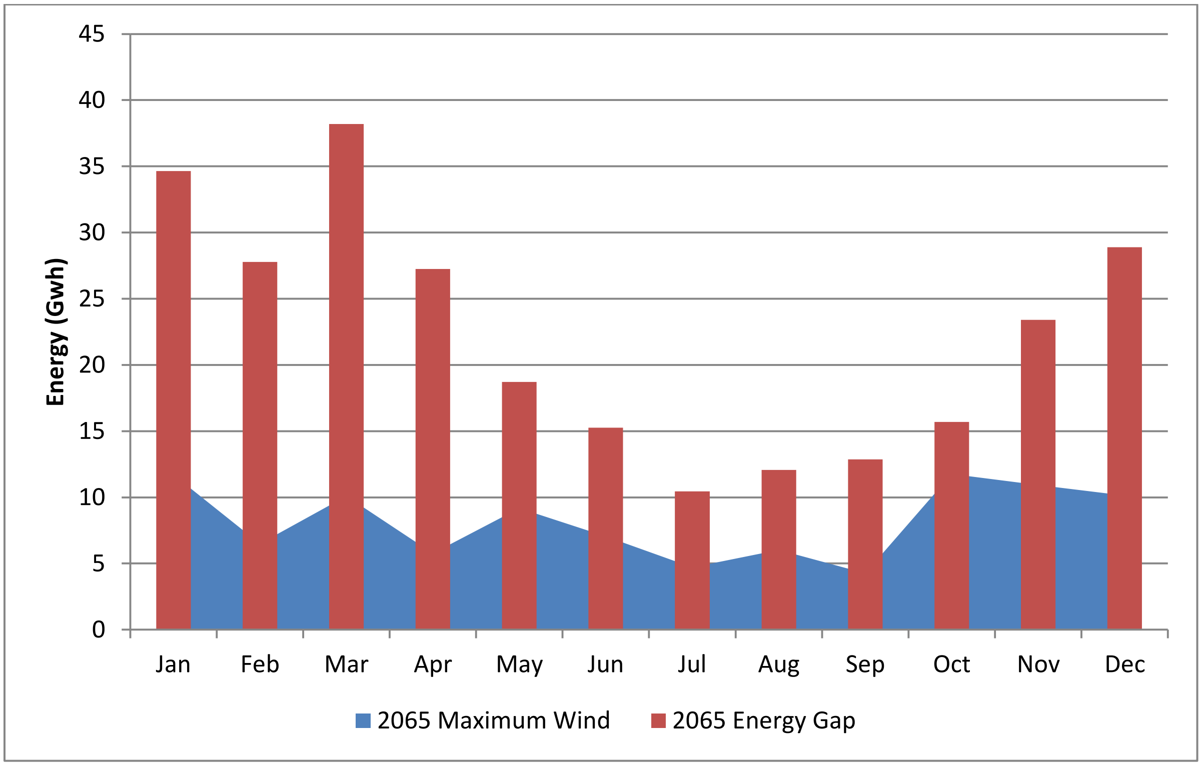
Year	Forecast Peak Demand (MW)	Maximum Wind Penetration (% of Peak Demand)	Maximum Wind Installed Capacity (MW)	Capacity Factor (%)	Maximum Annual Wind Energy (GWh)
2035	109	20%	22	35%	66
2065	141	20%	28	35%	88

Therefore, although the wind generation shape is a reasonable match to the shape of the forecast future energy gap on an average monthly basis, wind integration limits cap the maximum energy available from

[14] Based on Environment Canada hourly measurements for Whitehorse Airport on July 15, 2015 and power curve data for 21x1MW WWD turbines. Actual wind generation variability for Yukon wind sites will be different than at the Whitehorse Airport.

wind as shown in Figure 19. Moreover, as a consequence of wind integration limits, wind is not able to close the forecast energy and capacity gaps without the support of other generation resources and, therefore must be considered in combination with other generation resources when meeting future energy and capacity needs.

Figure 19: Wind Energy – Monthly Average Generation & Gap



In summary, accounting for the limits on installed capacity, the firm (dependable) capacity and energy that can be provided by wind power to the Yukon grid are shown in Table 12.

Table 12: Wind Technical Factors -

Year	Maximum Wind Installed Capacity (MW)	Maximum Wind Firm Capacity (MW)	Capacity Factor (%)	Maximum Annual Wind Energy (GWh)
2035	22	0	35%	66
2065	28	0	35%	88

4.1.2 Wind - Economic Factors

Using assumptions for capital cost, operating cost, transmission and project lifetimes detailed in Appendix B: and based upon previous studies of wind power in the Yukon, the current full utilization LCOE of wind power without battery storage in Yukon in this report is estimated at **$157/MWh** and the full utilization LCOE of wind power with battery storage is **$192/MWh**. It is noted that the cost of wind turbines has been decreasing over time, however, the equipment and labour costs required to erect, operate and maintain wind turbines that make up the majority of the cost of wind generation are based on Yukon pricing.

Table 13: Wind Economic Factors

	Levelized Capital Cost ($/MWh)	**Fixed O&M** ($/MWh)	**Fuel Cost** ($/MWh)	**Total Full Utilization LCOE** ($/MWh)
Without Battery Storage	119	38	0	157
With Battery Storage	151	41	0	192

4.1.3 Wind - Socio-Economic Factors

For the purposes of this study it is assumed that a suitable wind generation project site could be developed. Therefore, wind generation is considered potentially socially acceptable.

Table 14: Wind Socio-Economic Factors

Acceptability
Potentially Acceptable

4.1.4 Wind - Environmental Factors

The land-use impact of wind generation can be thought of as either the direct land requirements of wind turbine foundations, access roads and electrical works, or as the total area of the wind farm, including the area between turbines. Although the space between turbines often remains usable for other purposes, in this report the total land-use requirement is considered for the purpose of consistency. This treatment is similar to that used for transmission lines where the entire right of way is considered as the footprint (rather than just the tower/pole locations).

There are no GHG emissions associated with wind power during direct energy generation.

Table 15: Wind Environmental Factors

Impact	**Intensity**
Land-Use	36 ± 22 hectares/MW
GHG Emissions	0 gCO_2e/kWh

4.1.5 Wind – Summary

As a consequence of wind integration limits, wind is not able to close the forecast energy and capacity gaps without the support of other generation resources, and therefore must be considered in combination with other generation resources when meeting future energy and capacity needs. The contribution wind makes to closing (at least partially), energy and capacity gaps as a resource option are listed in Table 16.

Table 16: Wind Resource Summary[15]

	Technical			Economic	Socio-Economic	Environmental	
	Max. 2065 Energy (GWh/year)	**Max. 2065 Installed Capacity (MW)**	**Max. 2065 Firm Capacity (MW)**	**Full Utilization LCOE ($/MWh)**	**Social Impact**	**Land-Use Footprint (hectares/MW)**	**Production GHG Emissions (gCO_2e/kWh)**
Without Battery Storage	65	21	0	157	Potentially Acceptable	36 ± 22	0
With Battery Storage	88	28	0	192	Potentially Acceptable	36 ± 22	0

4.2 Solar PV Energy

Solar-electric technologies use the energy of the sun to generate electricity, and the most common technology is photovoltaic ("PV") panels, which are placed in locations that get good exposure to the sun (in the northern hemisphere this means south-facing areas). When sunlight hits solar panel arrays, electricity is produced inside individual photovoltaic cells and the electricity is then collected and aggregated for conveyance onto electrical wires for use by a load. In the majority of installations, solar panels are installed in fixed orientations, but in some installations motors and actuators are added to the system so that the panels "follow" the sun over the course of the day. PV panels can be installed in small distributed areas (e.g. home or commercial building rooftops) or in large arrays, known as solar farms or PV power stations.

[15] See Appendix B: for more detail.

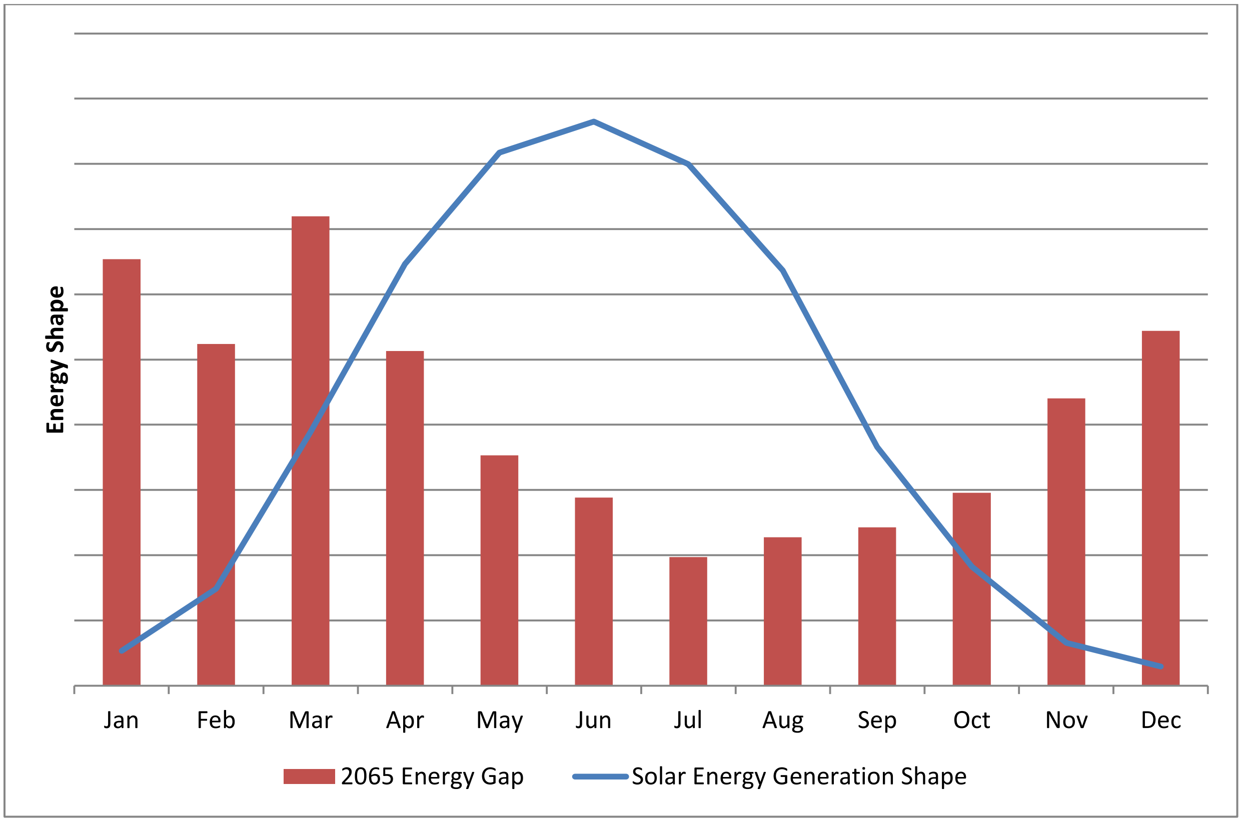
Figure 20: Yukon Solar Energy Pilot[16]

4.2.1 Solar - Technical Factors

Figure 21 compares the typical trend of solar power availability in the Yukon to the forecast future energy needs on a month-by-month basis. The shape of solar energy availability in the Yukon is not an ideal match for the shape of the forecast future energy gap because more solar energy is produced during the summer when demand is lowest, and less energy is produced in the winter when the demand is highest. There is a potential overlap between increased generation levels and higher energy demand in the time around the months of April and May.

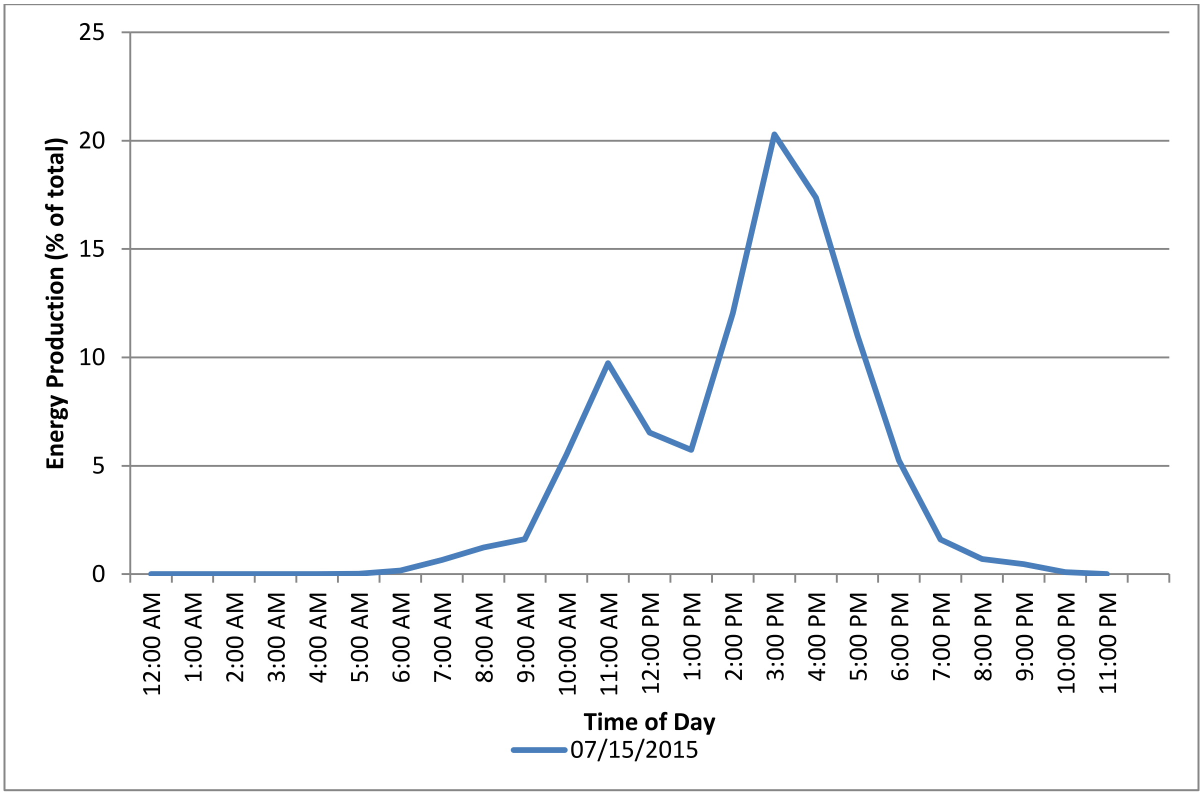
[16] Image Source: Yukon Energy Solutions Centre, 2014. http://www.energy.gov.yk.ca/pdf/report_solar_pilot_monitoring_feb2014.pdf

Figure 21: Solar Energy Generation Shape vs. Forecast Demand Gap



Similar to wind, the maximum contribution of solar energy to the Yukon grid is limited by the ability of the system to accommodate the variability of solar generation. Solar energy production can vary throughout the day with changing sunlight and cloud cover conditions, depending on the number and geographic diversity of solar panel locations. An example of this variation is shown for a rooftop solar installation in Whitehorse for July 15, 2015 in Figure 22.

Figure 22: Whitehorse Daily PV Energy[17]



The limits on solar integration are estimated in Table 17, based on assumptions detailed in Appendix C:. These assumptions may change when pairing solar with an energy storage option such as a battery bank (for more detail, see Appendix H:), but for the purposes of resource option planning a 10% integration limit has been assumed.

Table 17: Assumed Maximum Solar Integration

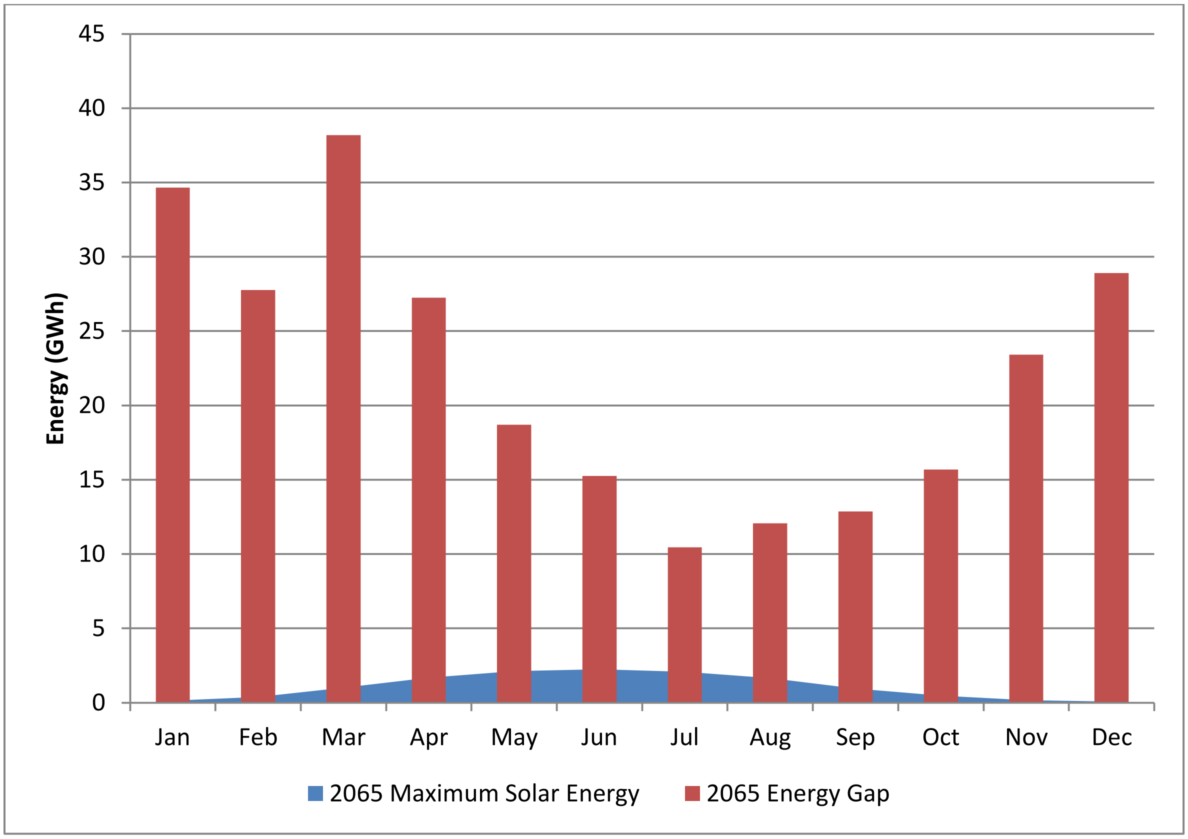
Year	Assumed Peak Demand (MW)	Maximum Solar Penetration (% of Peak Demand)	Maximum Solar Installed Capacity (MW)	Capacity Factor (%)	Maximum Annual Solar Energy (GWh)
2035	109	10%	11	11%	11
2065	141	10%	14	11%	13

The maximum total contribution of solar to the Yukon's energy needs is low due to technical integration limits and a relative lack of direct sunlight in the Yukon during many months of the year. As shown in Figure 23, the average monthly energy for solar generation is not an ideal match to the shape of the forecast future

[17] For July 15, 2015.

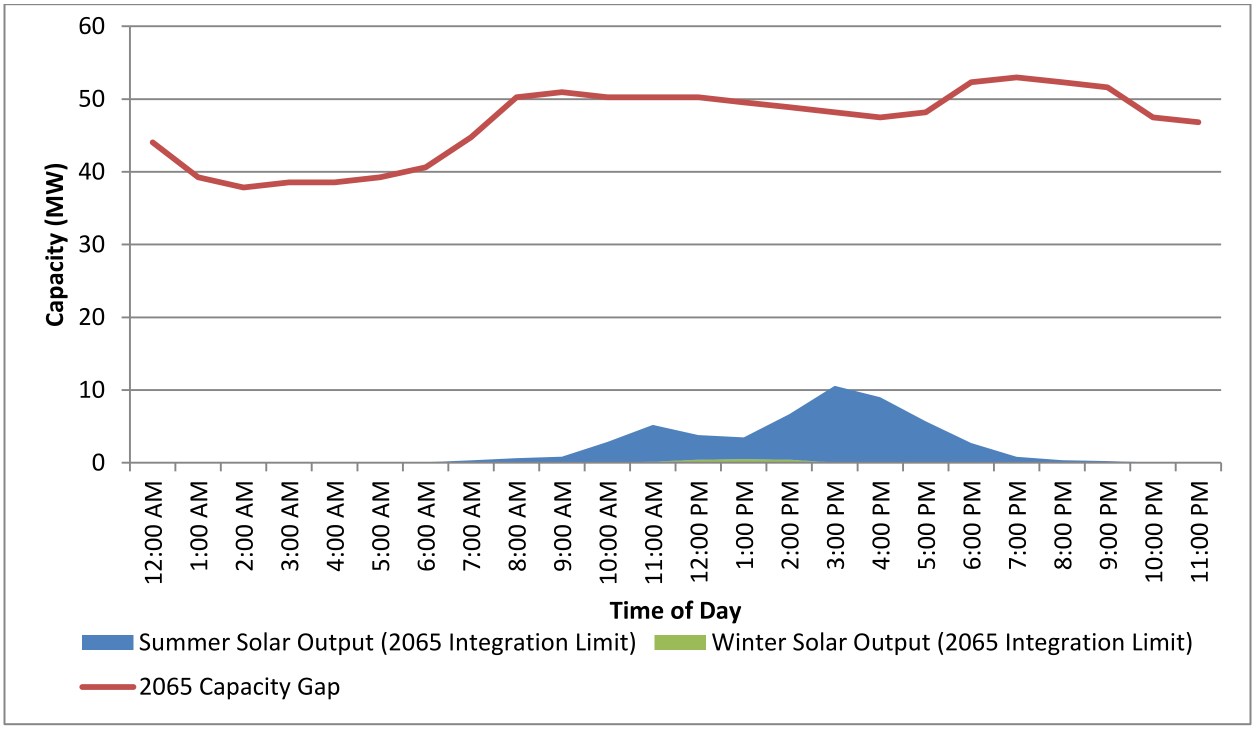
energy gap because solar generation is highest in the summer months when demand in the lowest, and lowest in the winter months when demand is the highest.

Figure 23: Solar Energy – Monthly Average Generation & Gap



As one might expect, the greatest amount of solar energy is available during the middle of the day, with energy production falling off with the setting of the sun. Solar energy is not always available to be called on when required to meet peak demand; therefore solar energy has a firm capacity of zero for the purposes of this report. As shown in Figure 24, after accounting for integration limits, the maximum capacity available from solar is small compared to the overall need, and is significantly reduced during the winter months.

Figure 24: Solar Daily Capacity - Example[18]



In summary, the limits on installed capacity, firm (dependable) capacity and energy that can be provided by solar to the Yukon grid are shown in Table 18.

Table 18: Solar Technical Factors

Year	Maximum Solar Installed Capacity (MW)	Maximum Solar Firm Capacity (MW)	Capacity Factor (%)	Maximum Annual Solar Energy (GWh)
2035	11	0	11%	11
2065	14	0	11%	13

4.2.2 Solar - Economic Factors

Using assumptions for capital cost, operating cost, transmission and project lifetimes detailed in Appendix C:, Midgard estimates the current full utilization LCOE of solar power in Yukon at **$192/MWh**, mainly due to the reduced energy yield of solar panels at higher latitudes. The cost of solar panels has decreased dramatically in recent years and continues to fall. However, the costs associated with construction labour, mounting hardware, foundations and electrical works is not decreasing and is subject to northern price premiums compared to other jurisdictions in southern Canada and the USA.

[18] Solar PV data courtesy of John Maissan and Environment Canada. Summer data from 15/07/2015; Winter data from 15/01/2011.

Table 19: Solar Economic Factors

Levelized Capital Cost ($/MWh)	**Fixed O&M** ($/MWh)	**Fuel Cost** ($/MWh)	**Total Full Utilization LCOE** ($/MWh)
181	11	0	192

4.2.3 Solar - Socio-Economic Factors

For the purposes of this study it is assumed that a suitable solar generation project site could be developed. Therefore, solar generation is considered potentially socially acceptable.

Table 20: Solar Socio-Economic Factors

Acceptability
Potentially Acceptable

4.2.4 Solar - Environmental Factors

The land-use impact associated with the solar PV resource is the area covered by the solar farm, including the panels themselves as well as associated mounting hardware, access roads and electrical infrastructure. In the case of rooftop solar installations, solar PV can take advantage of otherwise unutilized roof area, eliminating the need for incremental land-use change. Solar panels do not emit any GHGs during direct energy generation.

Table 21: Solar Environmental Factors

Impact	**Intensity**
Land-Use	0-3.5 hectares/MW
GHG Emissions	0 gCO_2e/kWh

4.2.5 Solar – Summary

Similar to wind generation, solar integration limits mean that solar generation is not able to close the forecast energy and capacity gaps without the support of other generation resources, and therefore must be considered in combination with other generation resources when meeting future energy and capacity needs. The contribution solar makes to closing (at least partially) energy and capacity gaps as a resource option are listed in Table 22.

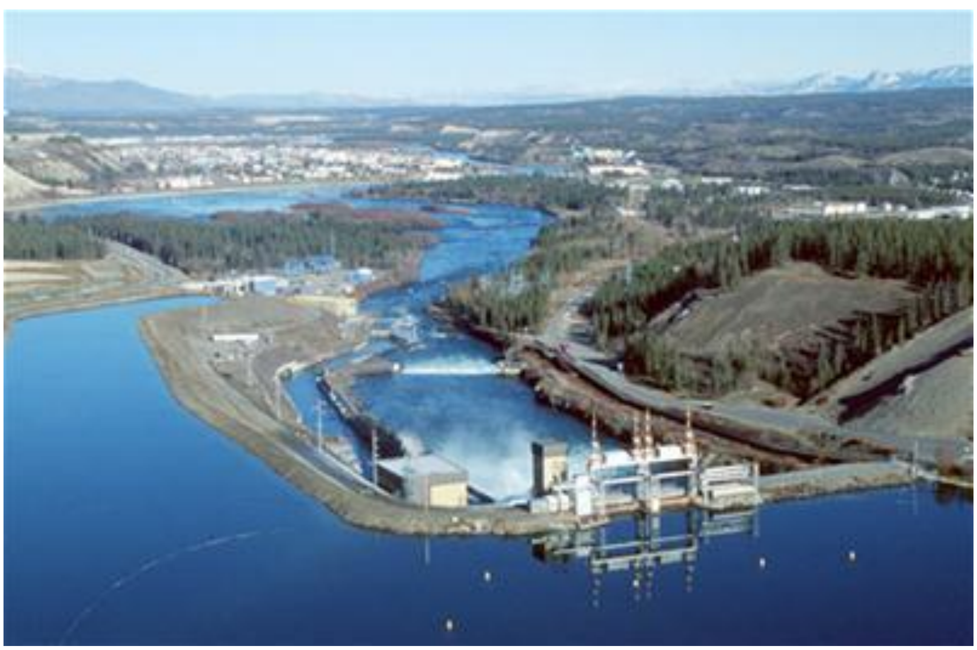
Table 22: Solar Resource Summary[19]

Technical			Economic	Socio-Economic	Environmental	
Max. 2065 Energy (GWh/year)	**Max. 2065 Installed Capacity (MW)**	**Max. 2065 Firm Capacity (MW)**	**Full Utilization LCOE ($/MWh)**	**Social Impact**	**Land-Use Footprint (hectares/MW)**	**Production GHG Emissions (gCO_2e/kWh)**
13	14	0	192	Potentially Acceptable	0-3.5	0

4.3 Hydroelectric - Storage

Hydroelectricity is generated from the gravitational force of falling or flowing water. Hydroelectric facilities with energy storage have water storage reservoirs, which require dams that modify lakes or river valleys. Larger hydroelectric storage facilities often store water from one season for use in another season. Operators manage reservoir storage levels so that they store water when it is plentiful, and use the stored water when it is needed and/or water is scarce.

Figure 25: Whitehorse Hydroelectric Plant[20]



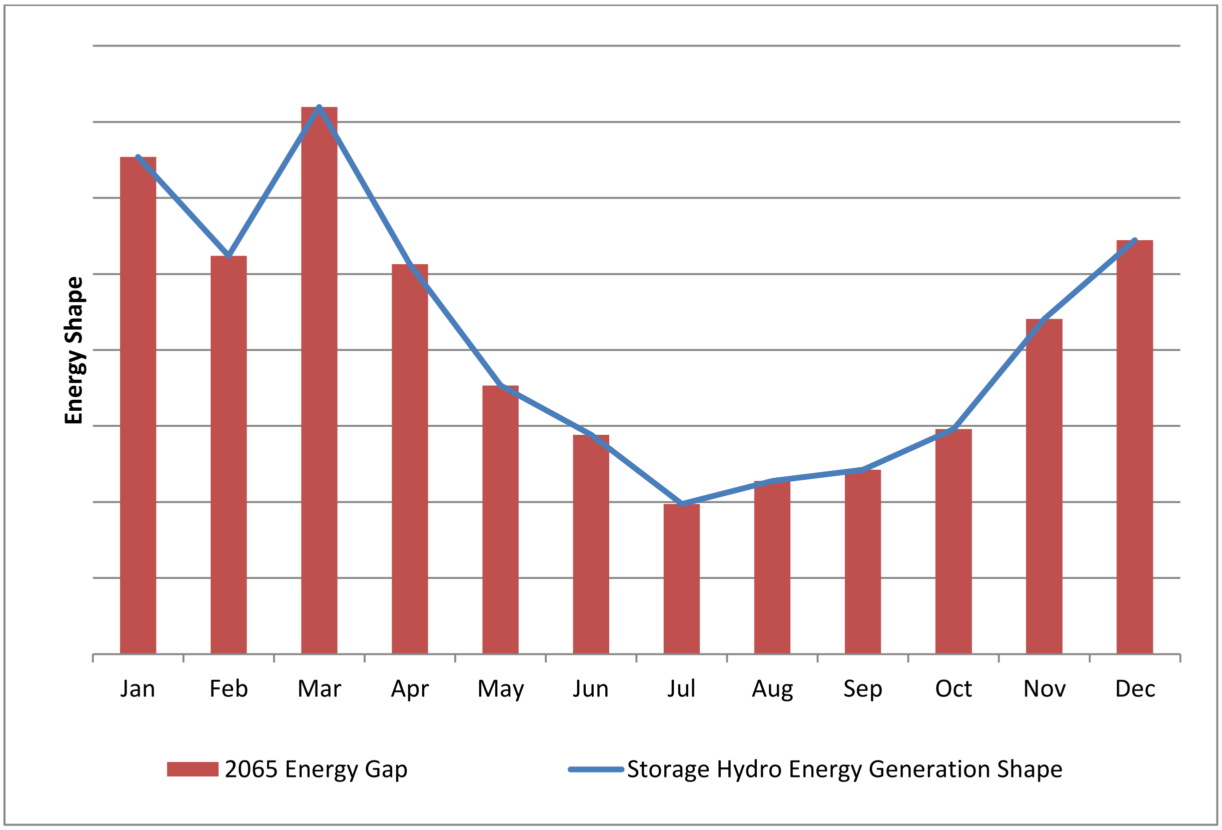
[19] See Appendix C: for more detail.

[20] Image Source: Yukon Water, 2013. http://yukonwater.ca/understanding-yukon-water/water-use-and-conservation/industry-and-natural-resource-sectors

4.3.1 Storage Hydro - Technical Factors

Figure 26 compares the trend of hydro power availability in the Yukon as compared to the forecast future energy needs on a month-by-month basis based on the hydroelectric facilities being evaluated for the Next Generation Hydro project. As can be seen in Figure 26, the shape of storage hydro generation can match the shape of the forecast future energy gap because these hydro projects are capable of storing water in the summer for the times of need in the winter. There is typically excess energy (not shown) compared to demand during the summer months when stream flows are higher and demand is lower.

Figure 26: Storage Hydro Energy Generation Shape vs. Forecast Demand Gap



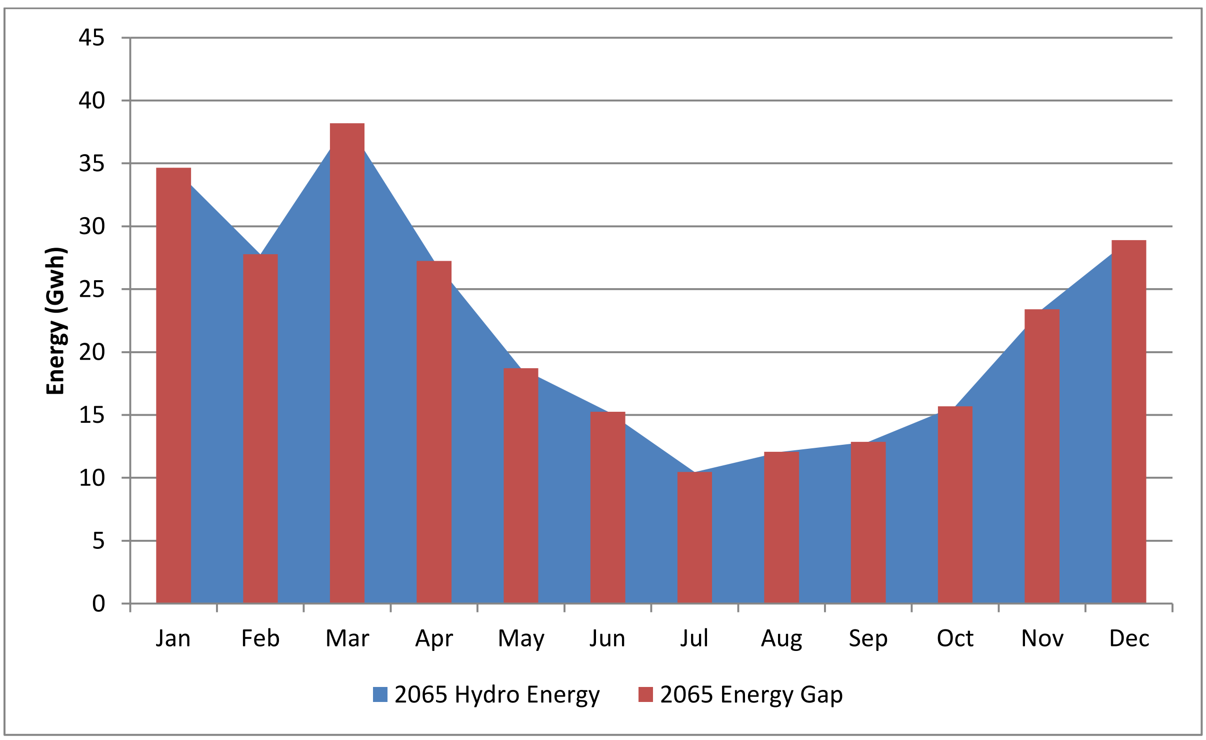
The Yukon grid is able to fully integrate storage hydro generation because hydro with storage is a dispatchable generation source whose output can be managed to exactly meet demand on both a monthly/seasonal basis and throughout the day as daily demands change. Therefore, there are no technical limits on the integration of storage hydro generation on the Yukon grid (see Appendix D: for detail).

Table 23: Assumed Maximum Storage Hydro Integration

Year	Assumed Peak Demand (MW)	Maximum Storage Hydro Penetration (% of Peak Demand)	Maximum Storage Hydro Installed Capacity (MW)	Maximum Annual Large Hydro Energy (GWh)
2035	109	Unlimited	38	393
2065	141	Unlimited	57	557

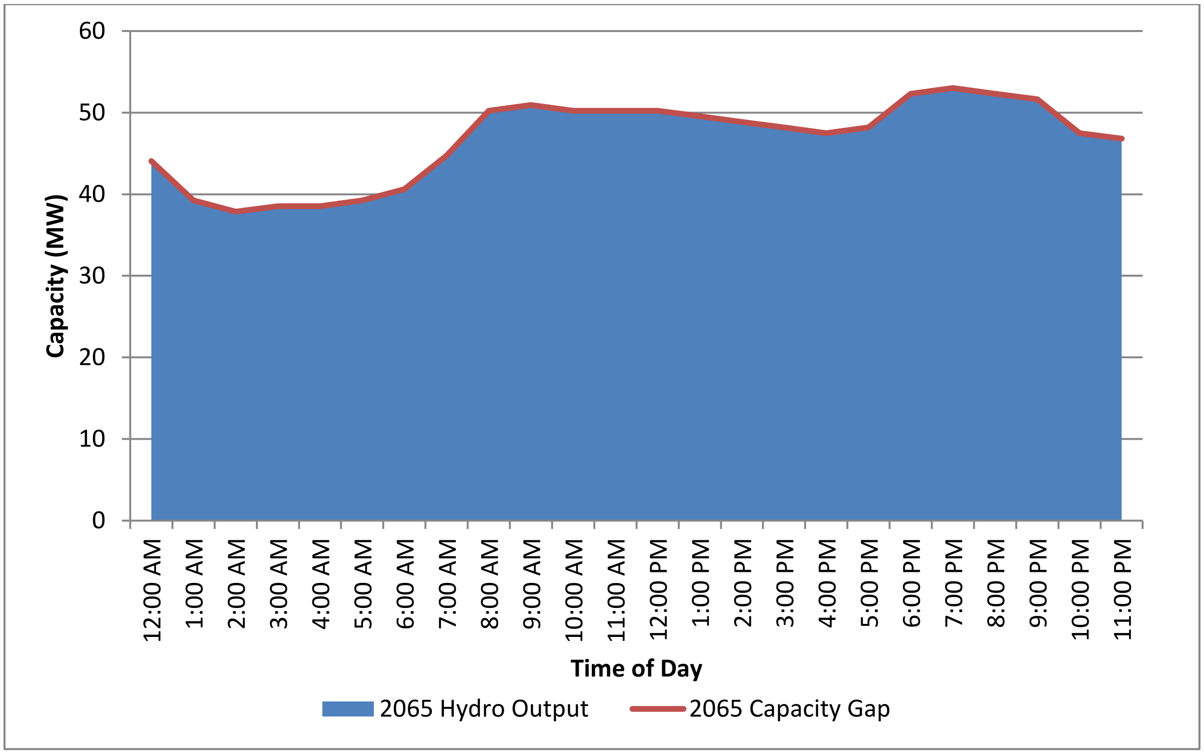
As shown in Figure 27, the annual energy output of a storage hydro plant can be matched to meet seasonal requirements in demand. Such a project would be able to fully meet the winter energy gap without additional resources such as natural gas or diesel generation. Storage hydro is therefore able to meet 100% of the Yukon forecast Baseline energy needs up to the end of 2065.

Figure 27: Storage Hydro Energy – Monthly Average Generation & Gap



Since storage hydro can be used as a "load following" resource, meaning that the output of a storage hydro plant can be continually adjusted to meet variations in demand, storage hydro generation is a dependable source of capacity and is able to meet the forecast capacity needs of the Yukon until and beyond 2065 (see Figure 28).

Figure 28: Storage Hydro Daily Capacity



In summary, the storage hydro projects being considered for Next Generation Hydro have the ability to meet the forecast energy and capacity gaps up to and beyond 2065. The maximum limits on installed capacity, firm (dependable) capacity and energy that can be provided by storage hydro for the purposes of this report are shown in Table 24.

Table 24: Storage Hydro Technical Factors

Year	Maximum Storage Hydro Installed Capacity (MW)	Maximum Storage Hydro Firm Capacity (MW)	Maximum Annual Storage Hydro Energy (GWh)
2035	38	38	393
2065	57	57	557

4.3.2 Storage Hydro - Economic Factors

Using assumptions for capital cost, operating cost, transmission and project lifetimes detailed in Appendix D:, and based on an average of the *Next Generation Hydro* projects with the four lowest estimated costs[21], Midgard estimates the average full utilization LCOE of Next Generation Hydro at **$92/MWh**.

[21] Fraser Falls, Granite Canyon, Detour Canyon and Two Mile Canyon.

Table 25: Large Hydro Economic Factors

Levelized Capital Cost ($/MWh)	**Fixed O&M** ($/MWh)	**Fuel Cost** ($/MWh)	**Total Full Utilization LCOE** ($/MWh)
77	15	0	92

4.3.3 *Storage Hydro - Socio-Economic Factors*

For the purposes of this study it is assumed that a suitable *Next Generation Hydro* project site could potentially be developed. Therefore, storage hydro generation is considered potentially socially acceptable.

Table 26: Storage Hydro Socio-Economic Factors

Acceptability
Potentially Acceptable

4.3.4 *Storage Hydro - Environmental Factors*

The land-use footprint of a storage hydro development is typically dominated by the water reservoir required for the purpose of storing water. The land area flooded as a result of a hydroelectric development is dependent on the characteristics of the project site, including the local topography, water flows (hydrology), water storage requirements, project head and ability to draw down the reservoir (e.g. permissible water level fluctuations). Flooding has social, cultural and environmental impacts that include, but are not limited to, sites of cultural, recreational or historic significance, aquatic ecosystems, terrestrial ecosystems and riparian ecosystems.

There are no GHG emissions associated with direct generation from storage hydro. Emissions due to the decomposition of organic matter in reservoirs are considered to be part of the construction phase in this report, and are not included in the analysis.

Table 27: Storage Hydro Environmental Factors

Impact	**Intensity**
Land-Use	313 hectares/MW (Range: 187 - 545 hectares/MW)
GHG Emissions	0 gCO_2e/kWh

4.3.5 *Storage Hydro – Summary*

As a generation resource, storage hydro provides the dependable energy and capacity required to meet the forecast energy and capacity gaps needs of the Yukon as shown in Table 28.

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Vancouver BC, Canada
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Table 28: Storage Hydro Resource Summary[22]

Technical			Economic	Socio-Economic	Environmental	
Max. 2065 Energy (GWh/year)	**Max. 2065 Installed Capacity (MW)**	**Max. 2065 Firm Capacity (MW)**	**Full Utilization LCOE ($/MWh)**	**Social Impact**	**Land-Use Footprint (hectares/MW)**	**Production GHG Emissions (gCO_2e/kWh)**
557	57[23]	57[24]	92	Potentially Acceptable	313 (Range:187 – 545)	0

[22] See Appendix D: for more detail.

[23] Expandable up to 90-107 MW if required.

[24] Expandable up to 90-107 MW if required.

4.4 Hydroelectric – Run-of-River Hydro

Hydroelectric facilities without water storage are known as "run-of-river" projects, and these projects produce electricity only when water is naturally available and water flows are above minimum ecological threshold levels because some water is always reserved for environmental (e.g. fish) flows. The primary advantage of a run-of-river hydro scheme is that it floods less area than a storage hydroelectric project because a run-of-river hydro project does not need to create an active (i.e. regularly rising & falling) water storage reservoir. However, it is important to note that a fixed level headpond is necessary to create hydrostatic head and cover the intake with water (see Figure 29 below of a 10MW project headpond in British Columbia), and headponds can be significant depending on the local topography. For example, Schwatka Lake is the head pond for the Whitehorse generation facility where a natural river course once flowed.

Since run-of-river hydro projects do not have water storage, they are at a disadvantage when it comes to dispatchable (firm) generation. Similar to wind and solar generation, run-of-river hydro has intermittent resource characteristics because generation output depends on natural river flows, and is not dispatched to match changes in electricity demand. This issue of non-dispatchability is particularly important in the Yukon context because there are significant seasonal variations in stream flow that result in low water flows (i.e. low fuel supply) occurring in the winter when electricity demand is high.

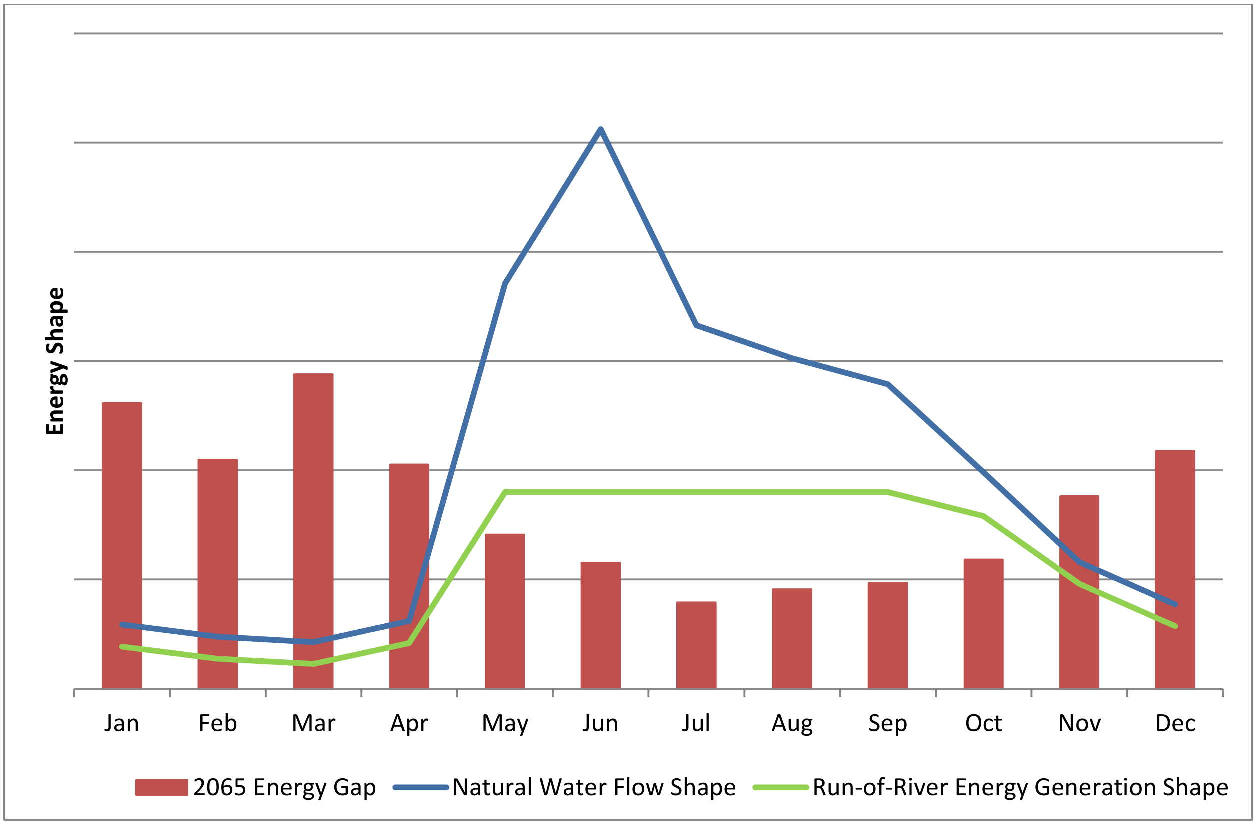
Figure 29: Run-of-River Hydro – Intake Headpond for 10MW Facility[25]

[25] Image Source: Midgard Consulting Inc.

4.4.1 Run-of-River Hydro - Technical Factors

For the purposes of this report, run-of-river hydro will be modeled as generating (<15MW) the maximum possible based on a typical Yukon hydrology for smaller river, typical ecological flows and typical installed generation capacity (see Appendix E: for a description of these typical values). Figure 30 shows the generation for a representative run-of-river hydro project on a monthly basis and illustrates that expected generation is not a great match to the forecast future energy gap[26]. The mis-match occurs because Yukon run-of-river hydro is characterized by an increased generation during the spring/summer freshet (i.e. snow melt period) when demand is lower, and lower generation during the colder/winter months when demand is the highest.

Figure 30: Run-of-River Hydro Energy Generation Shape vs. Forecast Demand Gap



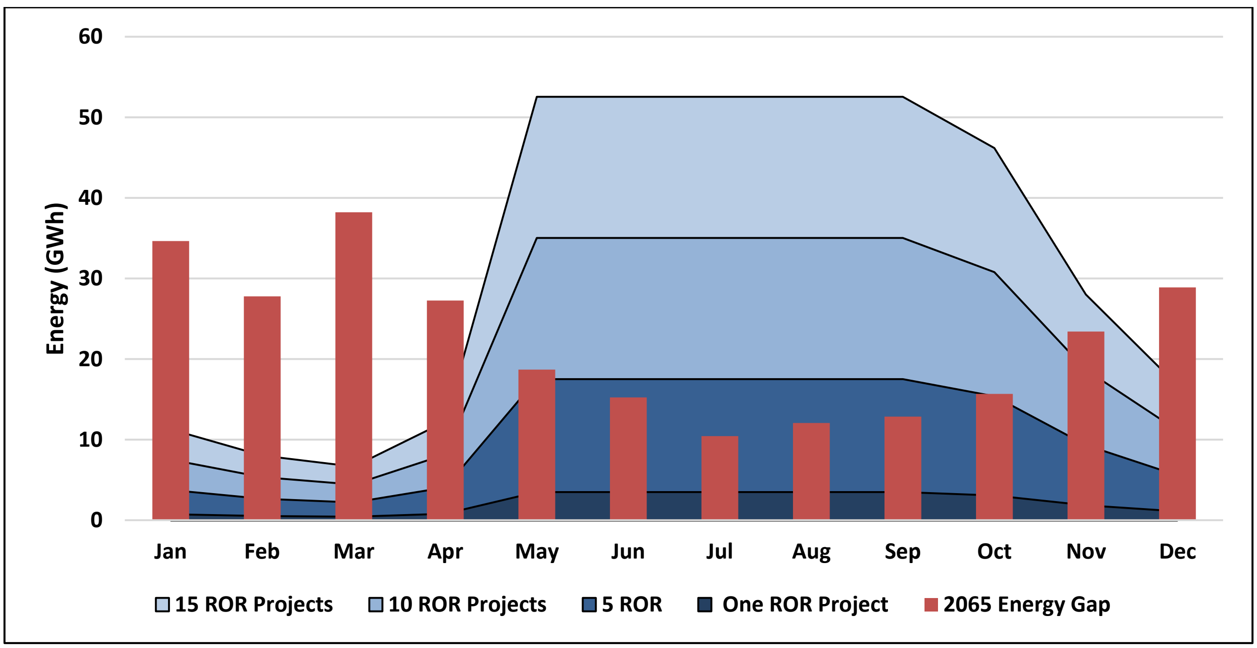
The maximum contribution of run-of-river hydro to dependable capacity on the Yukon grid is also constrained by natural fluctuations in daily generation output. These fluctuations must be accommodated by other generation resources on the Yukon grid because run-of-river electricity output follows changes in available water, rather than following changes in electricity demand.

[26] Midgard has sized the "typical" Yukon run-of-river hydro project so that it emphasizes the production of winter energy rather than maximizing annual energy because the Yukon has a need for winter generation and little/no need for additional summer generation. As a result, it is assumed that a typical project has an installed capacity of approximately 0.9 x MAD (Mean Annual Discharge), rather than the 1.5-1.7 x MAD that is more typical for projects that value summer energy more highly than in the Yukon context.

The limits on run-of-river hydro integration are less than for wind or solar generation because water flow variability tends to be moderate and more predictable. For example, the noon day sun melts snow more rapidly than at other times of day, and this snowmelt increase moves through the watershed and arrives at the run-of-river facility some hours later. This pattern often repeats on a daily basis and is predictably modified by events such as cloud cover, air temperature and rainfall events. As a result of this forecast generation predictability, for the purposes of this report no technical limits will be placed upon run-of-river hydro integration. However, in practice, limits on run-small hydro generation would be due to economic constraints because run-of-river hydro produces most of its energy during the freshet (snowmelt period) when demand is lower, and the electricity produced has little economic value (see Appendix E: for more detail).

Therefore, despite not having technical limits on run-of-river hydro integration, the relative absence of dependable winter energy render this resource poorly suited for meeting the Yukon's forecast energy needs. For example, as shown in Figure 31, as the number of run-of-river hydro projects increases, the quantity of spilled (and therefore wasted) energy increases dramatically with relatively little of the winter energy gap being satisfied. Therefore, run-of-river hydro is another generation resource that is not able to satisfy (at least in a practical and economic sense[27]) the Yukon's forecast energy and capacity gaps.

Figure 31: Run-of-River Hydro Energy – Monthly Average Generation & Gap



[27] Run-of-River could technically meet the forecast gap, but the quantity of run-of-river projects would be so large (e.g. >90 projects) that the economics and practicality of such a solution would not be reasonable. Therefore, run-of-river hydro must team up with other generation resources that provide firm winter energy and capacity.

Similarly, when considering the capacity attributes of a run-of-river facility, since the output of a run-of-river facility can be forecast with some certainty, run-of-river generation has more dependable capacity than either wind or solar generation. For example, during the summer with the backing of a melting snowpack, minimum stream flows can be reasonably predicted; therefore, a reasonable percentage of the installed capacity may be considered dependable capacity. However, stream flows during the winter are very low, and in practice many run-of-river hydro plants shut down entirely during the winter due to freezing and the need to maintain minimum environmental flows (which take water away from energy generation). As a result, during winter/colder periods, there is a comparatively smaller contribution to dependable winter capacity because there is less water reliably available for generation.

In summary, although there are no technical limits on installed capacity, firm (dependable) winter capacity and the annual energy that can be provided by a typical run-of-river hydro project to the Yukon grid, the technical factors for a typical run-of-river project are as shown in Table 29.

Table 29: Run-of-River Hydro Technical Factors

Typical Run-of-River Hydro Installed Capacity (MW/project)	Typical Run-of-River Hydro Firm Capacity (MW/project)	Typical Annual Run-of-River Hydro Energy (GWh/project)
4.7[28]	0.6	23.4

4.4.2 Run-of-River Hydro - Economic Factors

Using assumptions for capital cost, operating cost, transmission and project lifetimes detailed in Appendix E:, Midgard estimates the current full utilization LCOE for a representative run-of-river hydro project in the Yukon at **$116+/MWh**. However, it should be noted that this estimate is based on the development of the most economically viable potential projects assuming they are located relatively close to the existing electrical grid. This assumption may hold true for the first few projects developed in the Yukon, but is unlikely to hold as the quantity of projects increases and project remoteness increases. A detailed resource assessment would be required to determine how many sites exist at this favorable price point and what the cost increases are as additional projects are added. Adding more and more run-of-river hydro developments in Yukon would incur incrementally higher costs for each project, as the best sites would be developed first, and subsequent projects would likely cost considerably more than $116+/MWh.

[28] Midgard has sized the “typical” Yukon run-of-river hydro project so that it emphasizes the production of winter energy rather than maximizing annual energy because the Yukon has a need for winter generation and little/no need for additional summer generation. As a result, it is assumed that a typical project has an installed capacity of approximately 0.9 x MAD (Mean Annual Discharge), rather than the 1.5-1.7 x MAD that is more typical for projects that value summer energy more highly than in the Yukon context.

Table 30: Run-of-River Hydro Economic Factors

Levelized Capital Cost ($/MWh)	**Fixed O&M** ($/MWh)	**Fuel Cost** ($/MWh)	**Total Full Utilization LCOE** ($/MWh)
97	19	0	116

4.4.3 Run-of-River Hydro - Socio-Economic Factors

For the purposes of this study it is assumed that several suitable run-of-river hydro projects could be developed. Therefore, run-of-river hydro generation is considered potentially socially acceptable.

Table 31: Small Hydro Socio-Economic Factors

Acceptability
Potentially Acceptable

4.4.4 Run-of-River Hydro - Environmental Factors

A run-of-river hydro scheme generally has a very small land-use footprint when compared to storage hydro project due to the absence of a reservoir (but a headpond) and potentially shorter transmission and road distances to the electrical grid (at least for the first few projects). Typically the largest land-use impacts associated with run-of-river hydro development are not the direct impacts for water impoundment (e.g. intake weir and headpond), water conveyance (e.g. penstock), and powerhouse, but rather are the lands required for road and transmission rights-of-way.

As with other forms of hydropower, the GHG emissions for direct generation are zero.

Table 32: Small Hydro Environmental Factors

Impact	**Intensity**
Land-Use	≈11 hectares/MW
GHG Emissions	0 gCO_2e/kWh

4.4.5 Run-of-River Hydro – Summary

Although this report has imposed no technical limits on the quantity of run-of-river projects that could be implemented in the Yukon, in practice the poor match between generation supply (i.e. high summer generation) and demand (i.e. high winter demand) means that similar to wind and solar generation, run-of-river hydro generation must work with other generation types to economically (and practically) meet the forecast Yukon demands for energy and capacity.

Table 33: Run-of-River Hydro Resource Summary[29]

Technical			Economic	Socio-Economic	Environmental	
Typical Run-of-River Hydro Installed Capacity (MW/project)	**Typical Run-of-River Hydro Firm Capacity (MW/project)**	**Typical Annual Run-of-River Hydro Energy (GWh/project)**	**Full Utilization LCOE ($/MWh)**	**Social Impact**	**Land-Use Footprint (hectares/MW)**	**Production GHG Emissions (gCO_2e/kWh)**
4.7	0.6	23.4	116+	Potentially Acceptable	≈11	0

4.5 Hydroelectric – Small Hydro Storage

Similar to run-of-river hydro projects, small (<15MW) hydro storage projects can also be found across the Yukon. Small hydro storage projects are found in areas with suitable topography and are generally divided into two types of hydro storage projects; those that dam lakes to make a modified lake reservoir, and those that dam rivers to create a new reservoir. From the perspective of informing what a "typical" Yukon small hydro storage project looks like, Midgard reviewed past studies of small hydro storage projects and developed an "average" project to use for illustration purposes (see Appendix I:).

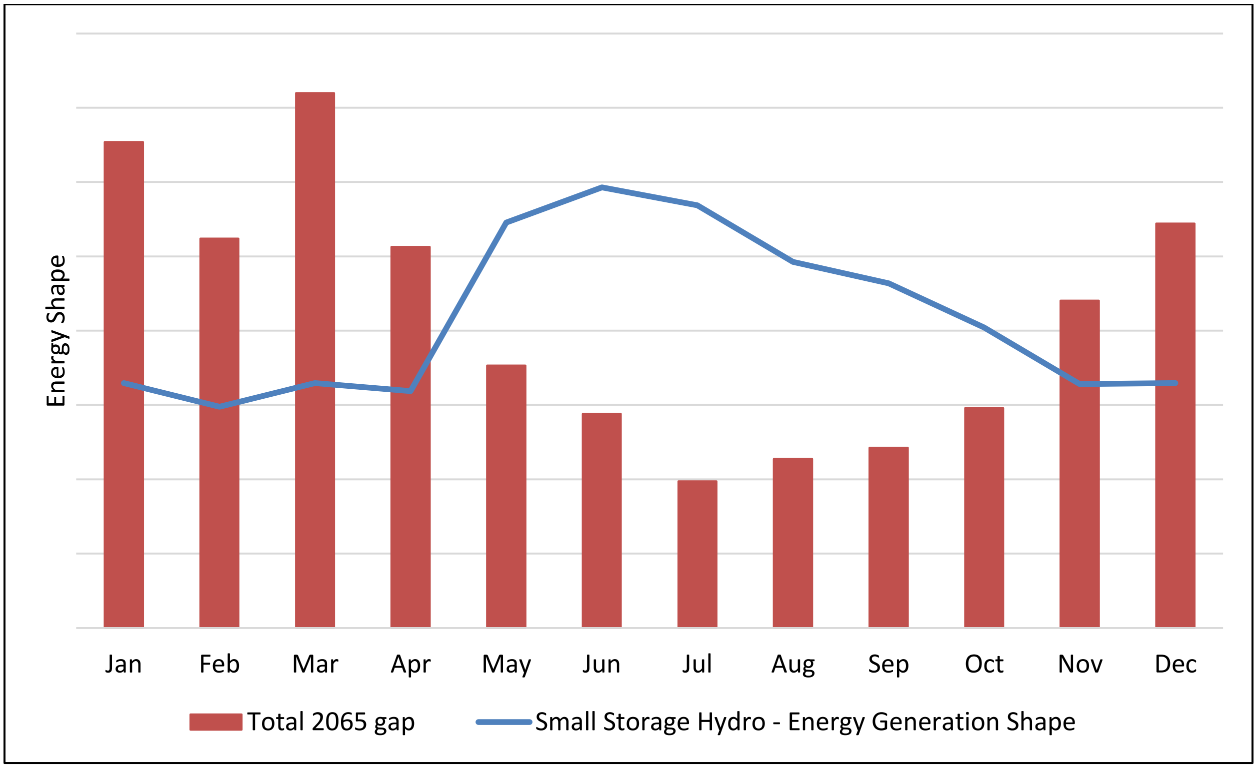
A challenge faced by small hydro storage is that there will be a limited quantity of projects that provide significant winter energy and winter capacity while being located close enough to the grid that they are economic and have small environmental footprints. Simply put, because a single small hydro storage project is smaller than a Next Generation Project, small hydro projects have less ability to absorb the cost of transmission necessary to interconnect with the Yukon's electrical grid, and may have comparable aggregated environmental impacts.

4.5.1 Small Hydro Storage - Technical Factors

For the purposes of this report, small hydro storage was modeled as generating the maximum possible based on a typical Yukon hydrology for smaller rivers and typical ecological flows (see Appendix I: for a description of these typical values). Figure 32 shows the generation for a representative small hydro storage project on a monthly basis and illustrates that expected generation has winter energy and capacity to meet the forecast future energy gap.

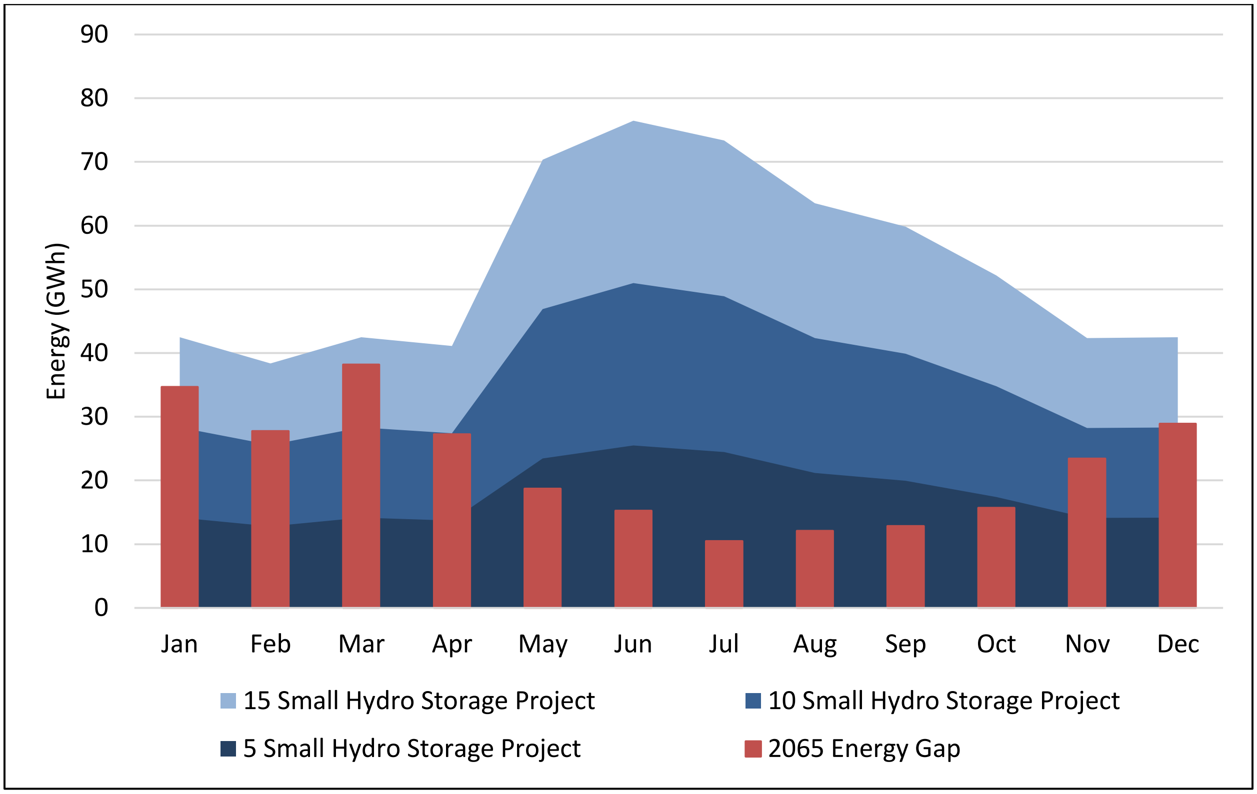
[29] See Appendix E: for more detail.

Figure 32: Small Hydro Storage - Energy Generation Shape vs. Forecast Demand Gap



Since small hydro storage projects have water storage and contribute to dependable winter capacity, for the purposes for this report there are no limits on small hydro storage integration. In practice however, the limits on small hydro generation would be due to economic constraints because small hydro storage projects will require significant transmission infrastructure (relative to project size) to connect to the grid, especially as any easily constructed projects are developed and the remaining projects become more challenging (& costly) to develop. Assessing which projects are suitable for development is outside the scope of this report and is part of a utility resource planning exercise. Nonetheless, as an illustration, if the Yukon forecast demand was met only with the typical small hydro storage projects, the Yukon would require approximately 14 small hydro storage projects during an average water year to meet the forecast energy demand.

Figure 33: Small Hydro Storage Energy – Monthly Average Generation & Gap[30]



In summary, although there are no technical limits on installed capacity, firm (dependable) capacity, and the annual energy that can be provided by a typical small hydro storage project to the Yukon grid, the technical factors for a typical small hydro storage project are shown in Table 34.

Table 34: Small Hydro Storage - Technical Factors

Typical Small Hydro Storage Installed Capacity (MW/project)	Typical Small Hydro Storage Firm Capacity (MW/project)	Typical Annual Small Hydro Storage Energy (GWh/project)
6.5	4.2	43

4.5.2 Small Hydro Storage - Economic Factors

Using assumptions for capital cost, operating cost, transmission and project lifetimes detailed in Appendix I:, Midgard estimates the current full utilization LCOE for a representative small hydro storage project in the Yukon at **$126+/MWh**. However, it should be noted that this estimate is based on the development of a small number of the most economically viable potential projects, and a detailed resource assessment would

[30] Based on the economical limit for 2065 in Scenario 3 (30MW)

be required to determine how many sites exist at this type of price point. Adding more small hydro storage projects in Yukon would incur incrementally higher costs for each project, as the best sites would be developed first, and subsequent projects would likely cost considerably more than $126+/MWh.

Table 35: Small Hydro Storage Economic Factors

Levelized Capital Cost ($/MWh)	**Fixed O&M** ($/MWh)	**Fuel Cost** ($/MWh)	**Total Full Utilization LCOE** ($/MWh)
106	20	0	126+

4.5.3 Small Hydro Storage - Socio-Economic Factors

For the purposes of this study it is assumed that suitable small hydro storage projects could be developed. Therefore, small hydro storage generation is considered potentially socially acceptable.

Table 36: Small Hydro Storage Socio-Economic Factors

Acceptability
Potentially Acceptable

4.5.4 Small Hydro Storage - Environmental Factors

In order to deliver winter energy, a small hydro storage project has a considerable land-use footprint when compared to run-of-river projects due to the presence of a water storage reservoir. Typically the largest land-use impacts associated with hydro storage projects are the direct impacts for water storage, road access, and transmission rights-of-way. When compared to Next Generation Hydro (i.e. large hydro storage projects), the footprint of small hydro storage projects is potentially greater than for Next Generation Hydro projects because the median[31] small hydro storage footprint is 390 Ha/MW compared to the average Next Generation Hydro footprint of 313 Ha/MW. However, it is important to state that the land use impacts cannot be directly compared because the impacts of modifying a lake (typically small storage hydro) and creating a new reservoir (Next Generation Hydro and some small hydro projects) are different.

As with other forms of hydropower, the GHG emissions for direct generation are zero.

Table 37: Small Hydro Storage Environmental Factors

Impact	**Intensity**
Land-Use	Median: 390 Ha/MW
GHG Emissions	0 gCO_2e/kWh

[31] Median footprint was chosen for small hydro storage projects because the small hydro storage footprint data is potentially skewed by the impact of small hydro projects with disproportionately large footprints relative to the installed capacity.

4.5.5 Small Hydro Storage – Summary

Although there are no technical limits on the quantity of small hydro storage projects that could be implemented in the Yukon, project availability and proximity to the transmission grid will limit the number of projects suitable for development in practice.

Table 38: Small Hydro Storage Resource Summary[32]

Technical			Economic	Socio-Economic	Environmental	
Typical Small Hydro Storage Installed Capacity (MW)	**Typical Small Hydro Storage Firm Capacity (MW)**	**Typical Annual Small Hydro Storage Energy (GWh)**	**Full Utilization LCOE ($/MWh)**	**Social Impact**	**Land-Use Footprint (hectares/MW)**	**Production GHG Emissions (gCO_2e/kWh)**
6.5	4.2	43	126+	Potentially Acceptable	390 (Median)	0

4.6 Hydroelectric - Pumped Storage

A pumped storage project has an upper reservoir and a lower reservoir (or other source of water), and can either operate in the familiar generation mode (releasing water from the upper reservoir and passing it through turbines to produce electricity), or in pumping mode (reversing the turbine direction and consuming power in order to pump water into the upper reservoir).

Pumped storage hydro is related to traditional storage hydro and has many similar characteristics such as water storage, but the fundamental difference is that pumped storage hydro is a *net consumer of energy* (i.e. it consumes more energy than it produces). The reason that pumped storage hydro is a net consumer of energy is that it first pumps water uphill from a lower reservoir/water source to an upper reservoir for later use, and the action of pumping water uphill consumes more energy (due to efficiency losses) than is recovered when the stored water is released for generation purposes.

[32] See Appendix I: for more detail.

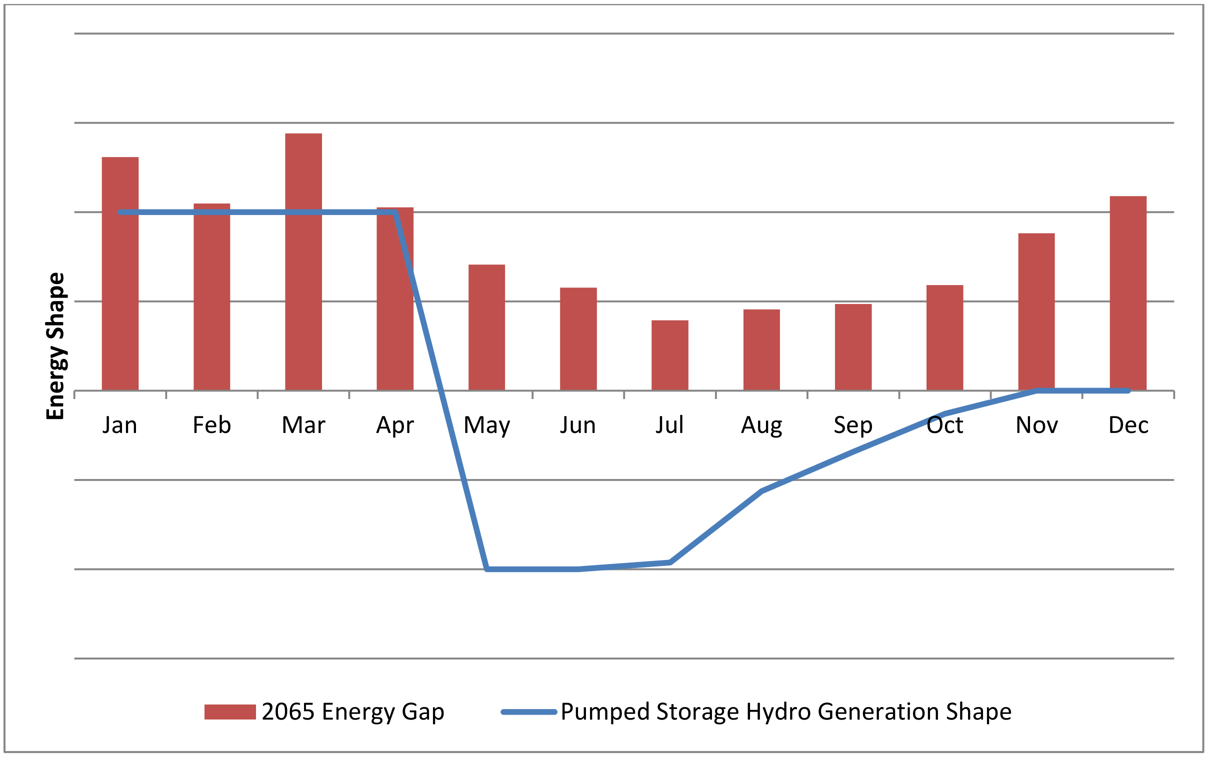
Figure 34: Pumped Storage Hydro[33]

4.6.1 Pumped Storage - Technical Factors

A pumped storage asset does not contribute to the overall energy supply and is a *net consumer of energy.* Pumped storage is, however, able to store energy from other resources when there is an excess of supply of generation, and to generate energy later when energy is in higher demand. In the Yukon context this means that pumped storage can store surplus summer energy for later use in the winter months when generation (e.g. solar, run-of-river hydro, small storage hydro) is scarce. The net energy consumption of pumped storage results from the inefficiencies associated with the process of pumping water uphill and then releasing it back downhill. Figure 35 illustrates how a pumped storage facility could be used on a seasonal basis in the Yukon to consume energy during the summer months (i.e. storing water) and produce energy during the winter months (i.e. releasing water).

[33] Image Source: Vattenfall, 2011; Reproduced under Creative Commons license.

Figure 35: Pumped Storage Hydro Generation Shape vs. Forecast Demand Gap



The maximum integration of pumped storage on the Yukon grid is theoretically limited only by the availability of suitable sites for development. A pumped storage project requires two reservoirs which are located close to each other, but with a significant elevation difference between them and the ability to pump water between the reservoirs. For the purposes of this study, it has been assumed that a single pumped storage facility with 20 MW of capacity and 50 GWh of seasonal storage could be developed in the Yukon (for more detail, refer to Appendix F:).

Table 39: Assumed Maximum Pumped Storage Integration

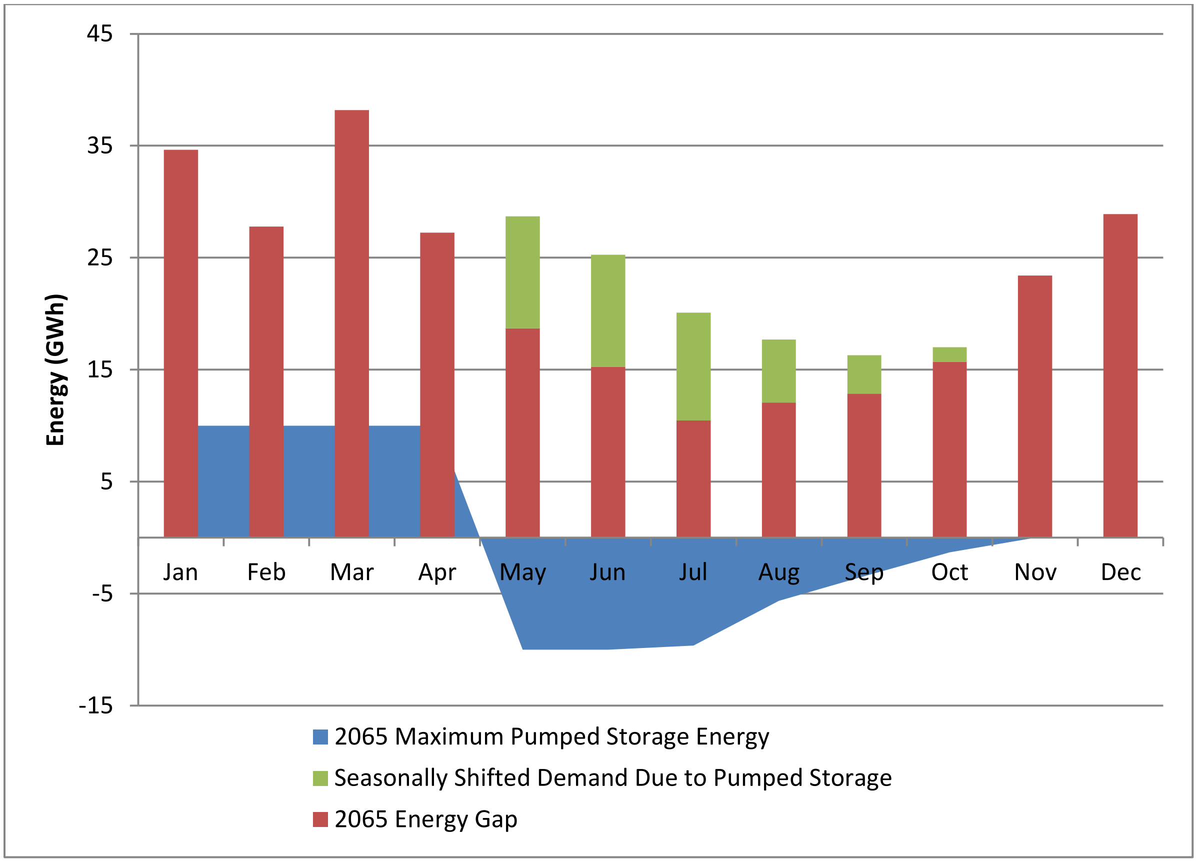
Year	Assumed Peak Demand (MW)	Maximum Pumped Storage Penetration (% of Peak Demand)	Maximum Pumped Storage Installed Capacity (MW)	Maximum Annual Pumped Storage Energy (GWh)[34]
2035	109	N/A	20	-10
2065	141	N/A	20	-10

Although a seasonally operated pumped storage project would not provide any additional energy to meet the forecast needs of the Yukon, it is able to *shift* energy demand from one season to another. In this way, pumped storage changes the shape of the forecast energy gap by reducing the demand for winter energy

[34] Based on an 80% round-trip efficiency, 50GWh of energy for pumping water to the upper storage reservoir, and 40GWh of resulting generation potential. Due to losses in the process, pumped storage is an overall consumer of energy on an annual basis.

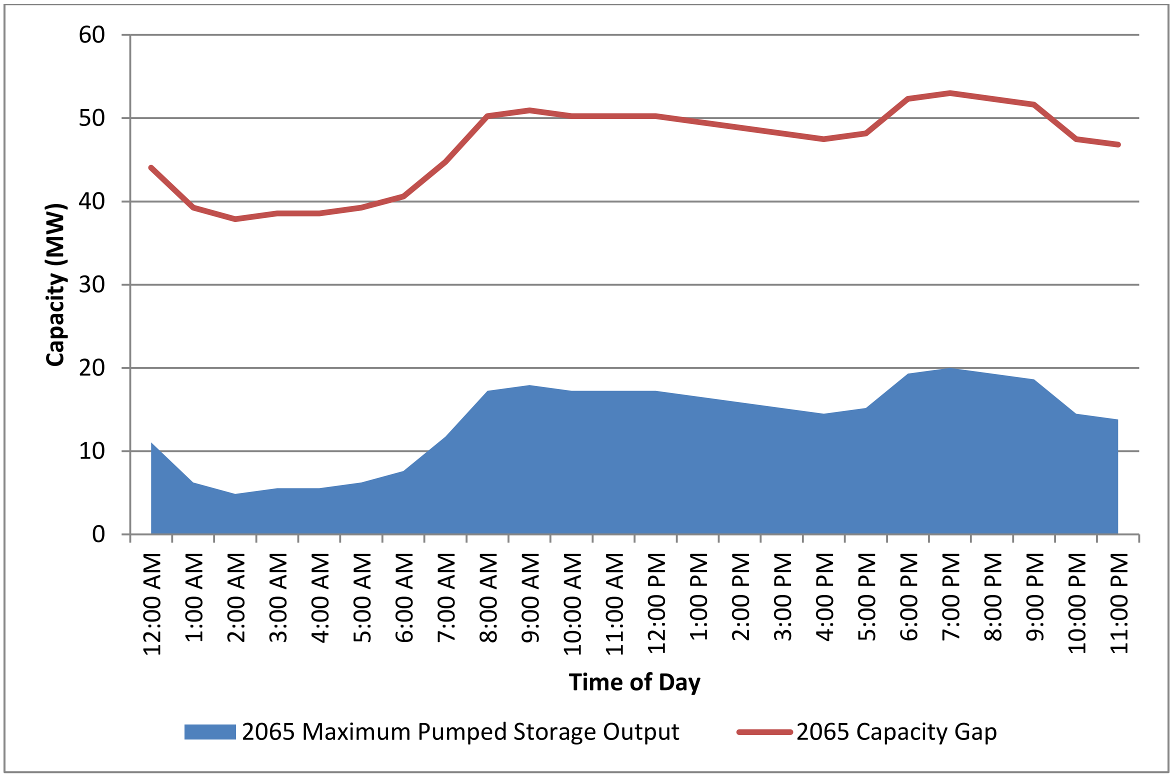
while increasing the demand for summer energy. Figure 36 demonstrates how the shape of the Yukon energy gap is changed by the presence of a pumped storage project.

Figure 36: Pumped Storage – Monthly Average Generation & Gap



A typical pumped storage resource is able to be dispatched to meet instantaneous changes in demand, and is therefore a “load following” resource providing dependable capacity to the grid. Its daily output is matched to the load (demand) curve exactly.

Figure 37: Pumped Storage Daily Capacity[35]



In summary, the limits on installed capacity, firm (dependable) capacity and energy that can be provided by pumped storage on the Yukon grid are shown in Table 40.

Table 40: Pumped Storage Hydro Technical Factors

Year	Maximum Pumped Storage Hydro Installed Capacity (MW)	Maximum Pumped Storage Hydro Firm Capacity (MW)[36]	Maximum Pumped Storage Hydro Hydro Energy (GWh)
2035	20	20	-10
2065	20	20	-10

4.6.2 Pumped Storage - Economic Factors

The full utilization LCOE for pumped storage is calculated differently than for other resources because it is not a *source* of energy. Rather, the LCOE is calculated as the cost of *storage* of surplus energy produced from

[35] Demand curve based on data for January 28, 2013. Source: Next Generation Hydro, http://www.nextgenerationhydro.ca

[36] If technically feasible.

other resources and provided to the pumped storage facility for free. Based on available literature as detailed in Appendix F:, Midgard has estimated the cost of seasonal pumped storage at **$183/MWh.**[37]

Table 41: Pumped Storage Economic Factors

Levelized Capital Cost ($/MWh)	**Fixed O&M** ($/MWh)	**Fuel Cost** ($/MWh)	**Total Full Utilization LCOE** ($/MWh)
149	34	0	183

4.6.3 Pumped Storage - Socio-Economic Factors

For the purposes of this study it is assumed that one suitable pumped storage project could be developed. Therefore, pumped storage is considered potentially socially acceptable.

Table 42: Pumped Storage Socio-Economic Factors

Acceptability
Potentially Acceptable

4.6.4 Pumped Storage - Environmental Factors

The total land-use impact of a pumped storage project may be less than for a traditional hydro project if the lower or upper reservoirs are pre-existing (utilizing natural lakes) because this removes the need for creating a new reservoir. The size of the reservoir will be determined by the amount of storage required; a pumped storage project utilized for load following with only a couple of days of storage may only need a small reservoir (because it is cycled regularly), whereas a pumped storage project operated on a seasonal basis (as would be the case in the Yukon context) will need a larger reservoir (because it must store water over an entire season). For the purposes of this report, land footprint was estimated based on previous pumped storage studies[38].

Direct energy production GHG emissions of pumped storage, like other forms of hydropower, are zero.

Table 43: Pumped Storage Environmental Factors

Impact	**Intensity**
Land-Use	145 hectares/MW
GHG Emissions	0 gCO_2e/kWh

[37] Note: This full utilization LCOE estimate is based on energy *generated* by the pumped storage project only. In other words, it is the cost per MWh of electricity when in generation mode and includes the cost of previously storing this energy.

[38] Midgard pumped storage studies and "Seasonal and Pumped Storage Hydro Opportunity Search in the Carmacks to Faro Road and Power Line Corridor", John F. Maissan, June 2015.

4.6.5 Pumped Storage – Summary

For the purposes of this study, it has been assumed that a single pumped storage facility with 20MW of capacity and 40 GWh[39] of seasonal storage could be developed in the Yukon at a yet to be determined location.

Table 44: Pumped Storage Resource Summary[40]

Technical			Economic	Socio-Economic	Environmental	
Max. 2065 Energy (GWh/year)	**Max. 2065 Installed Capacity (MW)**	**Max. 2065 Firm Capacity (MW)**	**Full Utilization LCOE ($/MWh)**	**Social Impact**	**Land-Use Footprint (hectares/MW)**	**Production GHG Emissions (gCO_2e/kWh)**
-10	20	20	183	Potentially Acceptable	145	0

[39] 50GWh of available energy for pumping and 80% round trip efficiency yield 40GWh of potential generation.

[40] See Appendix F: for more detail.

4.7 Natural Gas

Natural gas is sometimes considered a less expensive alternative to diesel generation for use in providing reliable peaking capacity. Several natural gas combustion technologies exist including reciprocating engines, simple-cycle gas turbines (SCGT) and combined-cycle gas turbines (CCGT).

Fuel supply for natural gas generation is provided using either continuous pipeline supply or Liquefied Natural Gas (LNG) storage. Despite its common usage, the acronym LNG does not reflect the underlying natural gas generation technology but instead refers to using liquefied natural gas as the fuel storage method. LNG is natural gas that has been compressed and stored in a liquid form at very low temperatures (-162°C). Liquefied natural gas is easier to transport and store in remote areas where natural gas pipelines do not exist.

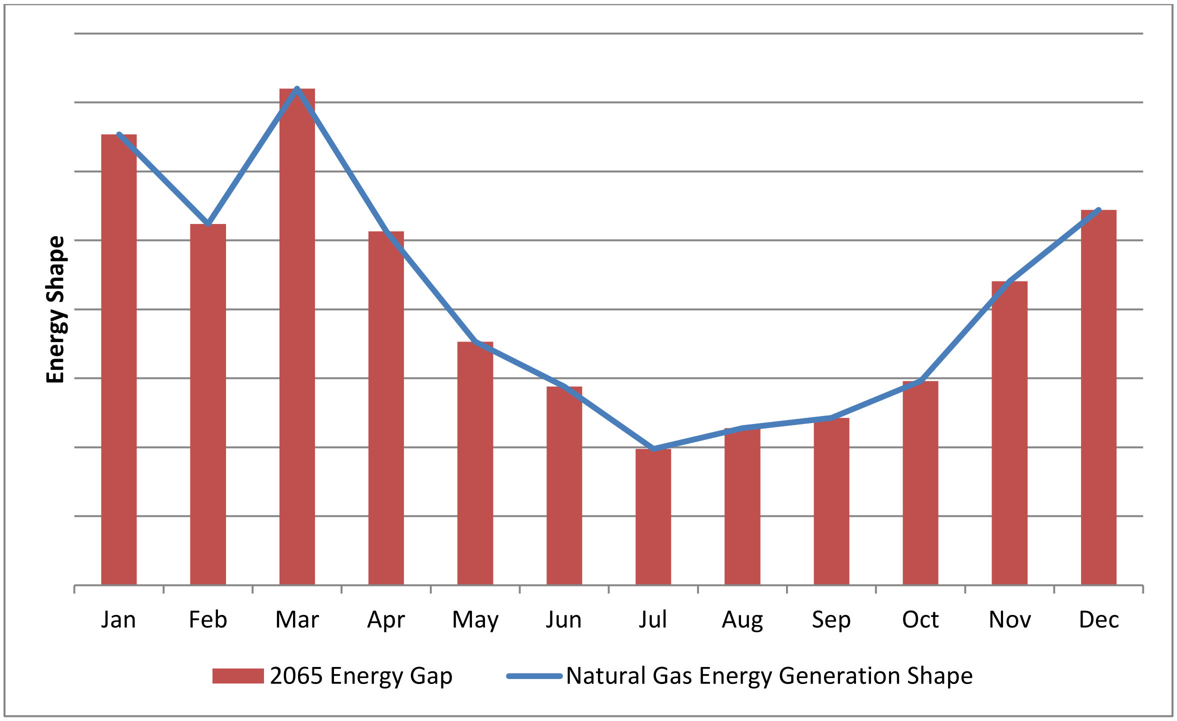
Figure 38: Whitehorse Natural Gas Generation Facility and LNG Storage[41]

4.7.1 Natural Gas - Technical Factors

Figure 39 compares the potential natural gas generation with LNG storage availability in the Yukon as compared to the forecast future energy needs on a month-by-month basis. The shape of natural gas generation is an exact match for the shape of the forecast future energy gap because natural gas generation is fully dispatchable and capable of meeting Yukon energy and capacity needs.

[41] Image Source: Yukon Energy Corporation, 2015.

Figure 39: Natural Gas Energy Generation Shape vs. Forecast Demand Gap



The Yukon grid is able to integrate an unlimited amount of natural gas generation because it is a dependable generation source, has a reliable fuel supply that can be stored as LNG to meet demand, and it does not cause system integration issues. Further, a reciprocating engine, such as is currently in use at the Whitehorse natural gas generation facility is able to vary its output throughout the day in order to match the changing demand for electricity.

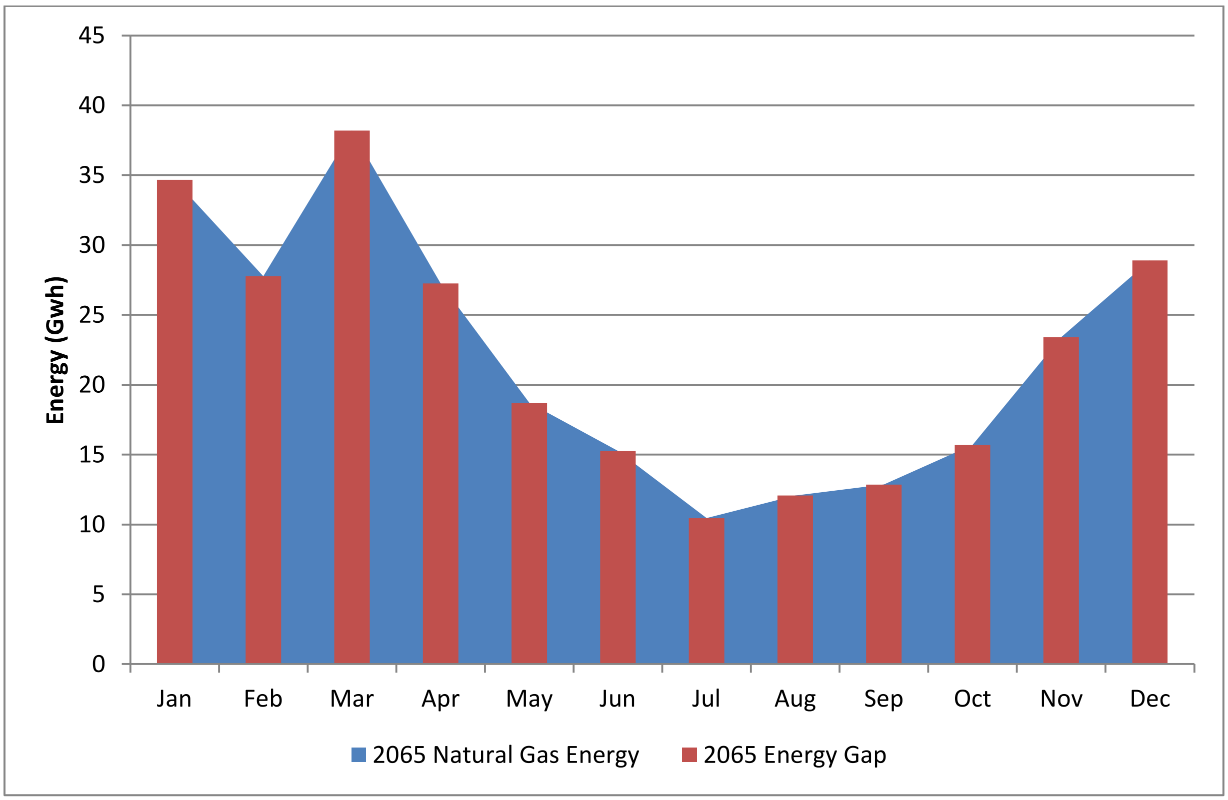
It should be noted that diesel generation still has a role to play in supporting the Yukon grid because a natural gas generation facility with LNG storage takes more time to start generating than a diesel generator, and diesel fuel can be stored in remote sites with very little infrastructure (i.e. a conventional fuel tank is required). Therefore, for the purposes of providing emergency backup power and fast response times, diesel generation may be required to bridge the time gap between emergency need and natural gas with LNG storage response. However, emergency events are not part of this analysis and it is therefore assumed that natural gas generation can respond to typical changes in electricity demand.

Table 45: Assumed Maximum Natural Gas Integration

Year	Assumed Peak Demand (MW)	Forecast Capacity Gap (MW)	Maximum Natural Gas Penetration (% of Peak Demand)	Maximum Natural Gas Installed Capacity (MW)	Maximum Annual Natural Gas Energy (GWh)
2035	109	21	Unlimited	21	103
2065	141	53	Unlimited	53	265

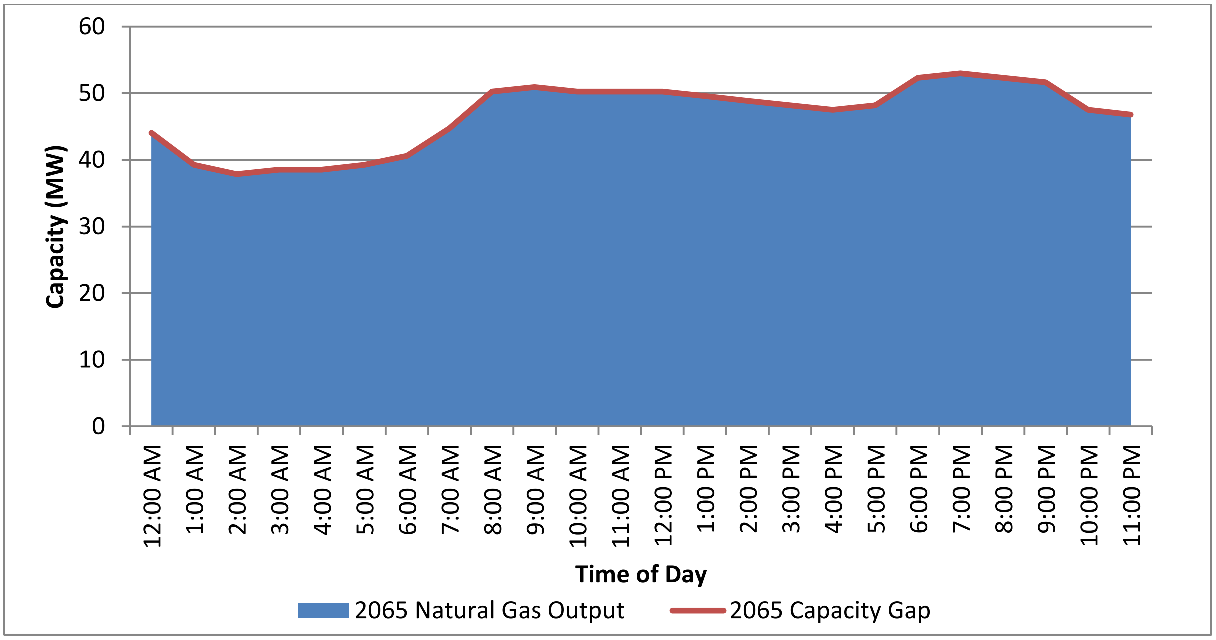
As shown in Figure 40, the annual energy output of a natural gas plant can be matched to meet seasonal demand requirements. Such a project would be able to fully meet the winter energy gap without additional resources, and is therefore able to meet 100% of the Yukon energy needs.

Figure 40: Natural Gas Energy – Monthly Average Generation & Gap



Natural gas generation can be dispatched to meet continuous changes in demand, and is therefore a “load following” resource providing dependable capacity. Its daily output is able to match the load (demand) curve exactly.

Figure 41: Natural Gas Daily Capacity



In summary, the limits on installed capacity, firm (dependable) capacity and energy that can be provided by natural gas generation on the Yukon grid are shown in Table 46.

Table 46: Natural Gas Technical Factors

Year	Baseline Energy Demand (GWh)	Existing Hydro Energy Generation	Forecast Energy Gap (GWh)	Maximum Natural Gas Installed Capacity (MW)	Maximum Annual Natural Gas Energy (GWh)
2035	546	443	103	21	103
2065	710	443	265	53	265

4.7.2 Natural Gas - Economic Factors

Full utilization LCOE is equivalent to the use of natural gas generation with LNG storage for “base load” energy, that is, it represents the cost of energy when a natural gas generation with LNG storage facility is used to produce power with an 85% utilization factor. The full utilization LCOE for natural gas energy in the Yukon is currently estimated at **$229/MWh.**[42]

[42] Based on 2015 Yukon Energy Corporation estimates ($43M for 8.8MW installed capacity, $15/MWh fixed O&M, and $180/MWh for fuel)

Table 47: LNG Economic Factors

Levelized Capital Cost ($/MWh)	Fixed O&M ($/MWh)	Fuel Cost ($/MWh)	Total Full Utilization LCOE ($/MWh)
34	15	180	229

4.7.3 Natural Gas - Socio-Economic Factors

For the purposes of this study it is assumed that suitable sites for natural gas generation facilities could be developed. Therefore, natural gas generation is considered potentially socially acceptable.

Table 48: Natural Gas Socio-Economic Factors

Acceptability
Potentially Acceptable

4.7.4 Natural Gas - Environmental Factors

The direct land-use impact of natural gas generation with LNG storage is typically small compared to other generation types because the direct land-use footprint is associated with only the generation and LNG storage facilities themselves, and the facilities will typically be located near to the loads they serve (e.g. Whitehorse).

The GHG emissions associated with the direct generation of energy for a natural gas facility are those associated with the combustion of natural gas as shown in Table 49. Potential GHG impacts due to the construction of a natural gas generation facility and supplying the fuel (e.g. natural gas exploration, drilling, processing, transport, LNG liquefaction, fugitive emissions, etc.) are not included here.

Table 49: Natural Gas Environmental Factors

Impact	Intensity
Land-Use	0.28-0.42 hectares/MW
GHG Emissions	708 gCO_2e/kWh

4.7.5 Natural Gas – Summary

Similar to Hydro with Storage, Natural Gas generation can meet the forecast demand for both energy and capacity in the Yukon. Natural Gas generation is an economic source of energy and capacity on demand at any time of year.

Table 50: Natural Gas Resource Summary[43]

Technical			Economic	Socio-Economic	Environmental	
Max. 2065 Energy (GWh/year)	**Max. 2065 Installed Capacity (MW)**	**Max. 2065 Firm Capacity (MW)**	**Full Utilization LCOE ($/MWh)**	**Social Impact**	**Land-Use Footprint (hectares/MW)**	**Production GHG Emissions (gCO_2e/kWh)**
710	Unlimited	141	229	Potentially Acceptable	0.28-0.42	708

4.8 Resource Type Summary

The types of generation resources available to meet the future Yukon energy demand are summarized below along with their individual costs (full utilization LCOE), maximum individual capacity and energy on the Yukon grid, and impacts such as land-use and GHG emissions.

[43] See Appendix G: for more detail.

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V6E 4A4

Table 51: Resource Type Summary[44]

	Technical			Economic	Socio-Economic	Environmental	
Resource	**Max. 2065 Energy (GWh)**	**Max. 2065 Installed Capacity (MW)**	**Max. 2065 Firm Capacity (MW)**	**Full Utilization LCOE ($/MWh)**	**Social Impact**	**Land-Use Footprint (ha/MW)**	**Production GHG Emissions[45] ($kgCO_2e/MWh$)**
Wind	65	21	0	157	Potentially Acceptable	36 ± 22	0
Wind + Battery Storage	88	28	0	192	Potentially Acceptable	36 ± 22	0
Solar	13	14	0	192	Potentially Acceptable	0 - 3.5	0
Next Generation Hydro[46]	557	57	57	92	Potentially Acceptable	313 (Range: 187 – 545)	0
Run-of-River Hydro	Unlimited (@23.4GWh / project)	Unlimited (@4.7MW / project)	0.6MW / project	116+	Potentially Acceptable	≈11	0
Small Hydro with Storage	Unlimited (@43.6GWh / project)	Unlimited (@6.5MW / project)	4.2MW / project	126+	Potentially Acceptable	390 (Median)	0
Pumped Storage Hydro	-10* *PS does not produce energy	20	20	183	Potentially Acceptable	145	0
Natural Gas	710	Unlimited	141	229	Potentially Acceptable	0.28-0.42	708

[44] Maximum energy and capacity for each resource does not take into account mutually exclusive generation options (such as high penetration of both wind and solar). For more detail, see Appendix H:.

[45] GHG emissions are based on the energy production phase only and are not full life-cycle emissions.

[46] It is assumed that only one Next Generation Project will be constructed.

5 Energy Development Scenarios

Since the Yukon electricity supply must at all times match demand in order to keep the electricity grid from blacking out, energy requirements must be met over the longer term (e.g. energy on a monthly basis up to the year 2065) and the shorter term (e.g. capacity to meet daily and seasonal peak demands). To fulfill these requirements, a series of scenarios was evaluated.

The generation types for the scenarios were considered on the ability to meet the forecast 2065 energy and capacity gap identified in the Baseline Scenario of the Yukon Electrical Energy and Capacity Need Forecast (as summarized in Figure 11 & Table 9 and Figure 12 & Table 10 respectively). A summary of the ability of different generation resources to meet the forecast needs is as shown in the following table:

Table 52: Resource Type – Ability to Meet Forecast Electricity Needs on a Standalone Basis

Resource	Standalone Resource (in 2065)	Rationale
Wind[47]	No	The integration limit for wind (plus utility battery support) is 28 MW[48] in 2065 (20% of installed capacity), and this is insufficient to meet the Yukon's forecast energy and capacity needs. Must be combined with other generation types.
Solar	No	The integration limit for solar is 14MW in 2065 (10% of installed capacity), and this is insufficient to meet the Yukon's forecast energy and capacity needs. Must be combined with other renewable generation types.
Next Generation Hydro	Yes	Next Generation Hydro provides sufficient dependable winter energy and capacity (57MW[49]) to meet the Yukon's forecast energy and capacity needs.
Run-of-River Hydro	No	Practical limits on easily developed Run-of-River projects limit the winter energy and capacity economically available from this resource type. On a standalone basis over 80 Run-of-River projects would be required to meet the winter energy and capacity needs in 2065. Hence, Run-of-River hydro is an expensive source of winter energy and capacity.
Small Hydro with Storage	No	Small Hydro Storage energy shape limits the winter energy and capacity economically available from this resource type. On a standalone basis, approximately 14 projects would be required to meet winter energy and capacity needs in 2065. To reduce the overall costs Small Hydro Storage will likely be combined with other generation types and is preferred over Run-of-River as a source of small hydro winter energy and capacity.
Pumped Storage Hydro	No	This 20MW resource is a net energy consumer; therefore it must be combined with other generation types as part of a generation portfolio.

[47] Wind integration is supported by a utility scale battery.

[48] Wind resources are added in 7.2 MW (4 X 1.8 MW turbines) steps for the purposes of scenario development.

[49] Expandable to 90-107MW as required.

As shown in Table 52, only Natural Gas Generation and Next Generation Hydro can meet the Yukon's forecast electricity needs on a standalone basis. The other generation types must collaborate with other generation types to potentially meet the Yukon's forecasted needs. As a result, four energy development scenarios were considered as follows:

Table 53: Energy Development Scenarios

Scenario	Description	Resources Included
Scenario 1 – Natural Gas	Build out natural gas generation	Natural Gas
Scenario 2 – Next-Generation Hydro	Build a single Next-Generation Hydro project	Next Generation Hydro
Scenario 3 – Renewables Portfolio (No Pumped Storage)	Build a combination of renewable generation resources (excluding pumped storage hydro) to satisfy energy needs. If required to satisfy residual capacity needs, add natural gas generation.	Wind (with utility scale battery), solar, run-of-river hydro, small hydro with storage and natural gas (capacity only)
Scenario 4 – Renewables Portfolio with Pumped Storage	Build a combination of renewable generation resources including pumped storage hydro to satisfy energy needs. If required to satisfy residual capacity needs, add natural gas generation.	Wind (with utility scale battery), solar, run-of-river hydro, small hydro with storage, pumped storage, and natural gas (capacity only)

In summary, the four energy development scenarios were compared according to the following parameters:

1) Technical: Energy – Annual energy measured in GWh
2) Technical: Capacity – Installed capacity measured in MW
3) Economic: Forecast Utilization LCOE
4) Environmental: Land-use footprint measured in hectares (ha)
5) Environmental: GHG emissions measured in tonnes of CO_2 equivalent (CO_2e) per year.

NOTE: It is assumed that all of the generation resources are potentially socially acceptable given suitable accommodations are made for potential impacts.

5.1.1 Scenario 1 - Natural Gas

Scenario 1 assumes that the Yukon's forecast energy and capacity are met using existing hydro and natural gas generation resources. Consequently, the order that the generation resources are added to the generation resource stack, listed in order of preference, is:

1) Existing Hydro
2) Natural Gas

The resulting overall energy mix and capacity gap closure in 2035 and 2065 are shown in Figure 42, Figure 43, Figure 46 and Figure 47 below.

Figure 42: Scenario 1 – Natural Gas - 2035 Overall Energy Mix

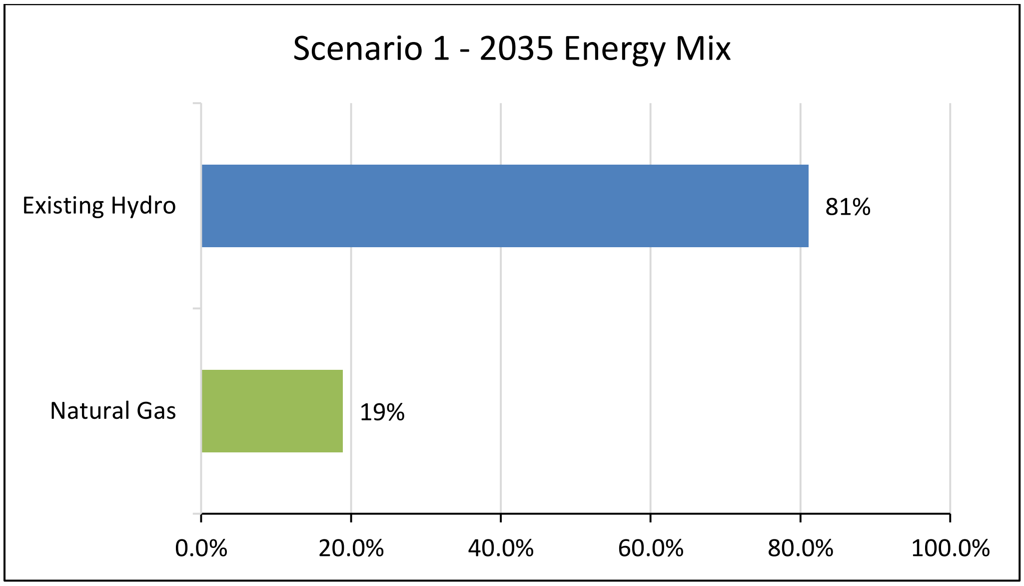


Figure 43: Scenario 1 – Natural Gas - 2065 Overall Energy Mix

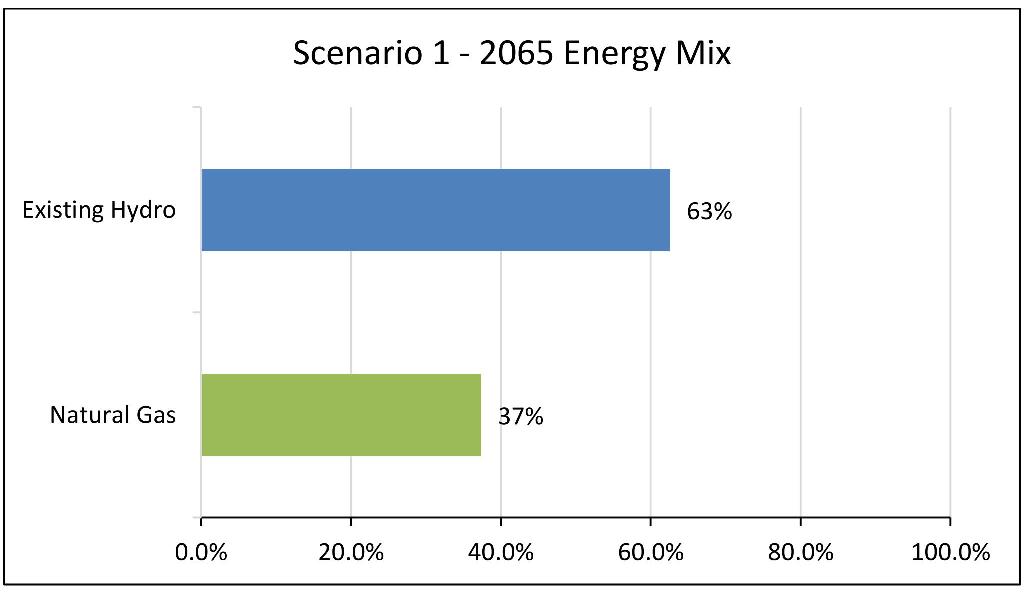


Figure 44: Scenario 1 – 2035 Capacity Gap Closure

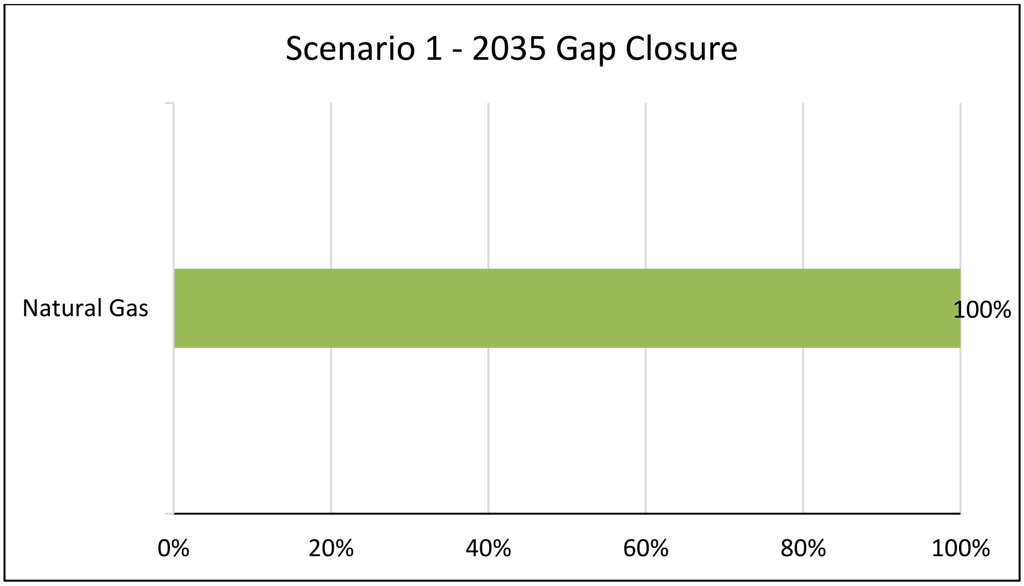
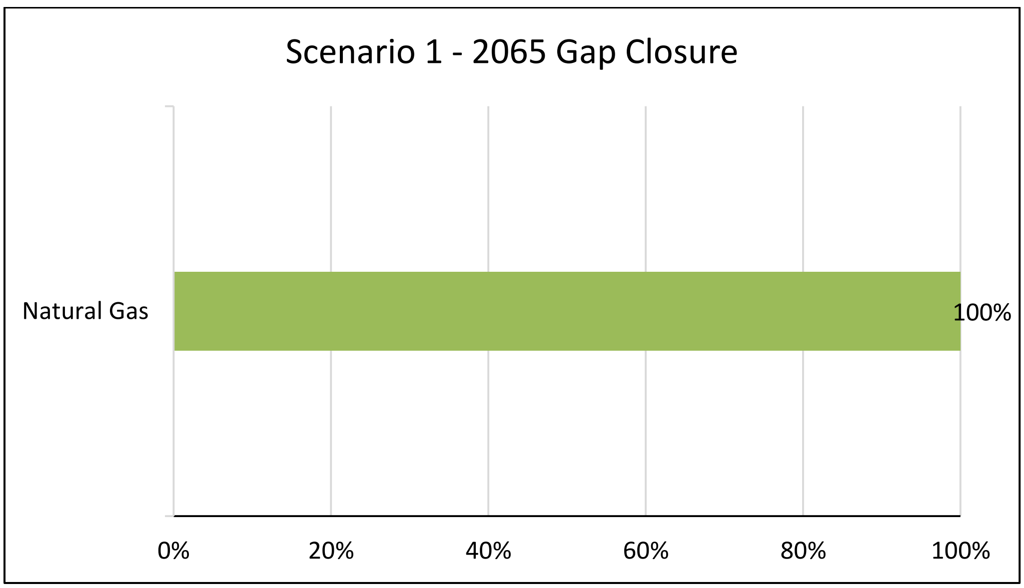


Figure 45: Scenario 1 – 2065 Capacity Gap Closure



The monthly energy mix in 2035 and 2065, shown in Figure 46 and Figure 47 respectively, highlights the importance of dispatchable energy resources during the winter/cold weather season when natural gas generation is utilized more heavily to meet energy and capacity needs. By 2065 there is a need for energy throughout the year, but the winter/cold weather months have larger generation demands. Figure 46 and Figure 47 also shows that generation output is fully dispatchable and exactly matches electricity demand, and therefore there is no spilled (wasted) energy generation.

Figure 46: Scenario 1 – Natural Gas - 2035 Monthly Energy Mix

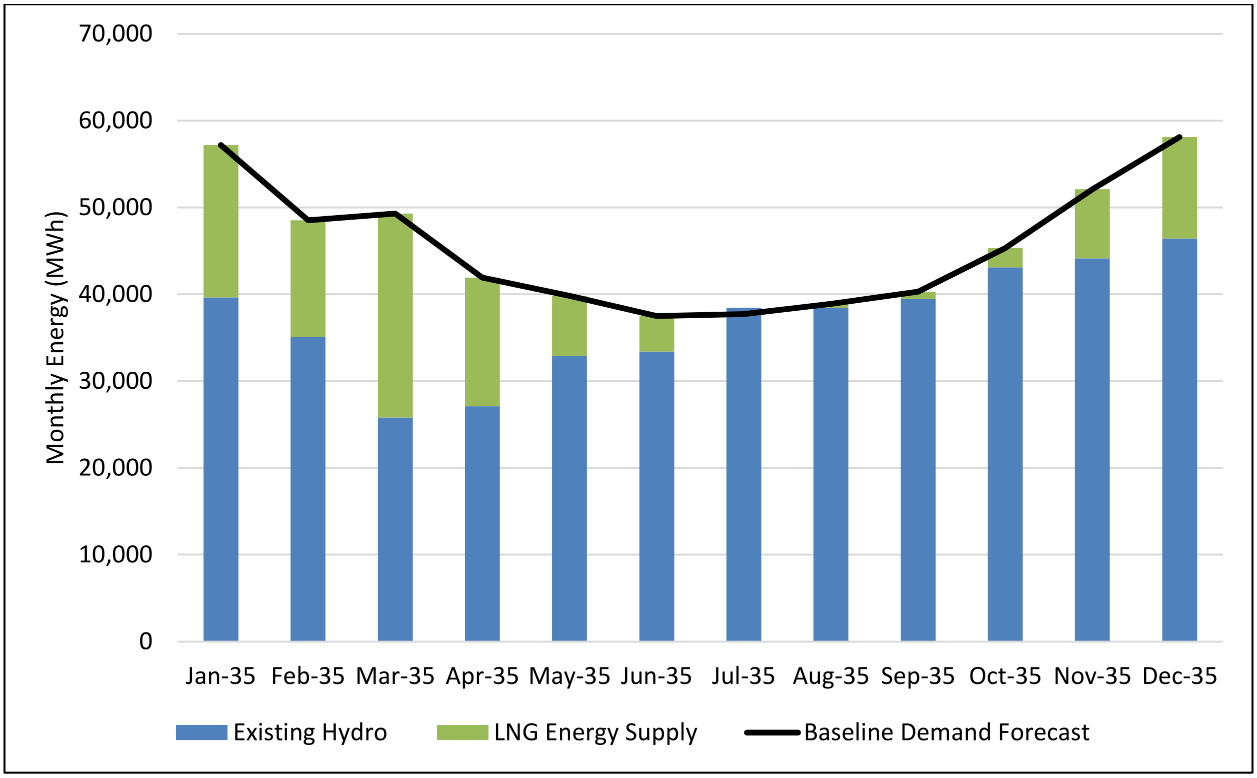
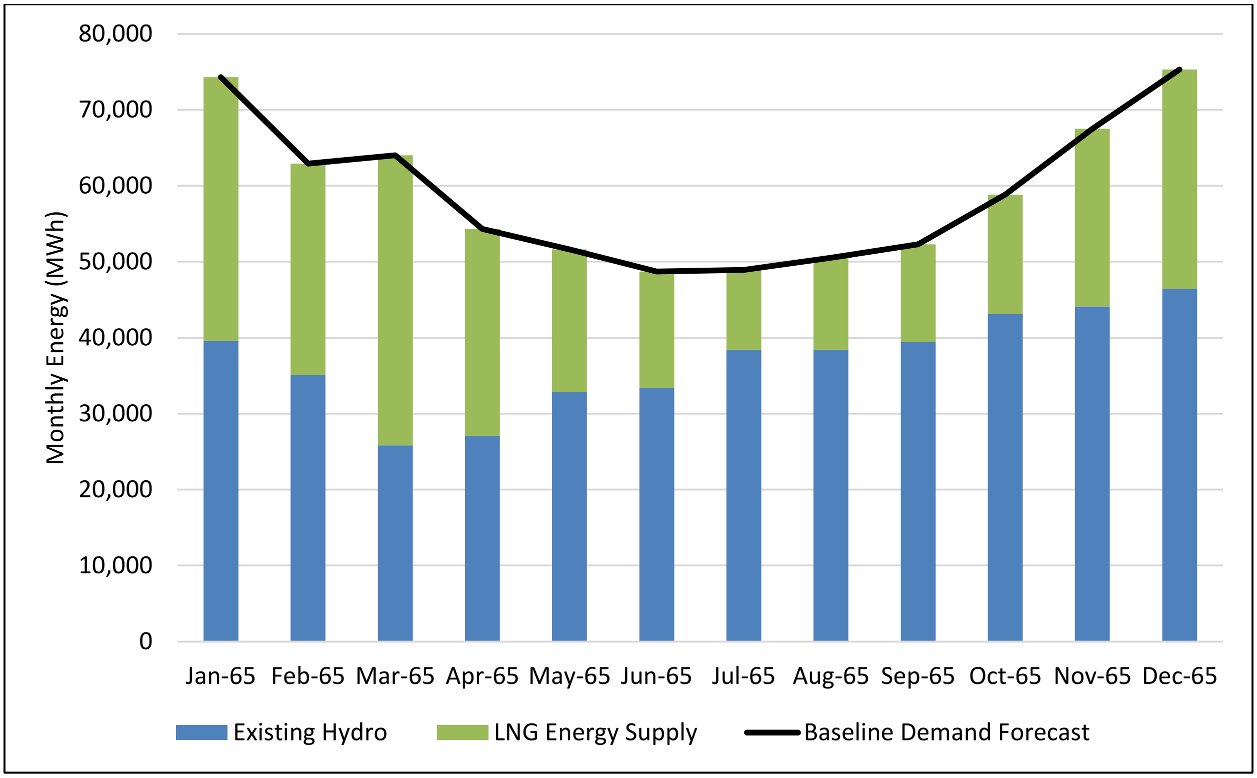


Figure 47: Scenario 1 – Natural Gas - 2065 Monthly Energy Mix



A summary of the scenario parameters are as follows:

Table 54: Scenario 1 – Natural Gas - Summary

		2035	2065
Technical	**Energy**[50]	444 GWh Existing Hydro 103 GWh Natural Gas	444 GWh, Existing Hydro 265 GWh Natural Gas
Technical	**Installed Capacity**	92 MW Existing Hydro 22 MW Natural Gas	92 MW Existing Hydro 53 MW Natural Gas
Economic	**Forecast Utilization LCOE**	$250/MWh	
Environmental	**Land-Use Footprint**	9 ha	22 ha
Environmental	**GHG Emissions**	74,000 tonnes/year	190,000 tonnes/year

The technical and environmental parameters are tabulated by project type below:

[50] The energy numbers represents the actual energy generated annually.

Table 55: Scenario 1 – Natural Gas – Technical and Environmental Parameters (2065)

Project Type	Number of Projects	GHG Emissions / Project	GHG Emissions Total	Footprint / Project	Footprint Totals	Energy / Project	Energy Totals	Capacity / Project	Capacity Totals
Existing Hydro	-	-	-	-	-	-	444 GWh	-	92 MW
Natural Gas	12	16,000 tonnes/yr	190,000 tonnes/yr	1.8 ha	22 ha	22 GWh	265 GWh	4.4 MW	53 MW
Totals	12		190,000 tonnes/yr		22 ha		710 GWh		150 MW

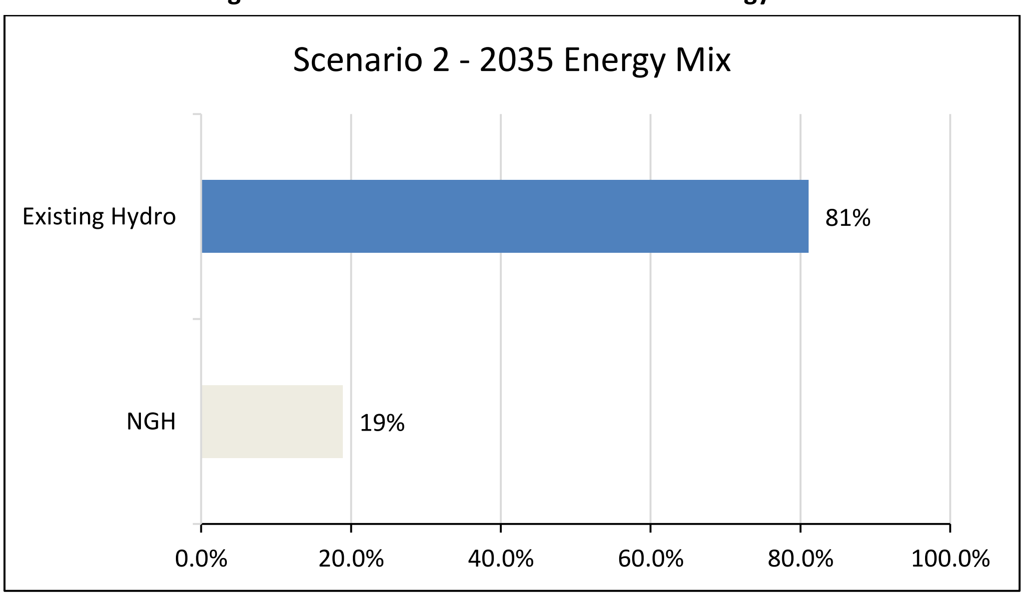
5.1.2 *Scenario 2 - Next Generation Hydro (NGH)*

Scenario 2 assumes that the remaining energy gap and capacity are met using existing hydro and the development of a single *Next Generation Hydro* project[51]. Consequently, the order generation resources are added to the generation resource stack, listed in order of preference, is:

1) Existing Hydro
2) Next Generation Hydro

The resulting overall energy mix and capacity gap closure mix in 2035 and 2065 are shown in Figure 48, Figure 49, Figure 50 and Figure 51 below.

Figure 48: Scenario 2 – NGH-2035 Overall Energy Mix



[51] Based on an average of energy yields from Detour Canyon, Fraser Falls, Granite Canyon & Two Mile Canyon NGH projects.

Figure 49: Scenario 2 – NGH-2065 Overall Energy Mix

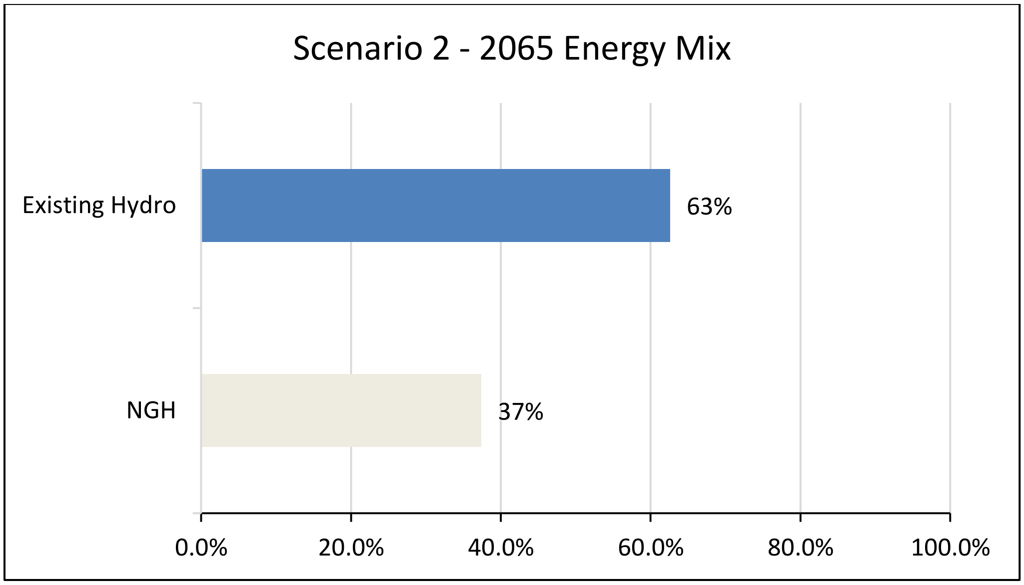


Figure 50: Scenario 2 – NGH-2035 Gap Closure

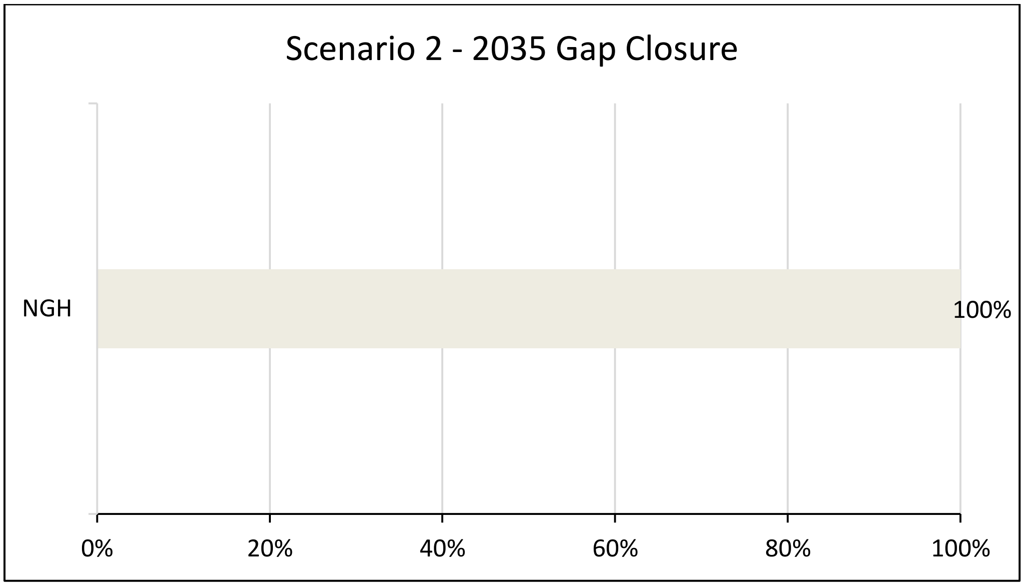
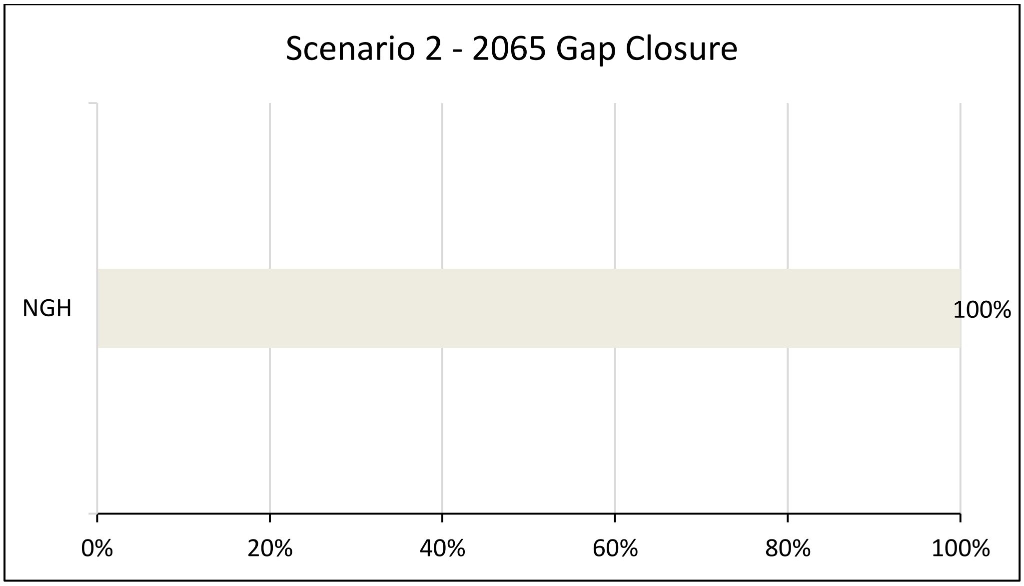


Figure 51: Scenario 2 – NGH-2065 2035 Gap Closure



As can be seen in Figure 52 and Figure 53, a significant portion of the summer energy from a NGH project is surplus to the Yukon's need and is spilled as wasted energy in the summer. This spilled energy is available for use should Yukoners find a secondary use for surplus summer electricity.

Figure 52: Scenario 2 – NGH- 2035 Monthly Energy Mix

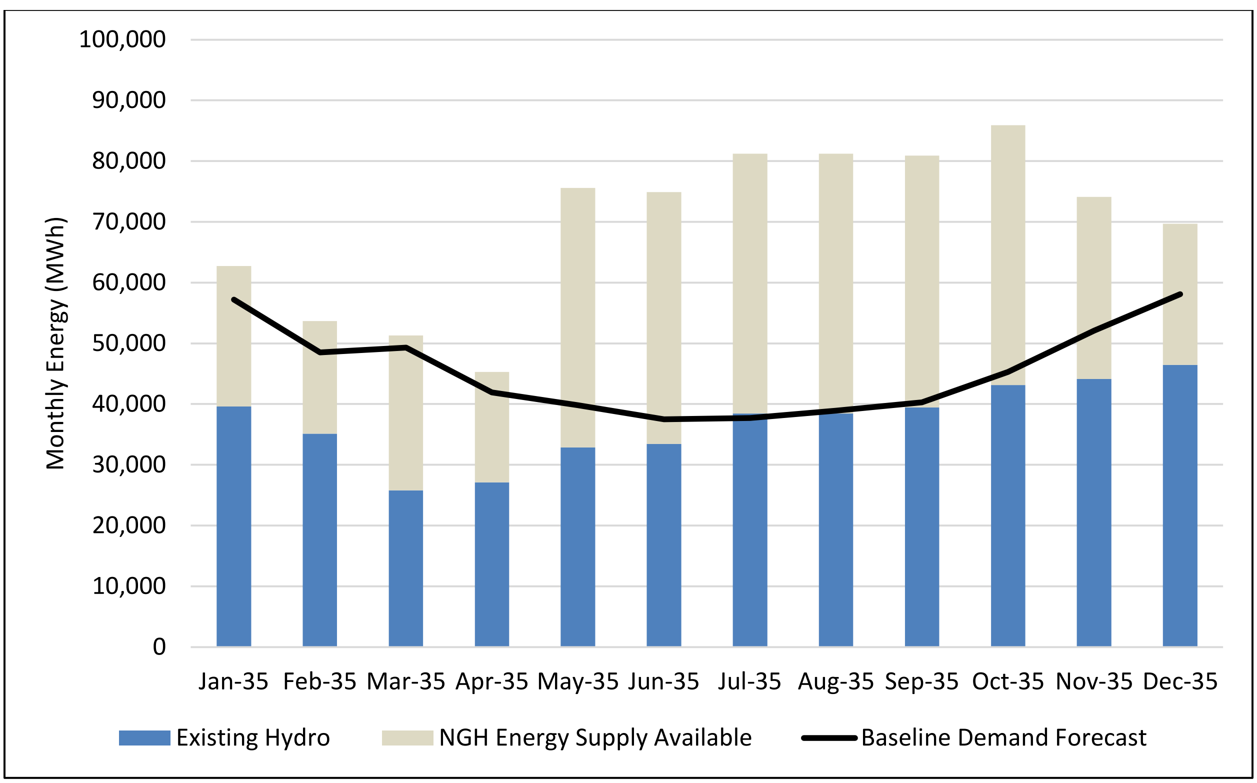
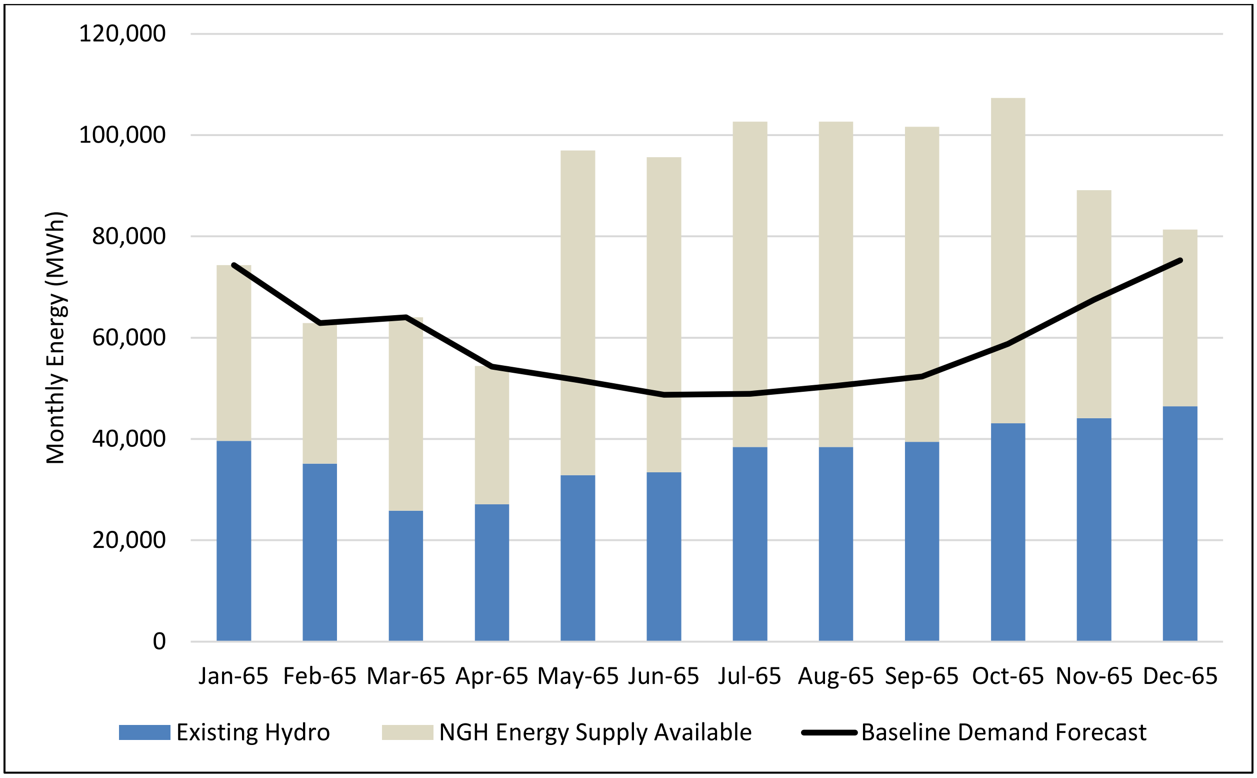


Figure 53: Scenario 2 – NGH- 2065 Monthly Energy Mix



A summary of the scenario parameters are as follows:

Table 56: Scenario 2 – Next Generation Hydro - Summary

		2035	2065
Technical	**Energy**[52]	444 GWh Existing Hydro 103 GWh NGH	444 GWh Existing Hydro 265 GWh NGH
Technical	**Installed Capacity**	92MW Existing Hydro 38 MW NGH	92 MW Existing Hydro 57 MW NGH
Economic	**Forecast Utilization LCOE**	$240/MWh	
Environmental	**Land-Use Footprint**	18,000 ha	18,000 ha
Environmental	**GHG Emissions**	0 tonnes	0 tonnes

The technical and environmental parameters are tabulated by project type below:

[52] The energy numbers represents the actual energy generated annually.

Table 57: Scenario 2 – Next Generation Hydro – Technical and Environmental Parameters (2065)

Project Type	Number of Projects	GHG Emission / Project	GHG Emissions Total	Footprint / Project	Footprint Totals	Energy / Project	Energy Totals	Capacity / Project	Capacity Totals
Existing Hydro	-	-		-	-	-	444 GWh	-	92 MW
Next Gen Hydro	1	0	0	18,000 ha	18,000 ha	265 GWh	265 GWh	57 MW	57 MW
Totals	1		0		18,000 ha		710 GWh		150 MW

5.1.3 Scenario 3 – Renewables (Solar, Wind, Small Storage Hydro & Run-of-River Hydro)

Scenario 3 assumes the construction of a series of renewable generation projects that are developed according to the following approach:

1) Solar: Solar is developed to a 5 MW limit in 2065 as part of a successful Micro-Generation Program (see Appendix C: for additional details).
2) Wind: Wind is developed to a 20% integration limits assuming that a utility scale battery system increases the total penetration of wind generation on the grid to 20% (see Appendix B: for additional details).
3) Hydro (Run-of-River, Small Storage): Depending on the shape of the residual gap after accounting for Solar and Wind generation additions, the hydro generation resource with a generation shape that best matches the residual gap is installed. The residual gap is then re-calculated and the next hydro resource is installed until the energy gap is completely satisfied.
4) Natural Gas: If after the energy gap is satisfied using renewable assets there remains a capacity gap, Natural gas assets will be added until such time as the residual capacity gap is filled. It is important to note that the Natural Gas assets do not fill any of the forecast energy gaps.

As can be seen in Figure 54 and Figure 55 the renewables portfolio is theoretically able to fulfill the forecast energy gaps in 2035 and 2065 respectively. However, it is important to note that by 2065 a significant number of small hydro storage projects (i.e. approximately 11 projects) are required to fill the energy gap, and two (2) additional natural gas generation projects (i.e. approximately 2 x 4.4 MW = 8.8 MW) are required to fill the capacity gap. Whether or not this quantity (approximately 11) of small hydro storage projects can practically be found and economically developed in the Yukon is outside the scope of this study. No run-of-river hydro projects were included in the portfolio due to the comparatively poor ability of run-of-river projects to provide winter energy and capacity when compared to small hydro storage projects. It should also be noted that considerable lengths of transmission lines at various voltages (approximately 200+ km by 2035, and 350+ km by 2065) will also be required to interconnect the renewable projects.

Figure 54: Scenario 3 – Renewables - 2035 Monthly Energy

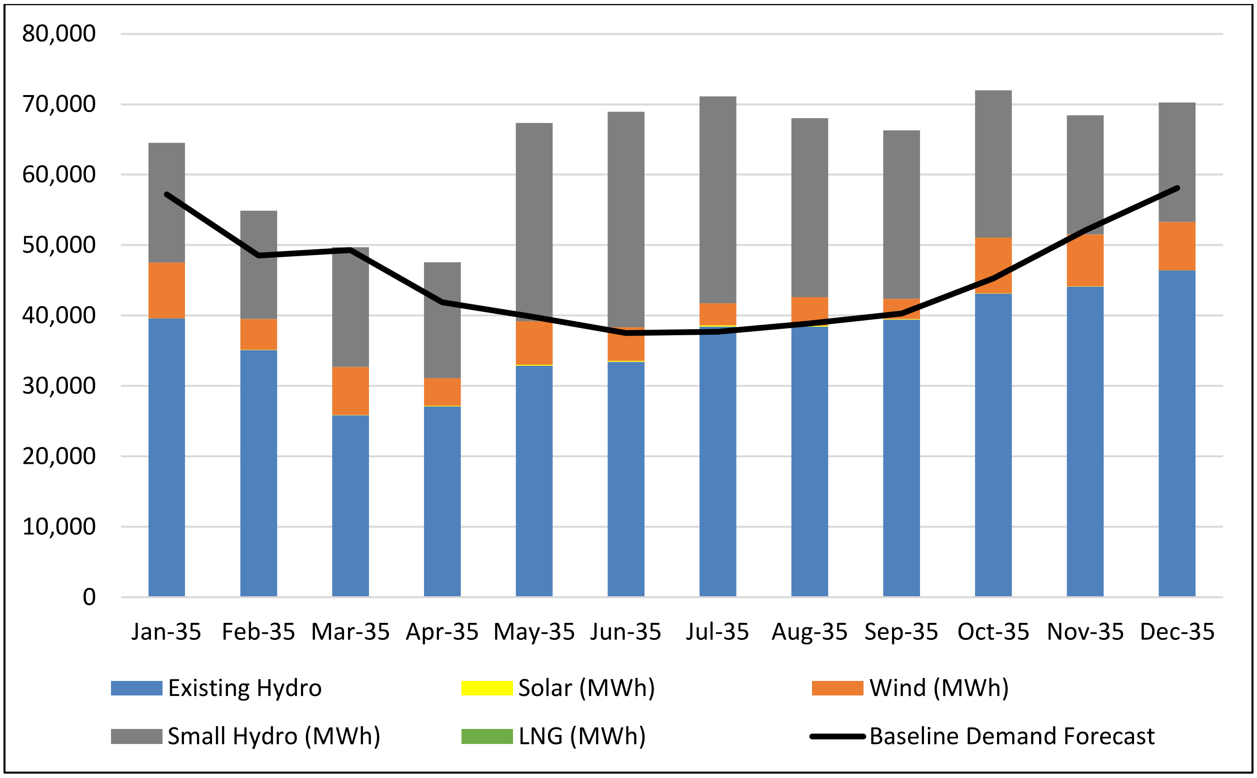


Figure 55: Scenario 3 – Renewables - 2065 Monthly Energy

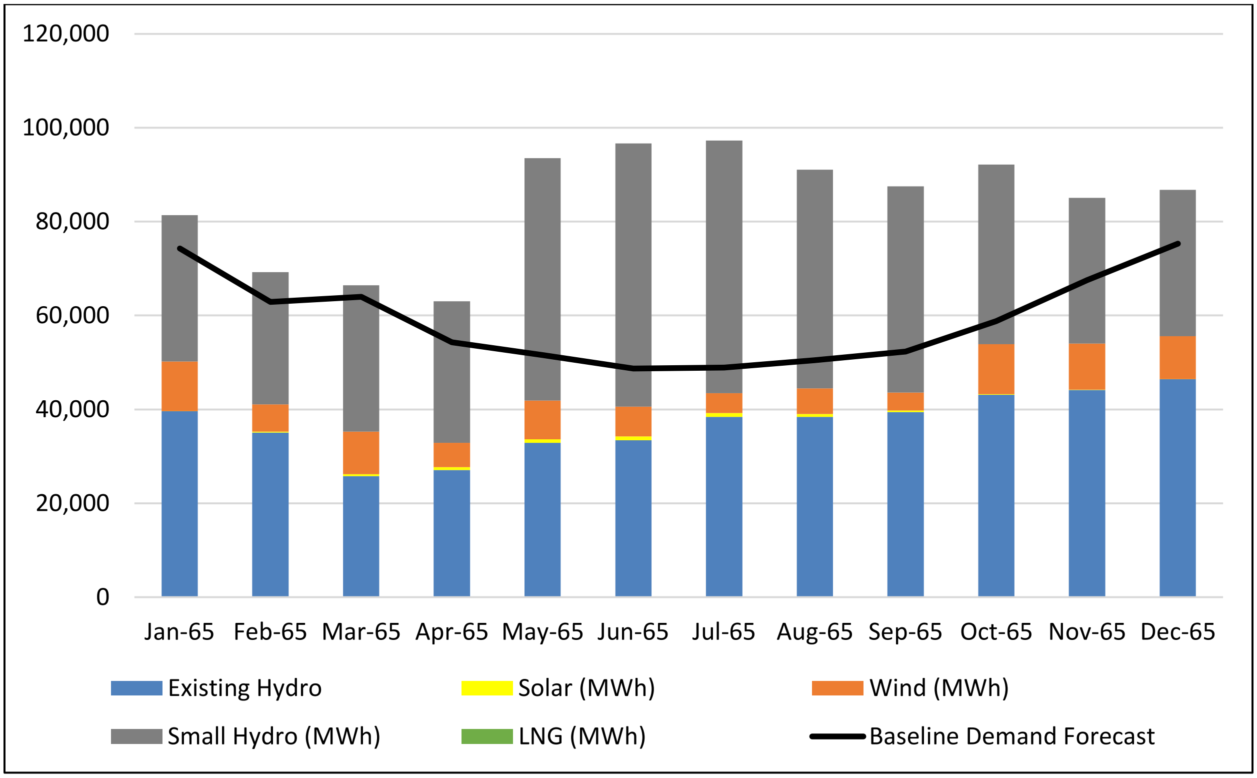


Figure 56: Scenario 3 2035 Capacity Gap Closure

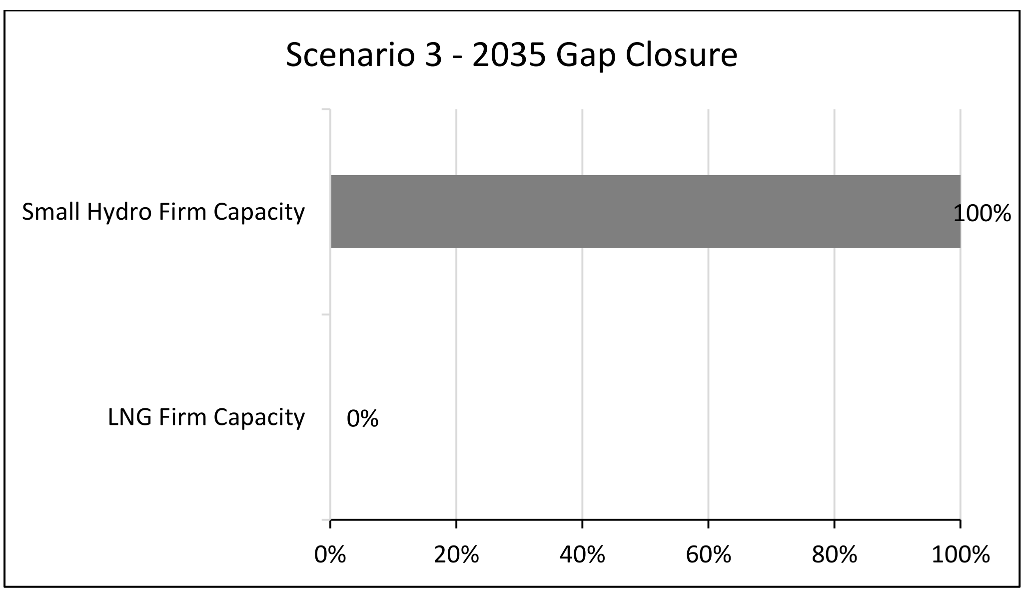
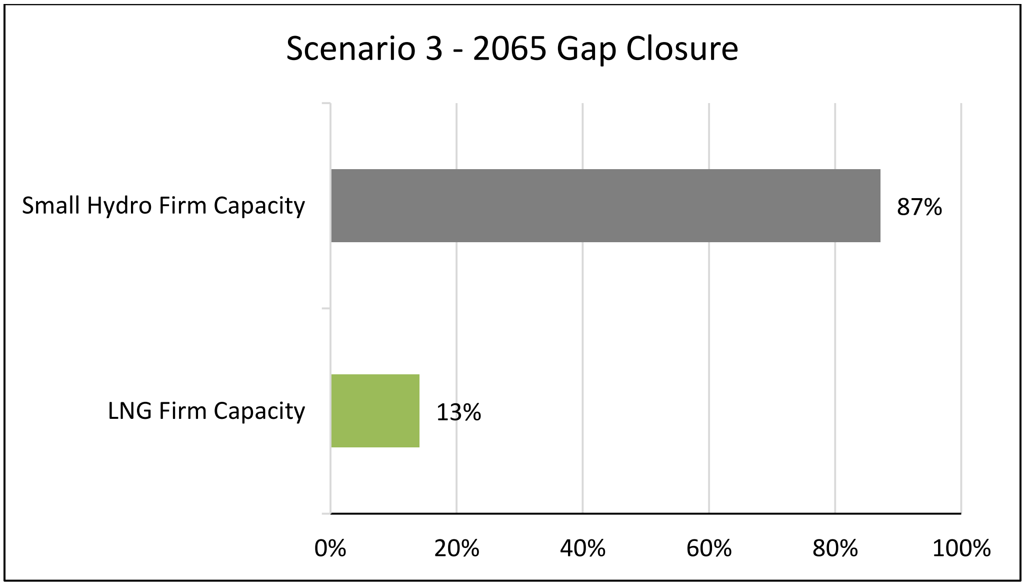


Figure 57: Scenario 3 2065 Capacity Gap Closure



A summary of the scenario parameters are as follows:

Table 58: Scenario 3 – Renewables with Battery Storage - Summary

		2035	2065
Technical	**Energy**[53]	444 GWh Existing Hydro 66 GWh Wind 1 GWh Solar 36 GWh Small Hydro Storage	444 GWh Existing Hydro 88 GWh Wind 5 GWh of Solar 172 GWh Small Hydro Storage
Technical	**Installed Capacity**	92 MW Existing Hydro 22 MW Wind with Battery Integration (7.5MW) 1 MW of Solar 39 MW Small Hydro Storage 0 MW Natural Gas	92MW Existing Hydro 29 MW Wind with Battery Integration (7.5MW) 5 MW Solar 72 MW Small Hydro Storage 8.8 MW Natural Gas
Economic	**Forecast Utilization LCOE**	$360/MWh	
Environmental	**Land-Use Footprint**	16,000 ha	29,000 ha
Environmental	**GHG Emissions**	0 tonnes	0 tonnes

The technical and environmental parameters are tabulated by project type below:

[53] The energy numbers represents the actual energy generated annually.

Table 59: Scenario 3 – Renewables with Battery Storage – Technical and Environmental Parameters (2065)

Project Type	Number of Projects	GHG Emissions / Project	GHG Emissions Total	Footprint / Project	Footprint Totals	Energy / Project	Energy Totals	Capacity / Project	Capacity Totals
Existing Hydro	-	-	-	-	-	-	444 GWh	-	92 MW
Wind	4	0	0	300 ha	1200 ha	22 GWh	88 GWh	7.2 MW	29 MW
Solar	5	0	0	0	0	1 GWh	5 GWh	1 MW	5 MW
Small Hydro	11	0	0	2500 ha	27500 ha	16 GWh	176 GWh	6.5 MW	72 MW
Natural Gas	2	≈0	≈0	1.8 ha	3.6 ha	≈0	≈0	4.4 MW	8.8 MW
Totals	22		≈0		29000 ha		710 GWh		207 MW

5.1.4 Scenario 4 – Renewables with Pumped Storage

Scenario 4 assumes the construction of a series of renewable generation projects that are developed according to the following approach:

1) Solar: Solar is developed to a 5 MW limit in 2065 as part of a successful Micro-Generation Program (see Appendix C: for additional details).
2) Wind: Wind is developed to a 20% integration limits assuming that a utility scale battery system increases the total penetration of wind generation on the grid to 20% (see Appendix B: for additional details).
3) Pumped Storage Hydro: A 20 MW pumped storage facility that uses 50 GWh of summer surplus energy to create water storage for 40 GWh of winter generation.
4) Hydro (Run-of-River, Small Storage): Depending on the shape of the residual gap after accounting for Solar, Wind and Pumped Storage generation additions, the hydro generation resource with a generation shape that best matches the residual gap is installed. The residual gap is then re-calculated and the next hydro resource installed until the energy gap is fully satisfied.
5) Natural Gas: If after the energy gap is satisfied using renewable assets there remains a capacity gap, Natural gas assets will be added until such time as the residual capacity gap is filled. It is important to note that the Natural Gas assets do not fill any of the forecast energy gaps.

As can be seen in Figure 58 and Figure 59, the renewables with pumped storage portfolio is theoretically able to fulfill the forecast energy gaps in 2035 and 2065 respectively. Due to the presence of a pumped storage facility the required number of small hydro projects with storage is reduced because the pumped storage facility makes winter use of previously spilled (wasted) surplus summer energy. Whether or not the approximately six (6) small hydro storage projects can practically be found and economically developed in the Yukon is outside the scope of this study. Two (2) natural gas generation assets are also required by 2065 to meet the Yukon's capacity needs. It should also be noted that considerable lengths of transmission lines at various voltages (approximately 180+ km by 2035, and 220+ km by 2065) will also be required to interconnection the projects in this scenario.

Figure 58: Scenario 4 – Renewables with Pumped Storage - 2035 Monthly Energy

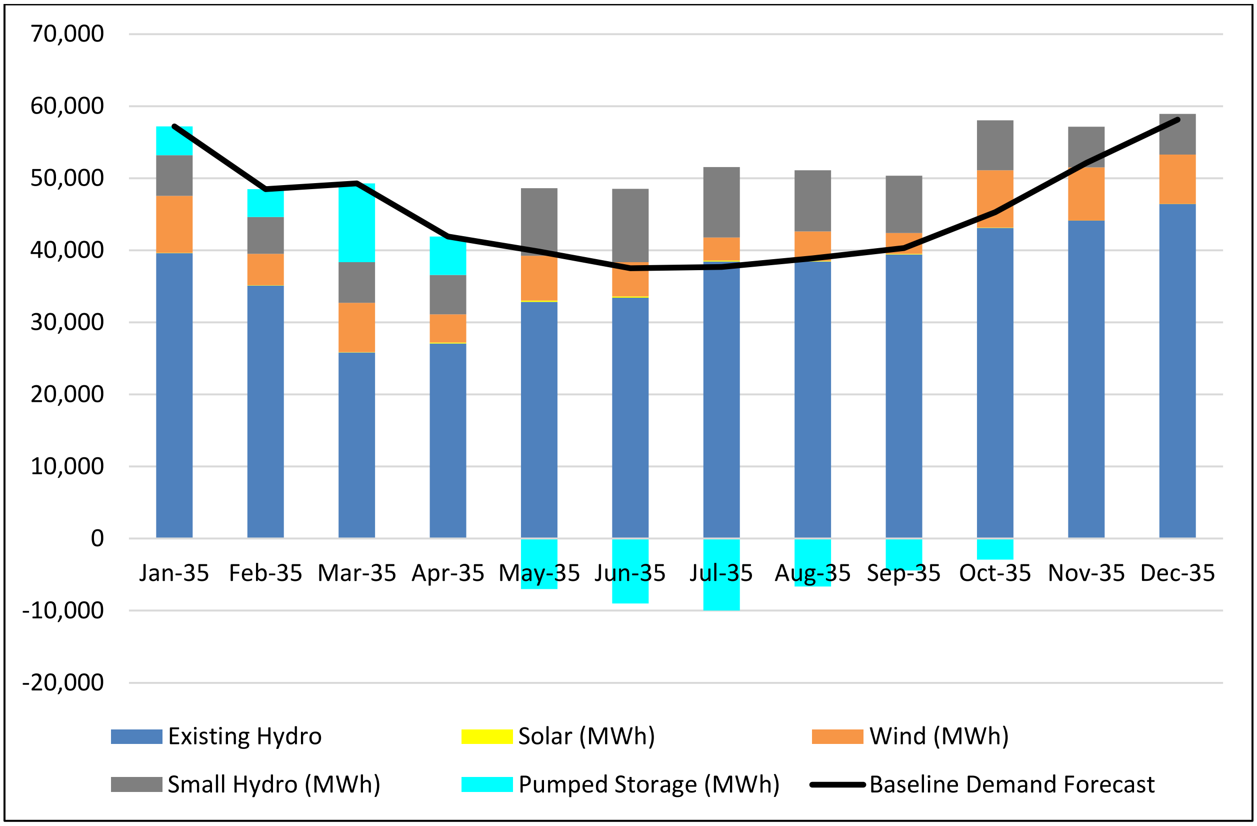


Figure 59: Scenario 4 - Renewables with Pumped Storage - 2065 Monthly Energy

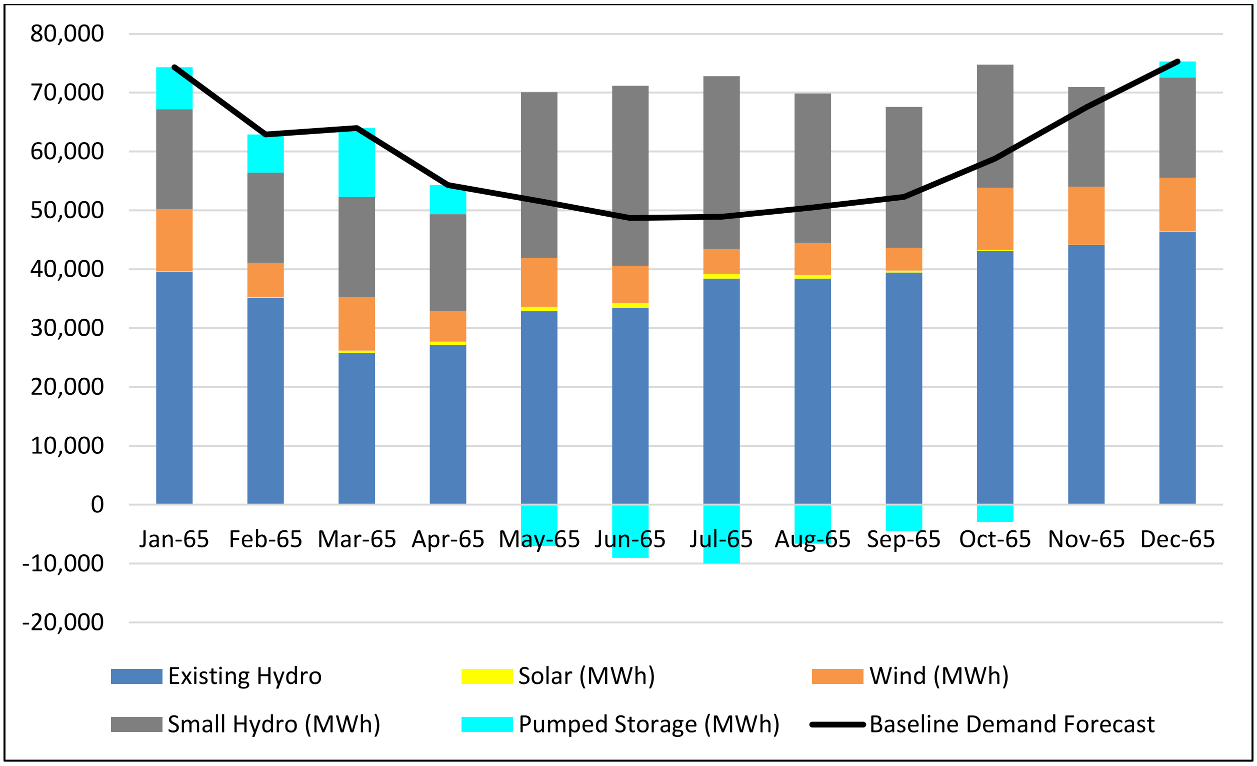


Figure 60: Scenario 4 - Renewables with Pumped Storage - 2035 Capacity Gap Closure

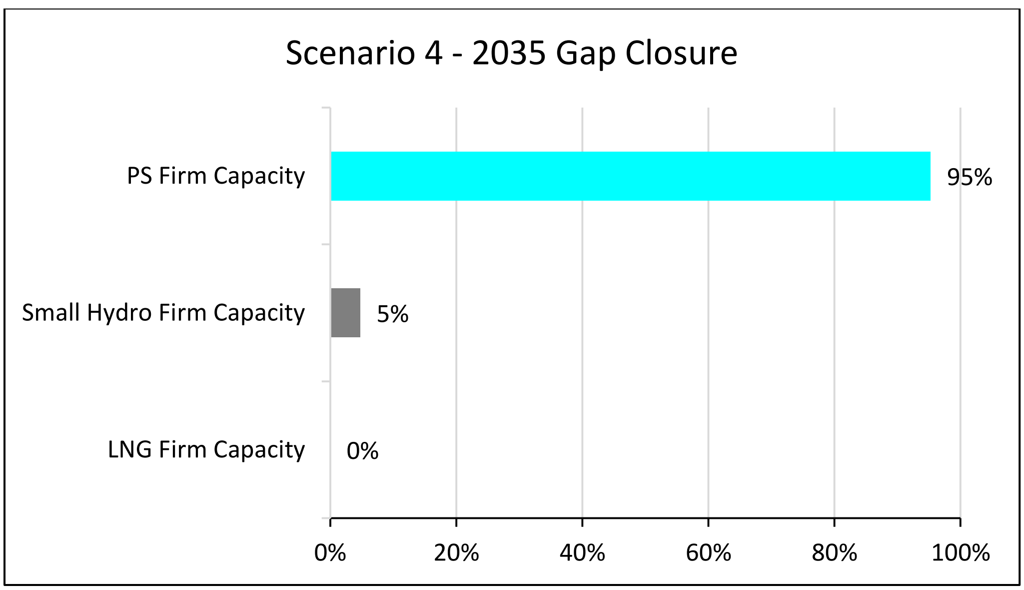
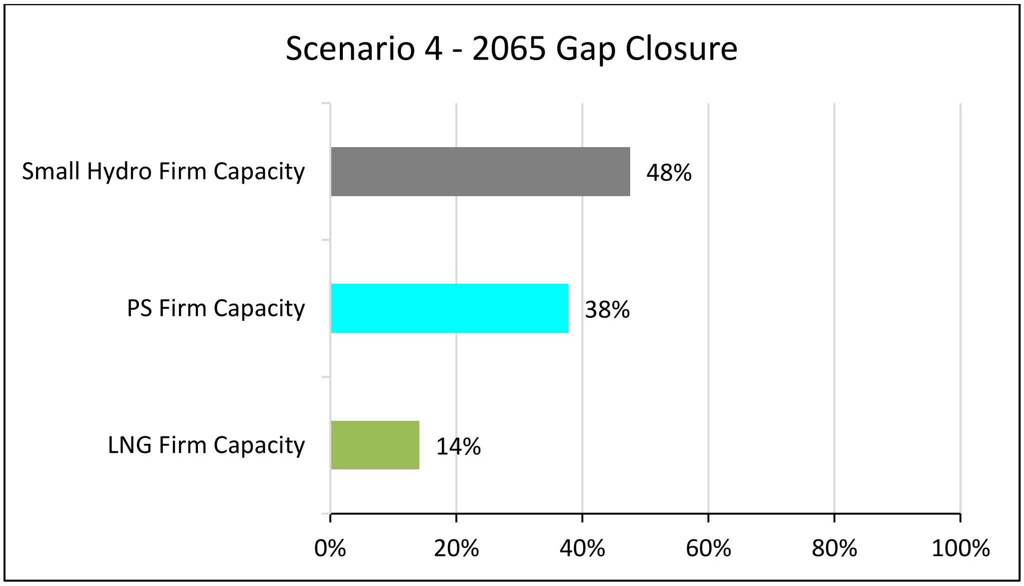


Figure 61: Scenario 4 - Renewables with Pumped Storage - 2065 Gap Closure



A summary of the scenario parameters are as follows:

Table 60: Scenario 4 – Renewables with Battery Storage and Pumped Storage - Summary

		2035	2065
Technical	**Energy**	444 GWh Existing Hydro 66 GWh Wind 1 GWh Solar 42 GWh Small Hydro -6 GWh Pumped Storage	444 GWh Existing Hydro 88 GWh Wind 5 GWh Solar 180 GWh Small Hydro -8 GWh Pumped Storage
Technical	**Installed Capacity**	92 MW Existing Hydro 22 MW Wind with Battery Integration (7.5MW) 1 MW Solar 13 MW Small Hydro 20 MW Pumped Storage 0 MW Natural Gas	92 MW Existing Hydro 29 MW Wind with Battery Integration (7.5MW) 5 MW Solar 39 MW Small Hydro 20 MW Pumped Storage 8.8 MW Natural
Economic	**Forecast Utilization LCOE**	$270/MWh	
Environmental	**Land-Use Footprint**	9,000 ha	20,000 ha
Environmental	**GHG Emissions**	0 tonnes	0 tonnes

The technical and environmental parameters are tabulated by project type below:

Table 61: Scenario 4 – Renewables with Pumped Storage – Technical and Environmental Parameters (2065)

Project Type	Number of Projects	GHG Emissions / Project	GHG Emission Total	Footprint / Project	Footprint Totals	Energy / Project	Energy Totals	Capacity / Project	Capacity Totals
Existing Hydro	-	-		-	-	-	444 GWh	-	92 MW
Wind	4	0	0	300 ha	1200 ha	22 GWh	88 GWh	7.2 MW	29 MW
Solar	5	0	0	0	0	1 GWh	5 GWh	1 MW	5 MW
Small Hydro	6	0	0	2500 ha	15000 ha	30 GWh	180 GWh	6.5 MW	39 MW
Pumped Storage	1	0	0	2900 ha	2900 ha	-8 GWh	-8 GWh	20 MW	20 MW
Natural Gas	2	≈0	≈0	1.8 ha	3.6 ha	≈0	≈0	4.4 MW	8.8 MW
Totals	18		≈0		20000 ha		710 GWh		194 MW

6 Scenario Summary

A summary of the results from the four (4) different development scenarios is shown in Table 62. As can be seen in the table all of the four development scenarios have the ability to meet the forecast energy demand for the Yukon until 2065 in a potentially socially acceptable manner.

Table 62: Scenario Summary Matrix

	Technical		Economic	Socio-Economic	Environmental	
Scenario	**Meets Yukon Energy Needs?**	**Meets Yukon Capacity Needs?**	**Forecast LCOE ($/MWh)**	**Social Impact**	**2065 Land-Use Footprint (hectares)[54]**	**2065 GHG Emissions (tonnes CO_2e)**
Scenario 1 – Natural Gas	Yes	Yes	250	Potentially Acceptable	22	190,000
Scenario 2 – Next-Generation Hydro	Yes	Yes	240	Potentially Acceptable	18,000	0
Scenario 3 – Renewables	Yes	Yes (with Natural Gas capacity)	360	Potentially Acceptable	29,000	0*
Scenario 4 – Renewables with Pumped Storage	Yes	Yes (with Natural Gas capacity)	270	Potentially Acceptable	20,000	0*

*NOTE: Although, Scenario 3 and Scenario 4 fill the forecast capacity gap in 2035 and the energy gaps up to 2065, they fail in practice to meet the capacity needs in 2065 and as a result will need thermal generation (natural gas, diesel) to meet the Yukon's capacity needs (and therefore the direct generation GHG emissions will be low, but not actually zero in practice).

However, beyond meeting the forecast energy need, the development scenarios differ in terms of the other evaluation parameters. Most notably, from a technical standpoint, the renewable scenarios (with and without pumped storage) do not meet the peak capacity requirements in 2065 without the support of capacity rich assets such as natural gas generation. Natural Gas generation is the likely candidate for providing winter capacity because natural gas generation is the least expensive source of dependable

[54] When comparing the scenario footprints it must be recognized that the impact of the different footprints are different for the different project types. For example, the majority of the Next Generation Hydro footprint is creating a new lake / water storage reservoir where a river previously existed, whereas the renewable portfolios (Scenarios 3 & 4) are a combination of new lakes / water storage reservoirs, modifying existing lakes, and general land use. Therefore, land use impacts cannot be directly compared without evaluating the types of impacts as well as the footprint.

capacity currently available to the Yukon, and the usage will be low enough that other renewables (e.g. run-of-river hydro and small hydro storage) will be too expensive to justify. In contrast, Next Generation Hydro and Natural Gas Generation both have sufficient energy and capacity to satisfy the forecast electricity needs from 2035 to 2065.

In terms of cost, Next Generation Hydro, Natural Gas Generation and Renewables with Pumped Storage (Scenarios 1, 2 & 4) are all a similar cost regions of $235 - $268 per MWh on a forecast LCOE basis. The Scenario 3 Renewables Only portfolio is more expensive ($356/MWh) because providing winter energy with renewables becomes expensive as the number of small hydro storage projects increases, the quantity of spilled (wasted) summer energy increases, and the transmission line lengths required to interconnect a larger number of renewable projects also increases.

From an environmental standpoint, both the renewables portfolios and the Next Generation Hydro options do not emit GHGs as a result of direct generation activities[55], whereas the Natural Gas generation scenario produces the most GHGs. By 2065, of the renewable generation options, Next Generation Hydro has the smallest expected land-use footprint when compared to the two renewable portfolios. However, it must be recognized that the impacts associated with the renewable generation options should not be compared on area alone because the types of impacts are different for the different scenarios. For example, the majority of the Next Generation Hydro footprint is general land use and creating a new lake / water storage reservoir where a river previously existed, whereas the renewable portfolios (Scenarios 3 & 4) are a combination of new lakes / water storage reservoirs, modifying existing lakes, and general land use. Therefore, land use impacts cannot be directly compared without evaluating both the land use area and the types of impacts.

As can be seen in Table 62, all of the generation scenarios have the potential to meet the forecast average energy and capacity needs of the Yukon in a socially acceptable manner. However, all of the generation scenarios also have certain advantages and disadvantages that make the decision about which generation types to pursue a selection among tradeoffs. Table 63 below summarizes the pros and cons of each scenario.

[55] In this report the full life cycle GHG production of the different generation resources was not evaluated. GHG were evaluated on the basis of direct generation activities only.

Table 63: Pros and Cons of Generation Proposed Generation Scenarios

Scenario	Pros	Cons
Scenario 1: Natural Gas	▪ Similar economic cost when compared to Scenarios 2 & 4. ▪ Dispatchable (as in, can be turned on and off) as required ▪ Can reliably supply power during winter months ▪ Meets Yukon electricity needs throughout the planning period ▪ Has the smallest land use footprint of all the energy supply scenarios	▪ Highest GHG emissions of all the energy supply scenarios
Scenario 2: Next-Generation Hydro	▪ Similar economic cost when compared to Scenarios 1 & 4. ▪ Zero GHG emissions ▪ Dispatchable (as in, can be turned on and off) as required ▪ Meets Yukon electricity needs throughout the planning period	▪ Similar land use footprint when compared to Scenario 4[56].
Scenario 3: Renewables Portfolio (with No Pumped Storage)	▪ Zero GHG emissions Note: In practice thermal (natural gas) generation is needed to provide dependable winter capacity to support the intermittency, or variability, of the renewables generation assets.	▪ Highest cost option ▪ Fails to meet the forecasted capacity gap in 2065 and will require additional capacity resources (e.g. natural gas or diesel generation). ▪ Larger footprint and transmission line infrastructure requirements compared to the other renewables scenario (Scenario 4).
Scenario 4: Renewables Portfolio (with Pumped Storage)	▪ Similar economic cost when compared to Scenarios 1 & 2. ▪ Zero GHG emissions Note: In practice thermal (natural gas) generation is needed to provide dependable winter capacity to support the intermittency, or variability, of the renewables generation assets.	▪ Fails to meet the forecasted capacity gap in 2065 and will require additional capacity resources (e.g. natural gas or diesel generation). ▪ Similar land use footprint when compared to Scenario 2.

[56] When comparing the scenario footprints it must be recognized that the impact of the different footprints are different for the different project types. For example, the majority of the Next Generation Hydro footprint is general land use and creating a new lake / water storage reservoir where a river previously existed, whereas the renewable portfolios (Scenarios 3 & 4) are a combination of new lakes / water storage reservoirs, modifying existing lakes, and general land use. Therefore, land use impacts cannot be directly compared without evaluating the types of impacts as well as the footprint.

In conclusion, Next Generation Hydro remains a viable candidate for further consideration because NGH has similar economic cost when compared to other generation options, zero Greenhouse Gas (“GHG”) emissions from electricity generation, and it meets the Yukon’s need for electrical winter energy and capacity from 2035 to 2065.

Appendix A: Assumptions and Constraints

Table 64: Summary of Assumptions and Constraints

Category	Approach
Data Sources	Use Yukon-specific data where available and otherwise use closest North American proxy (e.g. BC).
Demand Forecast	Assume the Baseline growth scenario from the *Yukon Electrical Energy and Capacity Need Forecast.*
Scope	Consider the Yukon interconnected grid (YEC system) only; remote communities excluded from study.
Next Generation Hydro	Assume a representative sample of the four (4) least cost NGH projects when considering cost of energy, land use, energy and capacity. The assumptions used in other NGH technical reports are retained (e.g. no flooding in National Parks, no development on the Yukon River, no flooding of Census division communities etc.)
Environmental Impact	Consider the direct impacts to land-use and greenhouse gas (GHG) emissions from electricity generation activities only.
Utility-Scale Solar Energy	Assume that wind energy is prioritized over solar energy at a utility scale (see Appendix H:).
Storage Hydro	"Storage Hydro" will be considered to refer Next Generation Hydro projects with seasonal water storage
Geothermal	Due to the uncertainty of the resource potential for the Yukon, geothermal energy will not be included as part of this report
Biomass	Due to issues of fuel supply security, land-use and variable cost, this study will not include biomass as a resource option for grid connected generation. Moreover, even if included in the analysis, the total contribution biomass would make to the overall energy picture would be small.

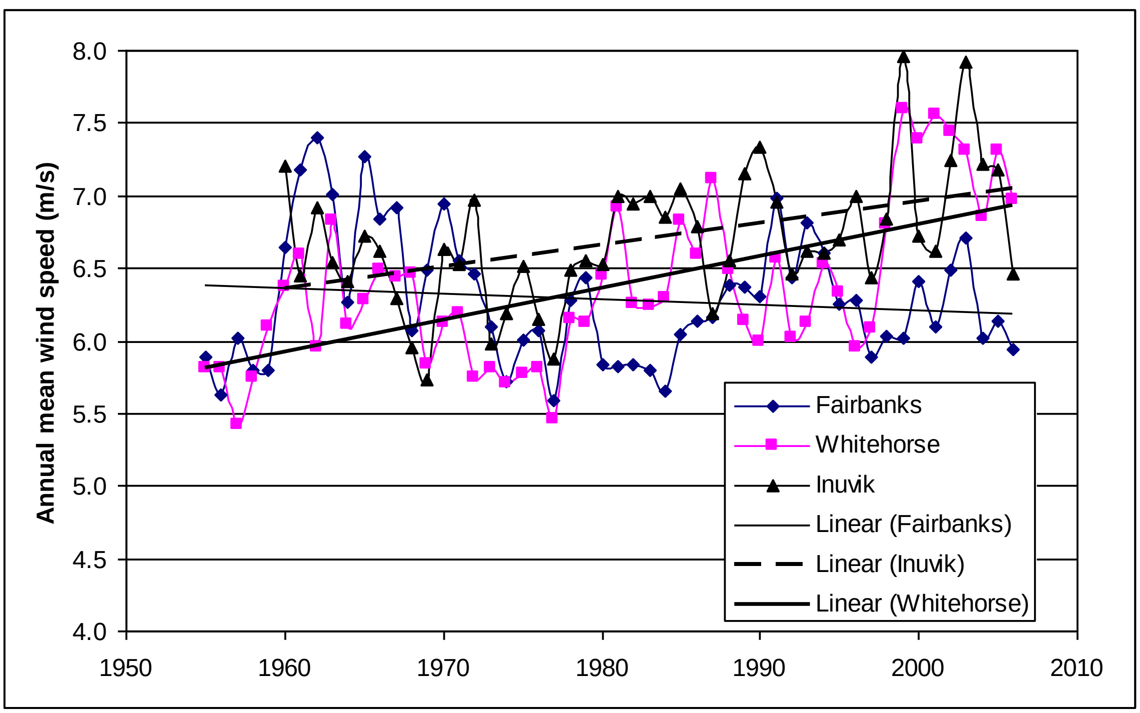
Appendix B: Wind

B.1 Yukon Potential

On an annual basis wind energy generation is relatively consistent, but on a minute-to-minute and day-to-day basis it is difficult to predict how much energy a wind installation will generate. Wind speed variations throughout the day are an important factor for electric system operators, who must exactly match power supply and demand in the grid. The power generated by a wind turbine varies with the third power of wind speed. The Yukon grid is particularly vulnerable to variations in power generation because it is an islanded grid and cannot utilize the firming capability of a larger adjacent interconnected grid such as the WECC (Western Electricity Coordinating Council) grid that interconnects western North America.

The Yukon has exploitable wind resources due to its mountainous geography creating several attractive ridge and mountain-top sites with high average wind speeds. Long-term observations of average wind speeds in the Yukon area suggest that the area is becoming warmer and windier over time (see Figure 62). These wind factors, combined with the generally decreasing capital costs of wind power turbines, make future wind development a potentially attractive option for the territory.

Figure 62: Yearly Average Wind Speed Trends[57]



[57] Time series of mean annual wind speed at 1200 m ASL for Whitehorse, Fairbanks and Inuvik. Best fit linear trends are applied to each series. Courtesy of John Maissan based on "*Wind Climate of the Whitehorse Area".* Jean-Paul Pinard, 2007.

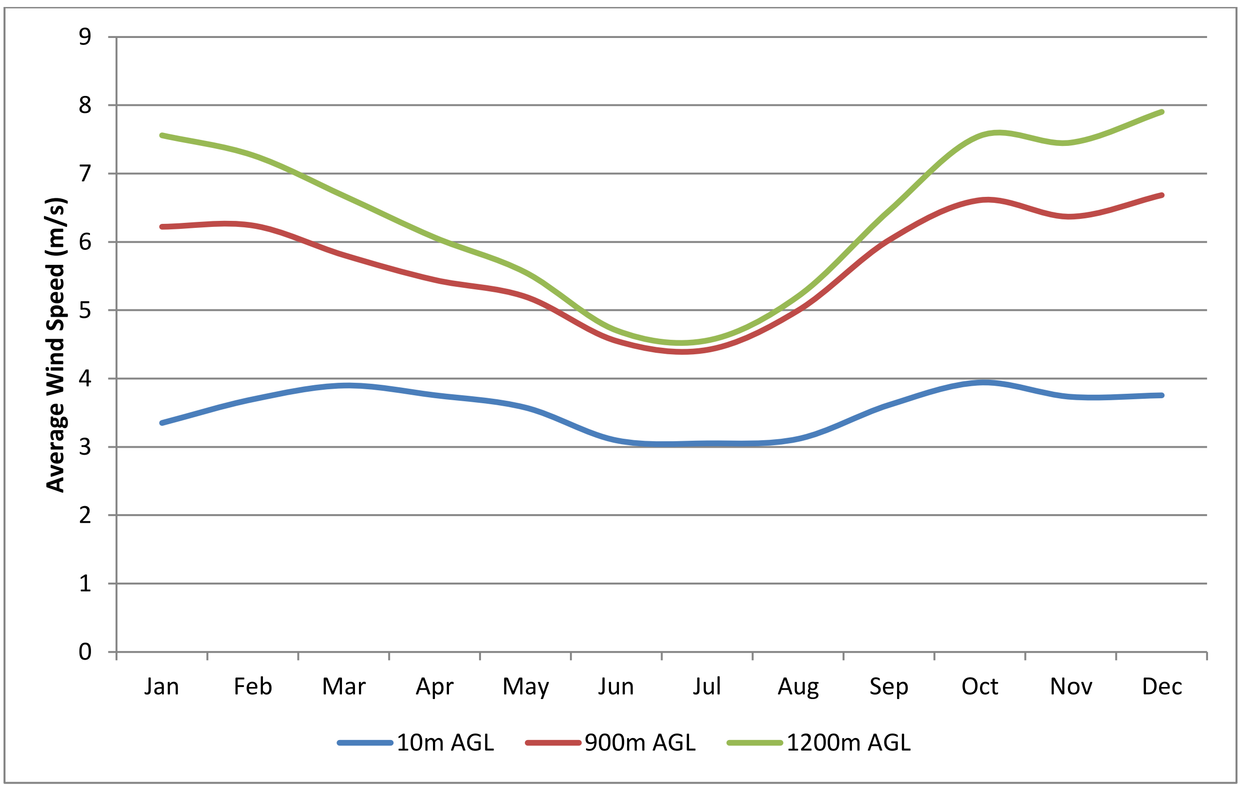
The average wind speeds in Yukon tend to be higher in winter months than summer months, and this is advantageous for two reasons:

1. Winter months are the periods which experience the greatest demand for power in the territory.
2. The winter months are also the period of lowest stream flows in rivers currently utilized for hydroelectric power production in Yukon.

These two factors make increased wind integration desirable on the Yukon grid. Wind power provides a supply profile which, although highly intermittent on an hourly and daily basis, is a good fit for Yukon demand on a longer term (i.e. monthly) basis.

The monthly average wind speeds for the Whitehorse region at different heights, as collected by weather balloon data from 1956 to 2008 are shown in Figure 63. It can be observed that the variation in seasonal wind speeds becomes more pronounced at higher elevations above ground level (AGL), and that higher elevations produce higher average wind speeds. Higher wind speeds at higher elevations is not unexpected given the territory's mountainous terrain where wind speeds on exposed ridges and mountaintops can be expected to be much higher than in valleys and low-lying areas.

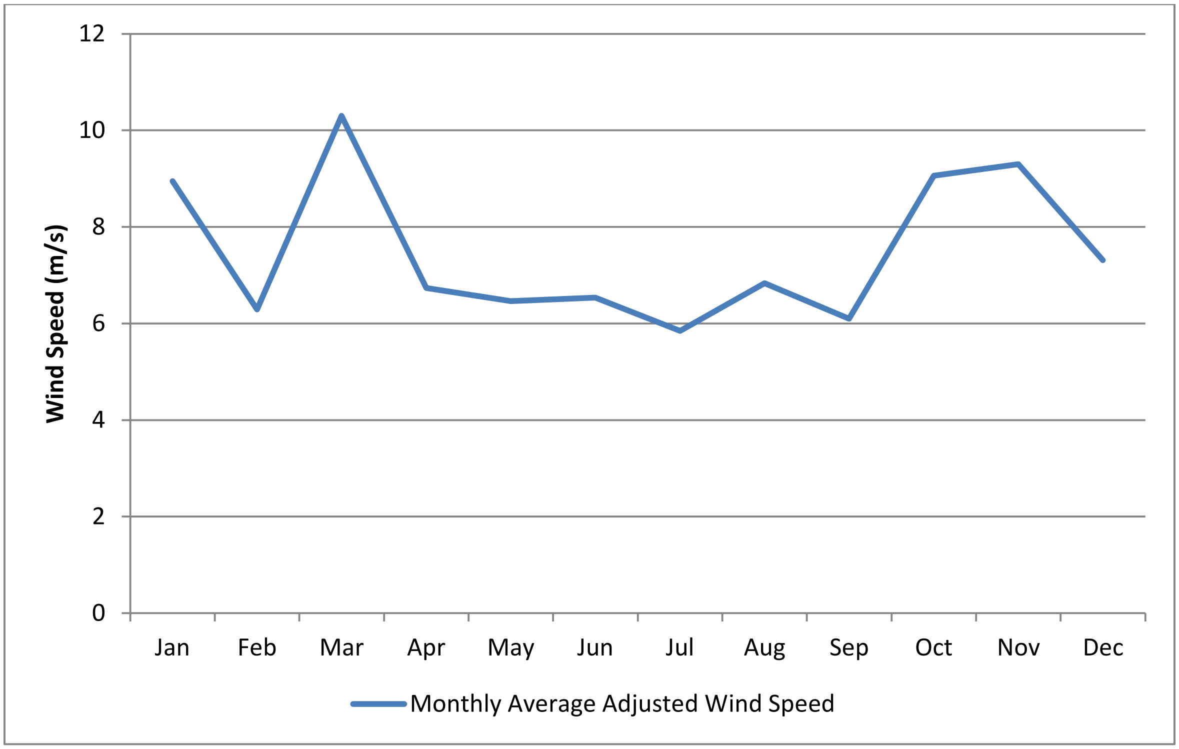
Figure 63: Whitehorse Area Monthly Average Wind Speeds 1965-2008[58]



[58] Source: NOAA Weather Balloon Data archives. https://www.ncdc.noaa.gov/data-access/weather-balloon-data

A more specific monthly wind speed profile is shown below in Figure 64, for measurements taken in 2002-2003 at Mt. Sumanik.

Figure 64: Mt. Sumanik Monthly Average Wind Speeds 2002-2003



The Yukon has some experience in the operation and integration of wind resources into the grid, with two turbines having been installed on Haeckel Hill in 1993 and 2000. Combined, they provide approximately 850kW of installed capacity; less than 1% of the territory's total installed capacity. Feasibility studies have been carried out for select high-potential sites in the territory, with expected installed capacities for each site in the range of 10-20MW.[59]

B.2 Maximum Capacity

The maximum amount of installed wind capacity that an interconnected grid can support is a function of its ability to maintain voltage and power flow stability as wind production varies throughout the day. The point at which firming capacity is no longer available to absorb the intermittency of wind defines the maximum installed capacity of wind.

As an islanded grid, the Yukon system has less ability than other interconnected jurisdictions to absorb wind variation because the Yukon does not have access to inter-jurisdictional energy trading, and must therefore absorb all wind variation through local generation control and local demand management. Making the

[59] Source: Yukon Energy Corporation, 2013.

integration problem more challenging in the Yukon context is the limitation that the Yukon can support only one or two utility scale wind farms, thus resulting in a lack of geographic diversity which might otherwise mitigate the local variability of wind speeds. Simply put, because larger wind farms will only be located at one (or possibly two) location(s), wind speed changes at that one (or two) location(s) is not moderated by wind speed changes at other locations, thereby making overall wind generation output highly variable (and more difficult to integrate).

B.2.1 Wind without Grid Scale Battery Storage

Recent research in isolated grid systems suggests that the maximum wind power penetration as a percentage of total demand is around 20% for a relatively small, islanded grid, depending on the presence of other intermittent generation sources (e.g. solar).[60] In the context of a non-isolated grid, a 2006 study of wind integration in Minnesota determined that up to 25% of peak demand could be delivered from wind without reliability issues.[61]

However, these penetration figures only consider the stability of the electricity grid, which is only half of the picture. Simply because wind capacity *can* be supported by the grid does not mean that this level of penetration can be operated *practically*. Operating at very high levels of wind penetration can mean that a greater amount of thermal or hydro generation must be developed for use as "spinning reserve" in order to absorb the intermittency of wind power. This extra reserve generation can lead to wasted capital and fuel costs, eventually reaching a point where the benefit of new wind power is negated by the concurrent need for new non-intermittent generation. For isolated systems, the practically feasible limit of intermittent integration without specific integration supports is closer to 15% of peak demand, and is set as a maximum allowable threshold for intermittent generation in jurisdictions such as Hawaii.[62] YEC has also previously estimated that the Yukon grid can accommodate the same maximum amount, 15% of total demand.[63] Therefore, a practical, economically reasonable limit for wind installed capacity in the Yukon today is therefore assumed to be 15% of the total demand.

B.2.2 Wind with Grid Scale Battery Storage

In recent years, progress has been made in the development of grid-scale battery storage systems which can be paired with intermittent generation resources such as wind and solar power. These systems serve to reduce the overall variation of an intermittent generator by storing energy during "peaks" in generation and releasing it again during generation "valleys". Currently available battery technologies are capable of

[60] Source: "*Determination of Maximum Wind Power Penetration in a Isolated Island System by Considering Spinning Reserve*" Chang et.al, 2014

[61] Source: "*Integration of Renewable Resources*" California ISO, 2007. http://www.caiso.com/1ca5/1ca5a7a026270.pdf

[62] 15% is the limit at which a detailed interconnection study must be done when installing distributed intermittent generation on a given circuit. Source: Hawaiian Electric, 2015.

[63] Source: "*Economics of Wind Energy and YEC Resource Plan*". Yukon Energy Corporation, 2013.

providing this service for short-term variations (a few minutes to an hour). Variability on a longer time frame (such as a calm wind day) cannot be mitigated using current battery technology because the batteries lack sufficient capacity to provide electrical output for more than a few hours.

For these reasons, a grid scale battery storage system can be considered to mitigate stability issues of intermittent resources in the short term, but not over longer time periods. A battery storage system cannot replace the need for “firm capacity”; for example a battery system integrated with a Yukon wind farm would not replace the need for thermal or hydro generation as a backup for when winds are low for several hours or more.

A grid scale battery system paired with a wind farm would, however, be easier to integrate onto the Yukon grid than a wind farm without grid scale battery storage. A grid scale battery may therefore allow the *maximum installed capacity* of wind energy on the Yukon grid to increase. A recent (2012) installation of a 3MW battery on Alaska’s Kodiak Island system allowed the islanded grid to increase wind penetration from 10% of installed capacity to 20%. Based on this Alaskan project and several others, including the Kahuku project in Hawaii and a Duke Energy project in Texas, effective voltage and frequency smoothing can be facilitated by 1 MW of battery storage for every 2-3 MW of installed wind capacity.[64]

Because grid-scale battery storage technology is still a relatively new technology, estimates of the cost of battery storage vary widely. Recent surveys of battery storage case studies by the International Renewable Energy Agency and Sandia National Laboratories demonstrated a range of around $1-6 million per MW for direct capital costs (including the Alaska, Hawaii and Texas examples mentioned above).[65] Allowances for contingency, owner’s costs and material permits increased the actual installed costs of these systems, with the overall cost of some projects exceeding $10M/MW.

Battery systems operating in cold environments such as the Yukon winter tend to experience reduced performance and operational lifetimes as a result of decreased charging capacity and increased internal resistance at low temperatures. This issue can be mitigated by keeping batteries in a climate-controlled enclosure which increases the energy required to run the battery system.

For the purposes of this study it is assumed that grid scale battery technologies will continue to develop and therefore increase the maximum installed capacity of wind from 15% today (without grid scale battery storage) to 20% in 2035+ using grid scale battery storage.

[64] Source: *Xtreme Power to Build 3MW Battery on Kodiak Island*. Greentech Media, 2012.

[65] Source: *Battery Storage Case Studies 2015.* International Renewable Energy Agency, 2015 and *DOE/EPRI 2013 Electricity Storage Handbook in Collaboration with NRECA.* Sandia National Laboratories, 2013.

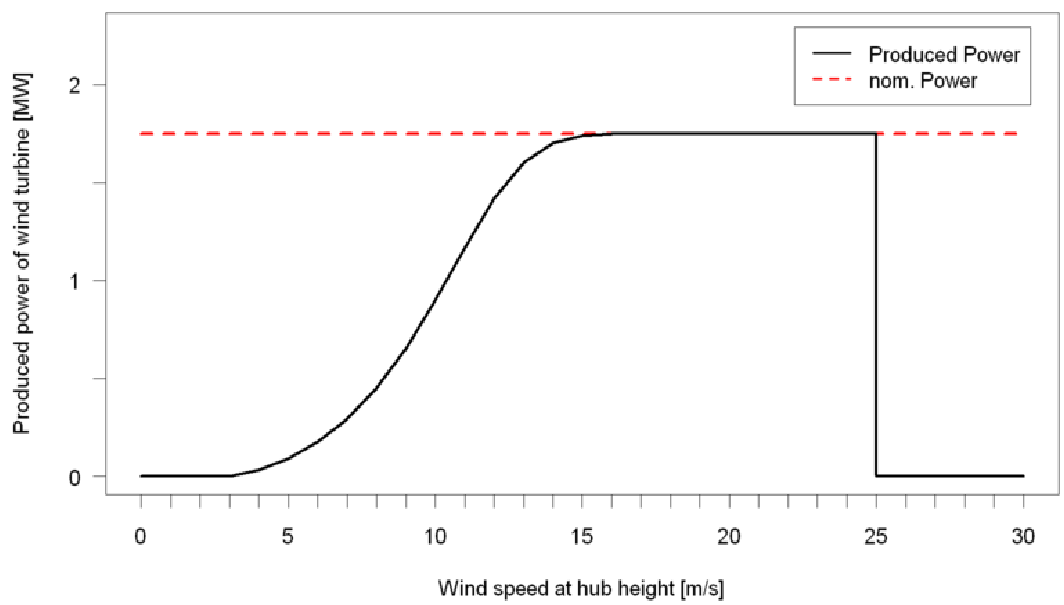
Table 65: Assumed Maximum Wind Capacity with Grid Scale Battery Storage

Year	Assumed Peak Demand (MW)	Maximum Wind Penetration (% of Peak Demand)	Maximum Wind Installed Capacity (MW)
2015	84	15%	13
2035	109	20%	22
2065	141	20%	28

B.3 Maximum Energy

The annual energy production of a wind installation is related to installed capacity by its “capacity factor”, a measure of how much of its theoretical energy production is typically realizable in practice. There are many factors influencing capacity factor, including the wind speed, wind farm layout, physical limitations of the wind turbines and turbine efficiencies. The physical turbine limitations of the turbine determine wind speeds below or above which the turbine will shut down and cease producing power. Typically this shut down is achieved by pitching the turbine blades out of the wind in order to stop them rotating. For example, cut-in wind speeds are typically between 3 and 4 m/s, while cut-out speeds are often around 25 m/s for certain classes of wind turbines. At an intermediate point, typically between 12 and 17 m/s, the turbine will reach its rated power output, and higher wind speeds will not result in higher output power.

Figure 65: Wind Turbine Output vs. Wind Speed[66]



[66] Source: Wikimedia Commons.

The capacity factor also depends on the characteristics of the site, including overall wind patterns, mandatory downtime, as well as the selection and siting of turbines. A feasibility study for a 20MW wind farm in the Yukon suggested a maximum capacity factor for the area of around 30%, before any additional real-world losses (such as icing, which will be discussed in more detail later).[67] 30% is a typical value for the current state of turbine technology; however, estimates for average capacity factors for new installations in 2020 are on the order of 36%, and it can be reasonably expected that capacity factors will reach or exceed 40% for well-sited locations by 2065.[68]

By scaling the currently available wind resource assessments and feasibility studies for Yukon to their assumed maximum capacities for 2015 and 2065, the theoretical maximum annual energy production can be estimated for wind resources in Yukon, assuming that the overall generation mix is unchanged between 2015 and 2065 (i.e. there is a corresponding increase in hydroelectric and/or thermal capacity in order to facilitate firming and grid integration).

Table 66: Assumed Maximum Wind Energy

Year	Total Assumed Energy Demand (GWh)	Existing Hydro Energy (GWh)	Energy Gap (GWh)	Maximum Wind Installed Capacity (MW)	Assumed Capacity Factor	Maximum Annual Wind Energy (GWh)	Maximum Total Energy From Wind
2015	448[69]	443	5	13	30%	34	**100%**
2035	547[70]	443	103	22	35%	66	**64%**
2065	710[71]	443	265	28	35%	88	**33%**

These estimates are, in general, corroborated by the YEC`s 2011 resource plan, which estimated a maximum energy production of 56GWh for a 20 MW Yukon wind farm. The seasonal trend observed using wind speed data at a potential wind farm site was for greater energy during the winter than the summer, with the energy curve having the following shape shown in Figure 66:

[67] Source: "*Mt. Sumanik Wind Assessment Feasibility Study* ". AECOM, 2009.

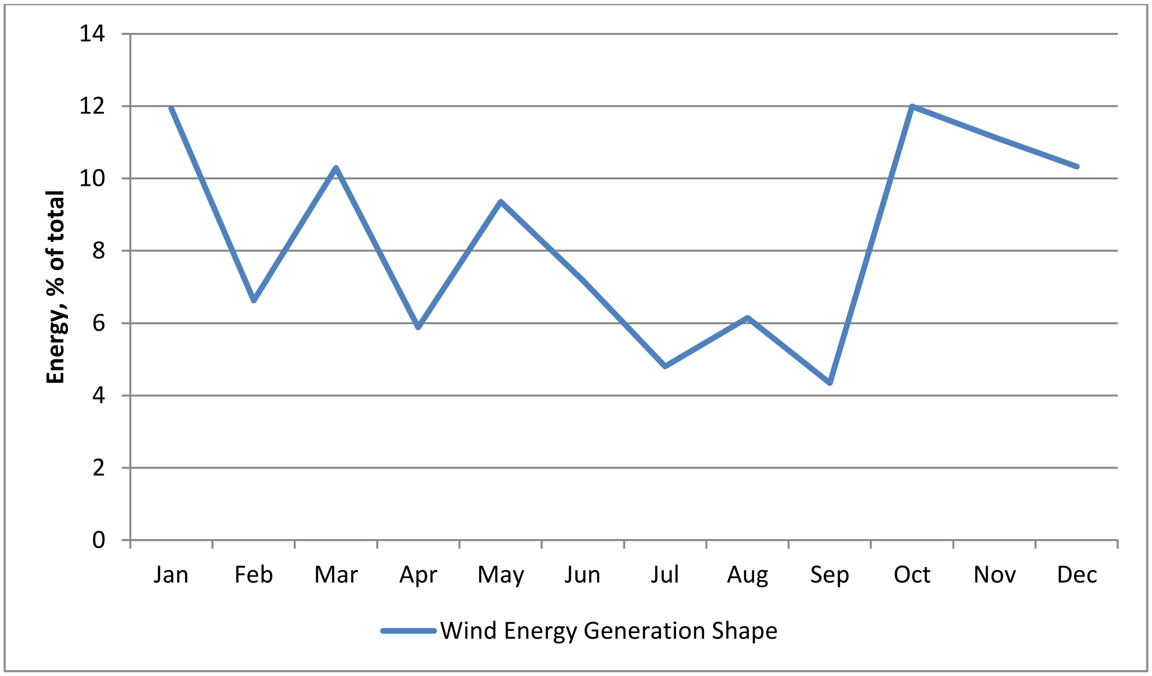
[68] Source: "*Annual Energy Outlook, 2015"* EIA, 2015.

[69] Source: Yukon Energy Corporation, based on 2013 consumption.

[70] Source: Midgard *Yukon Electrical Energy and Capacity Need Forecast (2035-2065)*

[71] Source: Midgard *Yukon Electrical Energy and Capacity Need Forecast (2035-2065)*

Figure 66: Yukon Wind Annual Energy Trend[72]



Applying the annual trend to the maximum forecast installed wind capacity gives the following monthly energy production for 2065:

Table 67: Monthly Maximum Wind Energy Supply - 2065

Month	2065 Monthly Wind Energy (MWh/Month)	Total Energy Gap (MWh/Month)
Jan	10,537	34,688
Feb	5,845	27,793
Mar	9,087	38,185
Apr	5,191	27,212
May	8,261	18,735
Jun	6,344	15,287
Jul	4,240	10,465
Aug	5,424	12,072
Sep	3,834	12,867
Oct	10,584	15,691
Nov	9,835	23,378
Dec	9,118	28,872

[72] Source: *"Economics of Wind Energy and YEC Resource Plan"*. Yukon Energy Corporation, 2013.

B.4 LCOE

The levelized cost of electricity (LCOE) is an estimate of the actual cost of electricity from a given source, including all costs over the lifetime of the generation asset including initial investment, operations and maintenance, cost of fuel and cost of capital.

Using assumptions for capital cost, operating cost, transmission and project lifetimes detailed below, Midgard estimates the current full utilization LCOE of wind power in Yukon at **$157/MWh**.

Four other estimates are shown in Table 68, two for previously conducted real-world feasibility studies for wind installation in Yukon, another being an aggregate of actual costs for recent wind power installations in BC, and the final being a generalized global forecast for 2020. The disparity between the four estimates illustrates three general factors in wind power costing:

1. The LCOE for wind power has been decreasing, a trend which is expected to continue for several more years, mostly due to reductions in capital cost of turbine equipment.
2. The Yukon presents special construction and operation challenges due to its climate and remoteness, driving wind LCOE higher than in other jurisdictions.
3. Yukon wind farms will be smaller than typical installations in southern Canada and the United States, therefore reducing the opportunities for economies of scale & scope for permitting, construction and operations.

The Yukon-specific estimates shown below take the factors in 2) and 3) above into account, in addition to considering the integration of wind energy into the current Yukon grid.

Table 68: Wind LCOE Estimates

Cost Component ($ / MWh)	Levelized Capital Cost ($/MWh)	Fixed O&M ($/MWh)	Variable O&M (including fuel) ($/MWh)	Total LCOE ($/MWh)
Yukon Wind Feasibility, 2009[73]	117	43	0	160-190
YEC Resource Plan 2012[74]	111	37	0	148 - 265
Yukon Wind Feasibility, 2013[75]	-	-	0	148-168
BC Clean Power Call,	-	-	0	90-130

[73] Source: "*Mt. Sumanik Wind Assessment Feasibility Study*". AECOM, 2009.

[74] Source: YEC Resource Plan, July 2012.

[75] Source: Yukon Energy Corporation, 2013.

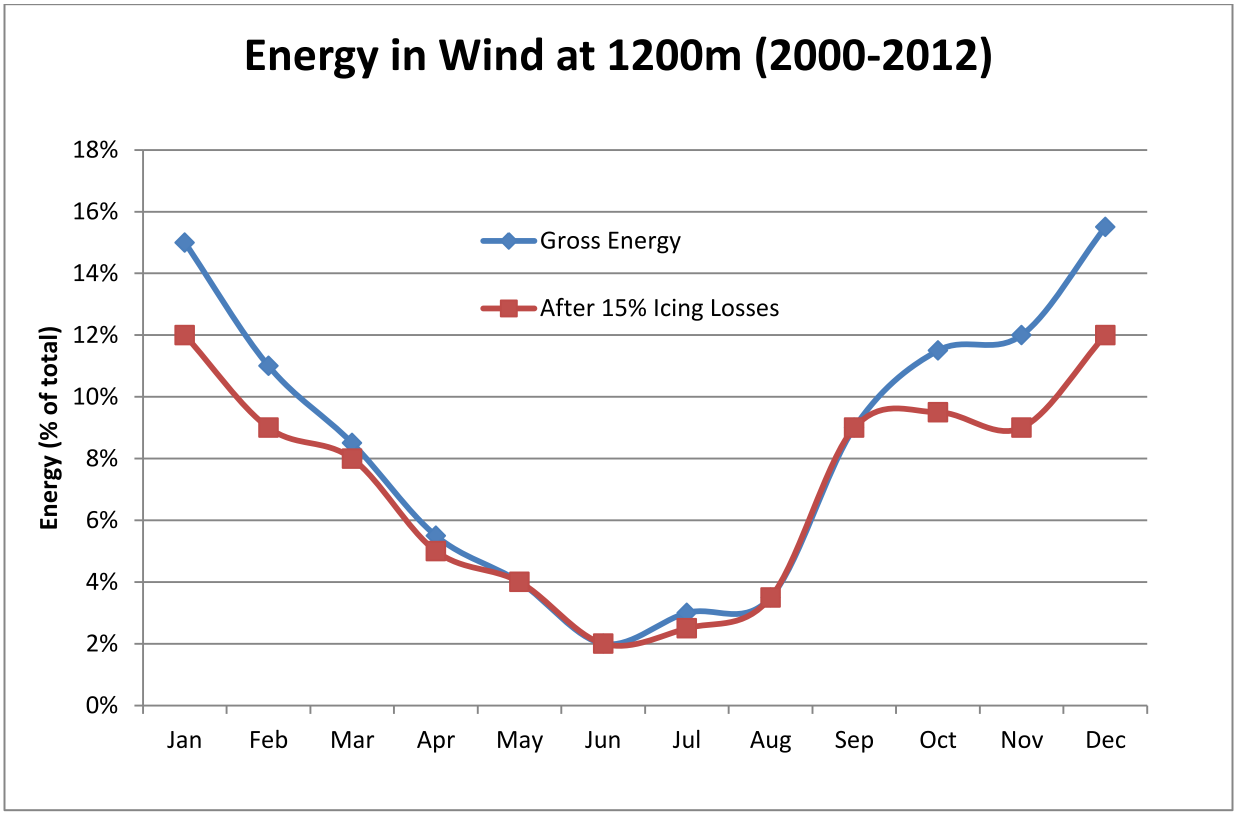
Cost Component ($ / MWh)	Levelized Capital Cost ($/MWh)	Fixed O&M ($/MWh)	Variable O&M (including fuel) ($/MWh)	Total LCOE ($/MWh)
2008[76]				
US EIA, 2020 estimate[77]	60.8	12.8	0	73.6
Midgard Estimate without battery storage	119	38	0	157
Midgard Estimate With Battery Storage	151	41	0	192

Wind turbines operating in cold climates experience some unique operational issues, including those due to rime icing on turbine blades. Rime icing occurs when moist air is pushed up and over mountains where it experiences a sudden drop in temperature, causing a buildup of ice on turbine blades and nacelles. With Yukon experiencing icing conditions at least 30 days of the year, icing losses due to reduced power output have been estimated at 15% annually. These losses are more severe during the winter months, as shown in Figure 67.

[76] Source: GL Garrad Hassan for BC Hydro, 2008. https://www.bchydro.com/content/dam/BCHydro/customer-portal/documents/corporate/regulatory-planning-documents/integrated-resource-plans/current-plan/irp-appx-3a-26-20130802.pdf

[77] Source: "*Annual Energy Outlook, 2015*." EIA, 2015.

Figure 67: Wind Turbine Icing Losses[78]



The typical mitigation strategy for icing losses is to install electric de-icing systems on turbine blades and other components. These systems can reduce icing losses by 50% but increase the capital cost of the turbine system as well as consuming some of the power produced by the turbine. Cost estimates for de-icing systems sufficient for use in Yukon are around $200/kW of installed capacity.[79] Annual energy production will either be reduced by 15% without de-icing, or by 7.5% with de-icing but at the expense of higher capital cost. For a 20MW wind farm, a de-icing system might therefore cost around $4M. Given an assumed 25-year turbine life and 56 GWh/year of energy production[80], this would correspond to an additional cost of $3 per MWh. These costs are accounted for in the Yukon-specific LCOE estimates above. The cost of transmission has also been accounted for in the Yukon wind feasibility studies done to date, along with estimates of the annual O&M costs.

B.5 Land Use Footprint

The land-use footprint of wind energy can be considered in two ways. The *direct* impact area is the actual land footprint taken up by tower foundations, buildings and electrical equipment including substations. The

[78] Courtesy of John Maissan

[79] Source: "*Mt. Sumanik Wind Assessment Feasibility Study*". AECOM, 2009.

[80] Based on "*Yukon Energy 20-Year Resource Plan: 2011-2030*". Yukon Energy Corporation, 2011.

total impact area is the entire area of the wind farm. It must be noted that the total land requirements of a wind development do not exclude other uses for the land; generally the area in between turbines is still useful for other purposes that do not conflict with the wind turbines.

A 2009 NREL study aggregated the impacts of 161 wind projects across the United States and found that the average land use requirements for wind power were 0.3±0.3 hectares/MW direct and 34.5±22.4 hectares/MW total.[81] Given the proximity of proposed wind developments in the Yukon to Whitehorse, approximately 15 km of new transmission line and road would be required to interconnect to the Yukon grid.[82] Assuming that a 21MW wind development would require a transmission line with a 30m right-of-way, an additional 30 hectares of land would be impacted[83]. Given a road width allowance of 6m, a further 6 hectares of land would be required for the access road.[84]

Table 69: Wind Land-Use Requirements[85]

Direct impact (hectare/MW)	0.3 ± 0.3
Total impact (hectare/MW)	34.5 ± 22.4
Total impact including transmission and roads (hectare/MW)	36.2 ± 22.4

B.6 GHG Emissions

In general, the full lifecycle greenhouse gas (GHG) emissions of wind power are low because consuming fossil fuels is not required to generate electricity. The Intergovernmental Panel on Climate Change (IPCC) provides annual updates on the full life cycle GHG performance of generation technologies. The 2014 IPCC estimate for life-cycle onshore wind emissions is 7-56 kg CO_2e[86]/MWh, with a median value of 11 kg CO_2e/MWh.[87]

The GHG emissions for wind energy generation (not considering life cycle emissions resulting from the manufacture, transport, erection, maintenance and eventual decommissioning of wind turbines) are zero.

[81] Source: "*Land-Use Requirements of Modern Wind Power Plants in the United States*". National Renewable Energy Laboratory, 2009.

[82] Source: "*Mt. Sumanik Wind Assessment Feasibility Study*". AECOM, 2009.

[83] Given a 69kV or 138kV interconnection. Source: AEP Ohio (2009). *Encroachments on Transmission Rights of Way.*

[84] Source: British Columbia Ministry of Forests (2002). *Forest Practices Code of British Columbia.*

[85] The total impact including transmission and roads will be assumed for the purposes of this study.

[86] Carbon Dioxide (CO_2) equivalent

[87] Source: "*Annex iii – Technology-Specific Cost and Performance Parameters",* In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, 2014.

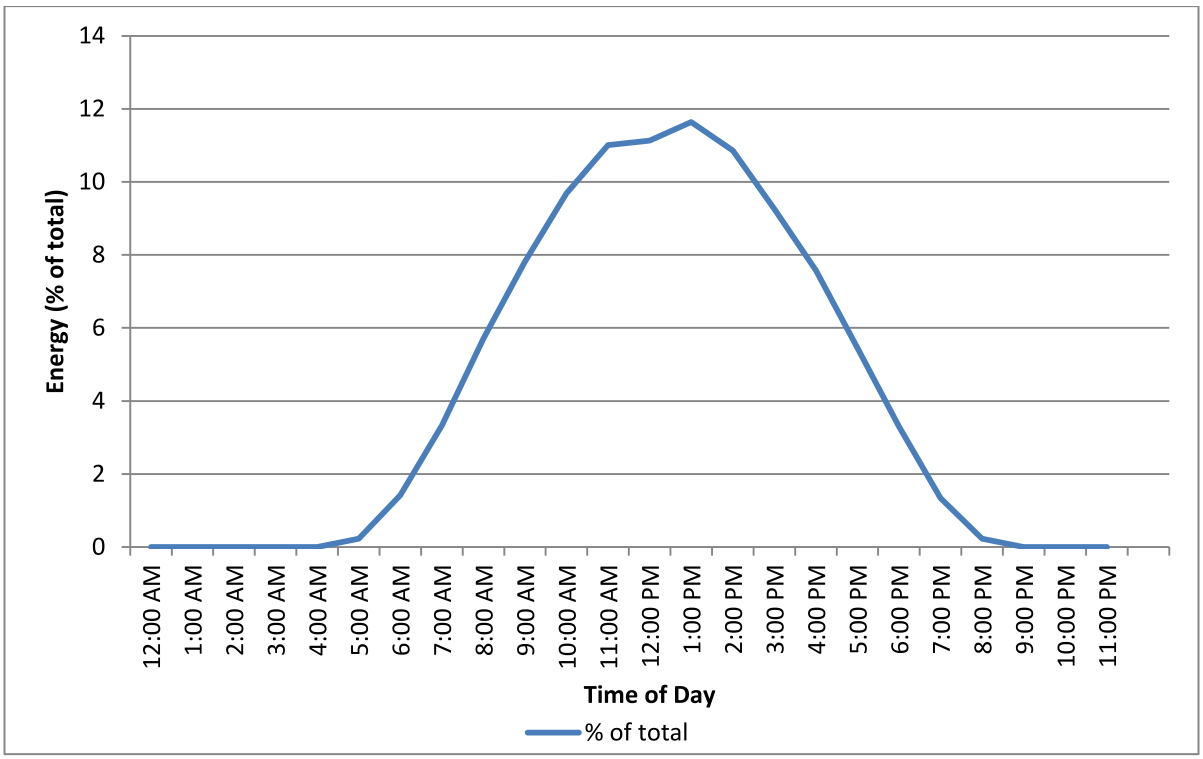
Appendix C: Solar PV

C.1 Yukon Potential

Photovoltaic energy is a form of “intermittent” energy, because solar PV systems/solar panels can only produce electricity when the sun is shining. Atmospheric effects such as clouds can have a significant impact on energy production from a PV cell. Therefore, similar to wind energy, the development of solar energy requires the concurrent development of “firm” energy which can be called upon when the output from solar panels decreases (i.e. at night).

The daily average energy potential for solar energy in Yukon is shown in Figure 68. As one might expect, the greatest amount of energy is available during the middle of the day, with energy production falling off with the setting of the sun.

Figure 68: Whitehorse PV Daily Energy[88]

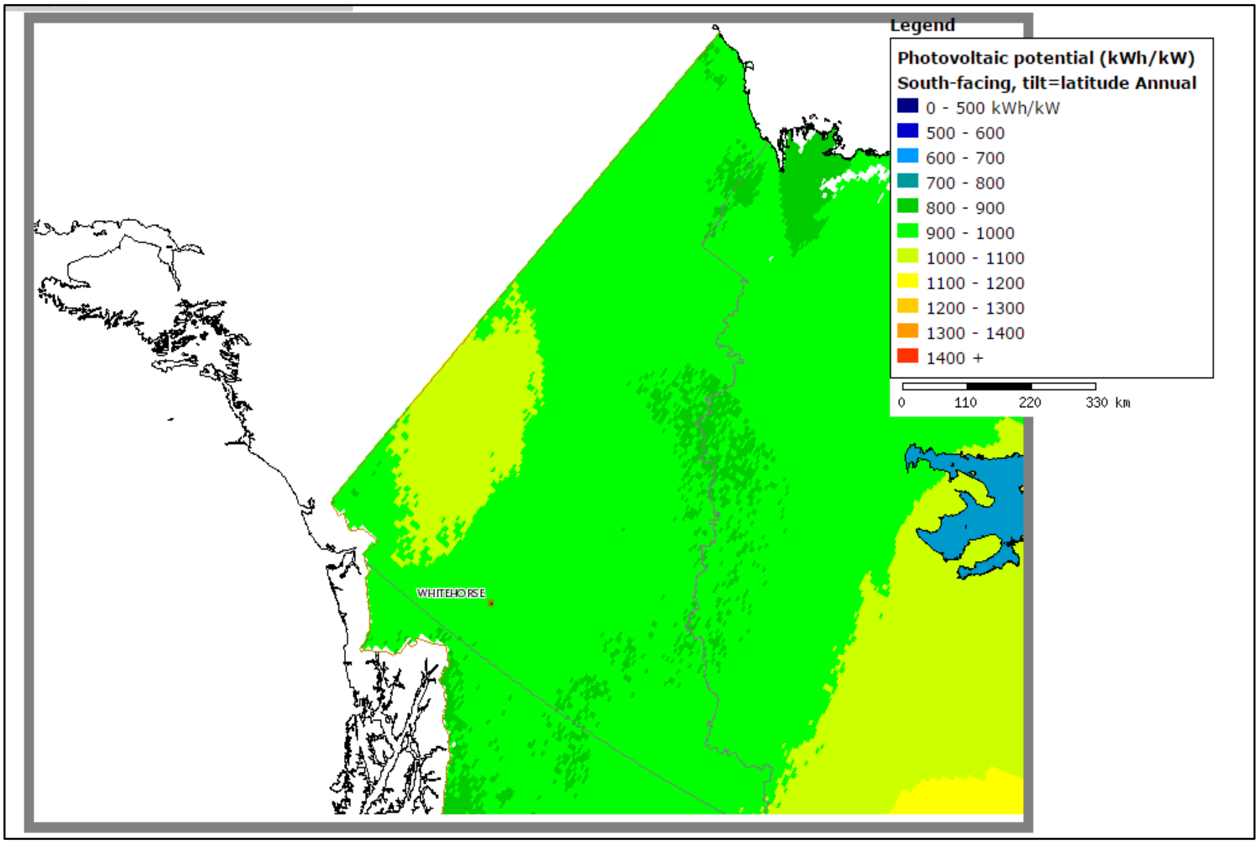


The Yukon is not ideally situated for solar PV energy production due to its high latitude and generally large angles between incoming solar radiation and the ground. Short winter days lead to low energy production for the peak demand parts of the year. Despite these drawbacks, there are a number of residential solar installations in the Yukon, both on and off-grid. The solar potential for the Yukon is shown in Figure 69, and

[88] Courtesy John Maissan

generally falls between 900-1000 kWh/kW. There is a region in southwestern Yukon which is more suitable for solar PV with a potential above 1000 kWh/KW.

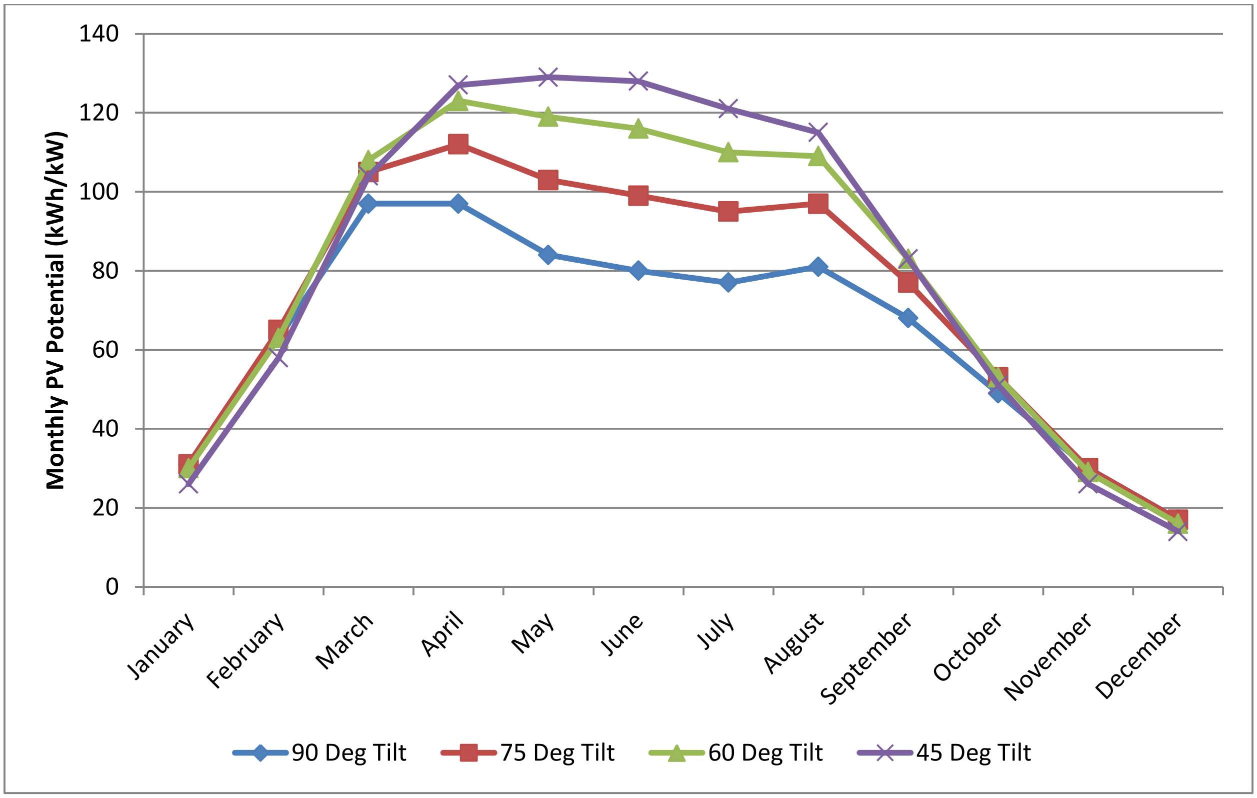
Figure 69: Yukon Solar PV Potential[89]



The annual energy profile for solar PV in Yukon at different panel angles is shown in Figure 70 and shows that in order to maximize energy production from a Yukon solar installation, the optimal tilt angle for a solar panel is around 45 degrees.

[89] Source: "*Photovoltaic potential and solar resource maps of Canada".* Natural Resources Canada, 2015.

Figure 70: Whitehorse Monthly PV Potential for Different Tilt Angles[90]



In much the same way as for wind energy, the capacity factor for solar energy can be estimated based on the incident solar energy and panel tilt angle. Natural Resources Canada estimates the annual energy production for a site near Whitehorse at 983 kWh/kW, given a tilt angle of 45 degrees, corresponding to a capacity factor of approximately 11%.[91]

This theoretical capacity factor is supported by actual historical data from existing solar installations in Yukon which have demonstrated a real-world energy production of around 825 kWh/kW, corresponding to a capacity factor of 9%.[92]

Table 70: Solar Capacity Factor Estimates

Energy Production (kWh/kW)	Theoretical Energy Available (kWh/kW)	Capacity Factor
983	8760	11%
825	8760	9%

[90] Source: *"Photovoltaic potential and solar resource maps of Canada".* Natural Resources Canada, 2015.

[91] Source: *"Photovoltaic potential and solar resource maps of Canada".* Natural Resources Canada, 2015.

[92] Source: Yukon Energy Corporation, 2014.

C.2 Maximum Capacity

The maximum realizable installed capacity of solar power in the Yukon is dependent on the stability of the electricity grid, and the availability of firm energy to counterbalance the intermittent supply of solar energy. Unlike wind energy, the supply of solar energy is more predictable because it follows the transit of the sun through the sky. However, the overall availability of solar energy is less than that of wind because there is no solar energy available after the sun sets.

Recent technical studies of maximum solar penetration on an electric grid have suggested that the limit of peak demand that can be realized by solar power is around 10% of the total. This is the maximum value suggested for both the Ontario power grid[93] and for the Hawaii power grid, where some circuits have already reached this limit and no additional solar capacity is being permitted. [94]

In the Yukon, the Micro-Generation Program also stipulates a maximum capacity for distributed generation (which is typically solar power) of 25kW of intermittent energy per transformer. Given that 250kVA is a common and typical size for a distribution transformer, this again suggests a maximum solar capacity of around 10% of the total peak demand. For the current Yukon system this would correspond to around 8MW of solar capacity, and for 2065 would represent 14MW of capacity.

Table 71: Assumed Maximum Solar Capacity

Year	Assumed Peak Demand (MW)	Maximum Solar Penetration (% of Peak Demand)	Maximum Solar Installed Capacity (MW)
2015	84	10%	8
2035	109	10%	11
2065	141	10%	14

C.3 Maximum Energy

The maximum annual solar energy realizable in Yukon is a function primarily of the available sunlight hours. As shown in Figure 71, almost 75% of the annual solar energy is primarily available during the summer months (November - April), with much less energy available during the winter, resulting in relatively poor capacity factors of between 9-11% for Whitehorse.[95] By way of comparison, a typical solar installation at lower latitudes would have a capacity factor of around 25%.[96]

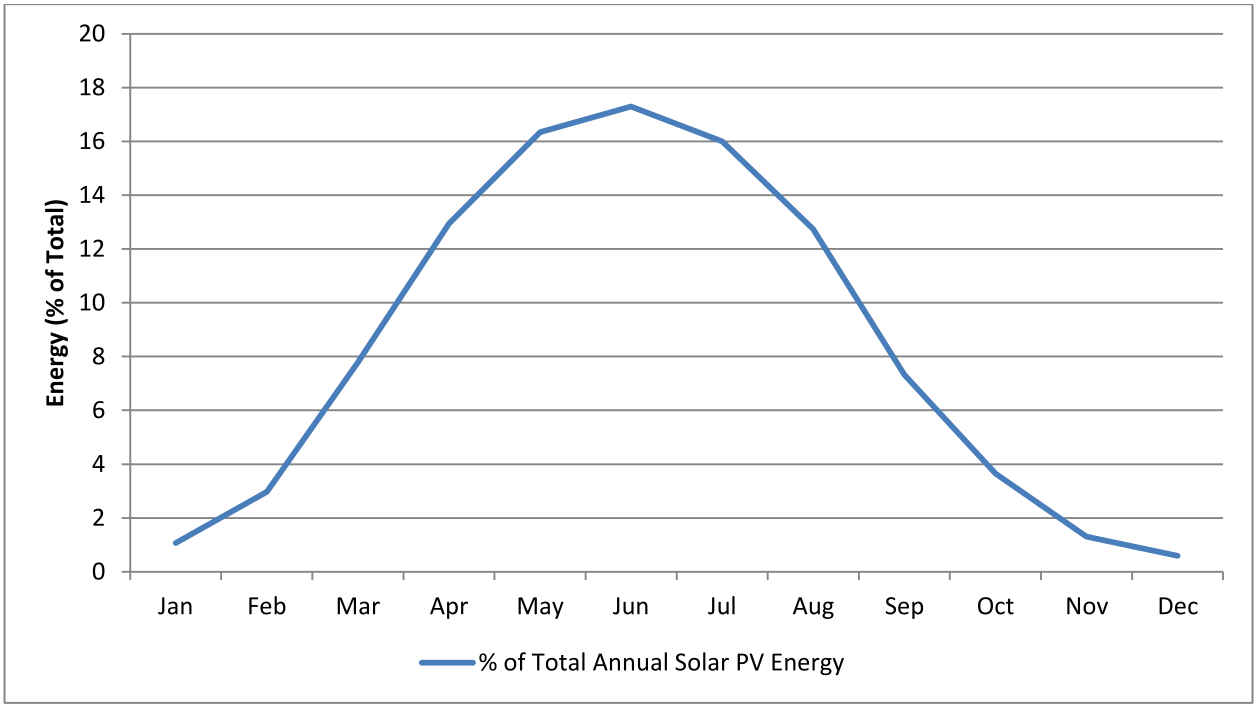
[93] Source: "*Limits to Renewable Energy Penetration*". Ontario Society of Professional Engineers, 2013.

[94] Source: Eric Wesoff, Greentech Media, 2014.

[95] Source: "*Photovoltaic potential and solar resource maps of Canada*." Natural Resources Canada, 2015.

[96] Source: "*Annual Energy Outlook 2015*". EIA, 2015.

Figure 71: Solar PV Annual Energy[97]



It is assumed that, due to recent improvements in the efficiency and tracking capability of solar PV installations, the upper end of estimates for capacity factor can be assumed for the 2065 scenario. Therefore, based on a maximum solar penetration of 10% and utilizing an 11% capacity factor, the total contribution to Yukon's energy supply from solar energy in 2065 could reach 2%.

Table 72: Assumed Maximum Solar Energy

Year	Total Assumed Energy Demand (GWh)	Existing Hydro Energy (GWh)	Energy Gap (GWh)	Maximum Solar Installed Capacity (MW)	Assumed Capacity Factor	Maximum Annual Solar Energy (GWh)
2015	448	443	5	8	9%	6
2035	547	443	103	11	11%	11
2065	710	443	265	14	11%	13

Table 73 illustrates the assumed maximum energy from solar for each month in 2065, as compared to the forecast energy gap.

[97] Courtesy John Maissan

Table 73: Monthly Maximum Solar Energy Supply, 2065

Month	2065 Monthly Solar Energy (MWh/Month)	Total Energy Gap (MWh/Month)
Jan	144	34,688
Feb	402	27,793
Mar	1,050	38,185
Apr	1,746	27,212
May	2,207	18,735
Jun	2,335	15,287
Jul	2,159	10,465
Aug	1,720	12,072
Sep	988	12,867
Oct	493	15,691
Nov	177	23,378
Dec	80	28,872

C.4 LCOE

Using assumptions for capital cost, operating cost, transmission and project lifetimes detailed below, Midgard estimates the current full utilization LCOE of solar power in Yukon at **$192/MWh**.

Currently, the best proxy for the cost of solar energy in the Yukon is the Micro-Generation Incentive rate, which reimburses customers who supply energy to the grid from rooftop solar installations at a rate of $210/MWh.[98]

However, the last five years have seen a steady decrease in the cost of solar energy, and the trend is expected to continue for several more years. The cost of solar PV panels is decreasing; however, the costs of foundations, tracking systems and labour remains relatively fixed.

The Lawrence Berkley National Laboratory estimates that the current capital cost for a North American solar project is $3/Watt installed. Similarly, the City of Edmonton's solar rebate program is based on a $3/Watt price. It is possible that solar projects in the Yukon could be realized for the same $3/Watt cost within a few years.

Based on an 11% capacity factor, a real discount rate of 3.38%, a 25-year project lifetime and a $3/Watt installation price, a representative solar project in the Yukon would produce power at an incremental cost of $181/MWh, not including the costs of operation and maintenance. Using EIA estimates of $11.4/MWh for these O&M costs, and assuming negligible transmission investment (due to the potential of rooftop solar and

[98] Source: "*Micro-Generation Policy*". Yukon Government, 2013.

the general availability of suitable solar project locations very close to load centers), Midgard estimates the full utilization LCOE of solar energy in Yukon at $192/MWh.

Table 74: Solar LCOE Estimates

	Levelized Capital Cost ($/MWh)	Fixed O&M ($/MWh)	Variable O&M (including fuel) ($/MWh)	Transmission /Roads ($/MWh)	Total LCOE ($/MWh)
Yukon Micro-Generation Program	-	-	0	-	210
US EIA, 2020 estimate[99]	109.8	11.4	0	4.1	125
Midgard Estimate	181	11	0	0	192

C.5 Land Use Footprint

The direct land-use impact of solar PV is the land area taken up by the solar panels themselves. The total land-use impact includes the balance of plant including foundations, equipment and local substations. The National Renewable Energy Laboratory estimates the total land-use of solar PV as 2.75±0.25 hectares/MW direct and 3.25±0.25 hectares/MW total.[100]

Table 75: Solar Land-Use Requirements

Direct impact (hectare/MW)	2.75±0.25
Total impact (hectare/MW)	3.25±0.25
Rooftop Solar (hectare/MW)	0

Land use impacts are negligible if solar panels are installed on rooftops because they occupy an area that has already resulted in a land use impact (i.e. buildings pre-exist). For the purposes of this study, all the solar PV energy resulting from adoption of the Micro-Generation Program is assumed to be installed on rooftops and therefore has no appreciable land-use impact. Similarly, rooftop solar requires no road or transmission infrastructure because buildings are assumed to already be grid-connected.

[99] Source: *"Annual Energy Outlook 2015".* EIA, 2015.

[100] Source: NREL, 2013. The total impact will be used in this report where applicable.

C.6 GHG Emissions

Global GHG life-cycle emissions data tabulated by the Intergovernmental Panel on Climate Change (IPCC), estimates life-cycle solar GHG emissions as being between 18-180 kg CO_2e[101]/MWh, with a median value of 48 kg CO_2e/MWh.[102]

The direct energy production GHG emissions of solar energy are zero.

[101] Carbon Dioxide (CO_2) equivalent

[102] Source: "*Annex iii – Technology-Specific Cost and Performance Parameters*", In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, 2014.

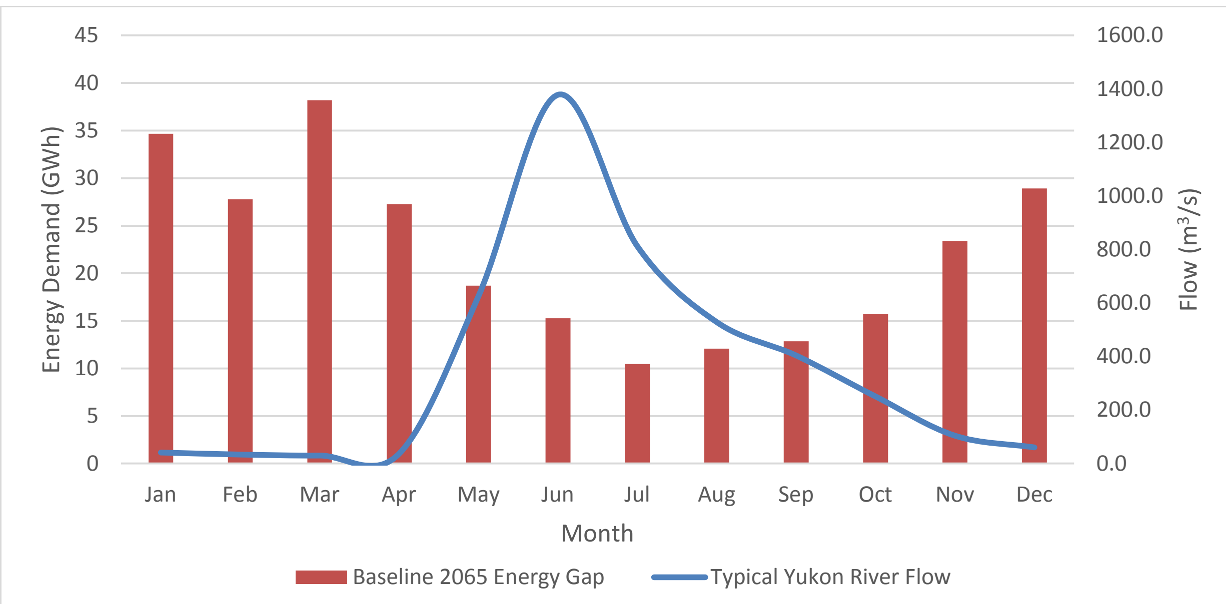
Appendix D: Next Generation Hydro - Storage

D.1 Yukon Potential

Hydroelectric storage projects have higher firm energy and dependable capacity than projects without water storage because storing water allows the project to save water that would otherwise be spilled during high inflow times for use during low inflow times.

As described in the *Yukon Electrical Energy and Capacity Need Forecast* report, the Yukon's energy gaps are largest in the winter months, specifically from November through April. Unfortunately, the typical river flows (i.e. fuel for hydroelectric generation) in the Yukon have an inverse relationship, with the smallest river flows occurring during the months of greatest demand. This inverse relationship is at the root of the Yukon hydroelectric generation challenge, as illustrated in Figure 72.

Figure 72: Yukon 2065 Baseline Monthly Energy Gap and Typical Yukon River Flow[103]



D.2 Maximum Capacity

As described in the *Yukon Next Generation Hydro* technical papers completed by Midgard to date, the capacity of a baseline Next Generation Hydro storage hydro development in the territory would be around 54-60 MW, with expansions to 90-107MW through the addition of turbines as needed.

It is assumed that since any one of the currently shortlisted NGH projects would be sufficient to meet the Yukon 2065 energy gap, a maximum of one such project will be developed. Although the maximum installed

[103] The flow pattern from Fraser Falls was used to illustrate the typical flow patterns in the Yukon.

capacity of storage hydro is technically unlimited, for the purposes of this study, the average capacity of the four (4) lowest-cost NGH projects is used.

Table 76: Assumed Maximum Storage Hydro Capacity

Year	Assumed Peak Demand (MW)	Maximum NGH Installed Capacity (MW)	Maximum NGH Penetration (% of Peak Demand)
2015	84	-	-
2035	109	38	35%
2065	141	57	40%

D.3 Maximum Energy

The currently studied NGH alternatives have a forecast energy production of between 450-600 GWh/year of full utilization energy. Of this energy, 265 GWh/year is forecast to be utilized in 2065, with the remainder being surplus or spilled energy primarily in the summer months.

Table 77: Assumed Maximum Storage Hydro Energy

Year	Total Yukon Energy Demand (GWh)	Existing Hydro Energy (GWh)	Energy Gap (GWh)	Maximum NGH Installed Capacity (MW)	Next Generation Hydro Energy (GWh)[104]	Maximum Annual Hydro Energy (GWh)	Maximum Total Energy From Hydro
2015	448	443	5	-	0	443	99%
2035	547	443	103	38	393	836	100%
2065	710	443	265	57	557	1000	100%

D.4 LCOE

Using assumptions for capital cost, operating cost, transmission and project lifetimes detailed below, Midgard estimates the average full utilization LCOE for the four lowest-cost representative NGH projects at **$92/MWh**[104]. The LCOE of energy produced from existing storage hydro facilities will not be included in this study. Existing Hydro assets are already constructed and will be fully utilized by the 2035-2065 planning period, and as a result they do not contribute to the cost of meeting the forecast energy gap.

[104] Average of Fraser Falls, Two Mile Canyon, Granite Canyon and Detour Canyon projects

Full utilization LCOE (including capital cost and fixed O&M) is calculated using an average of the projects with the four lowest LCOE values found in the *Next Generation Hydro* study.[105]

Table 78: NGH LCOE Estimates

Cost Component ($ / MWh)	Levelized Capital Cost	Fixed O&M	Variable O&M (including fuel)	Total LCOE
Yukon *Next Generation Hydro* Study	77	15	0	92

D.5 Land Use Footprint

The NGH study found that incremental (additional) flooding due to a new large hydro development in Yukon ranges from 100-300 km^2 for the four least expensive shortlisted sites, and this corresponds to 313 hectares/MW of land use[106].

Table 79: Land-Use Requirements of Storage Hydro

NGH Shortlist Average (hectares/MW)	313

D.6 GHG Emissions

The direct electricity production emissions associated with hydro energy are zero.

Life cycle GHG emissions due to hydroelectric power production are primarily due to carbon dioxide and methane release from decomposing organic matter in reservoir. These releases are more prominent in the first years after flooding, when the bulk of materials decompose. There is also a small GHG emission associated with the construction of the plant, primarily due to the use of large amounts of concrete.

The IPCC median value for estimates of hydroelectric GHG emissions is 24 gCO_2e/kWh, however, there is a wide variation in the estimates, from as little as 1 to as much as 2100 gCO_2e/kWh being cited in various studies. Estimates on the higher end of the range are typically associated with reservoirs in tropical environments where the releases due to decomposing vegetation are more pronounced.

A 2012 study of typical boreal forest reservoirs, conducted on the Eastmain-1 reservoir in Quebec, found that there are emissions of between 150-250 gCO_2e/kWh for newly flooded, boreal reservoirs over first five years. This value dropped and stabilized to around 40 gCO_2e/kWh after the bulk of flooded organic material had decomposed.[107] Considering an assumed project lifetime of 65 years, and assuming 200 gCO_2e/kWh for the

[105] Average of Fraser Falls, Two Mile Canyon, Granite Canyon and Detour Canyon projects

[106] Average of Fraser Falls (30,000 Ha & 57 MW), Two Mile Canyon (10,000 Ha & 54 MW), Granite Canyon (17,500 Ha & 57 MW) and Detour Canyon (13,000 Ha & 60 MW) projects

[107] Source: Synapse Energy (2012), based on Teodoru et al. (2012)

first five years and 24 gCO_2e/kWh thereafter gives an overall average for the project of 40 gCO_2e/kWh on a full lifecycle basis.

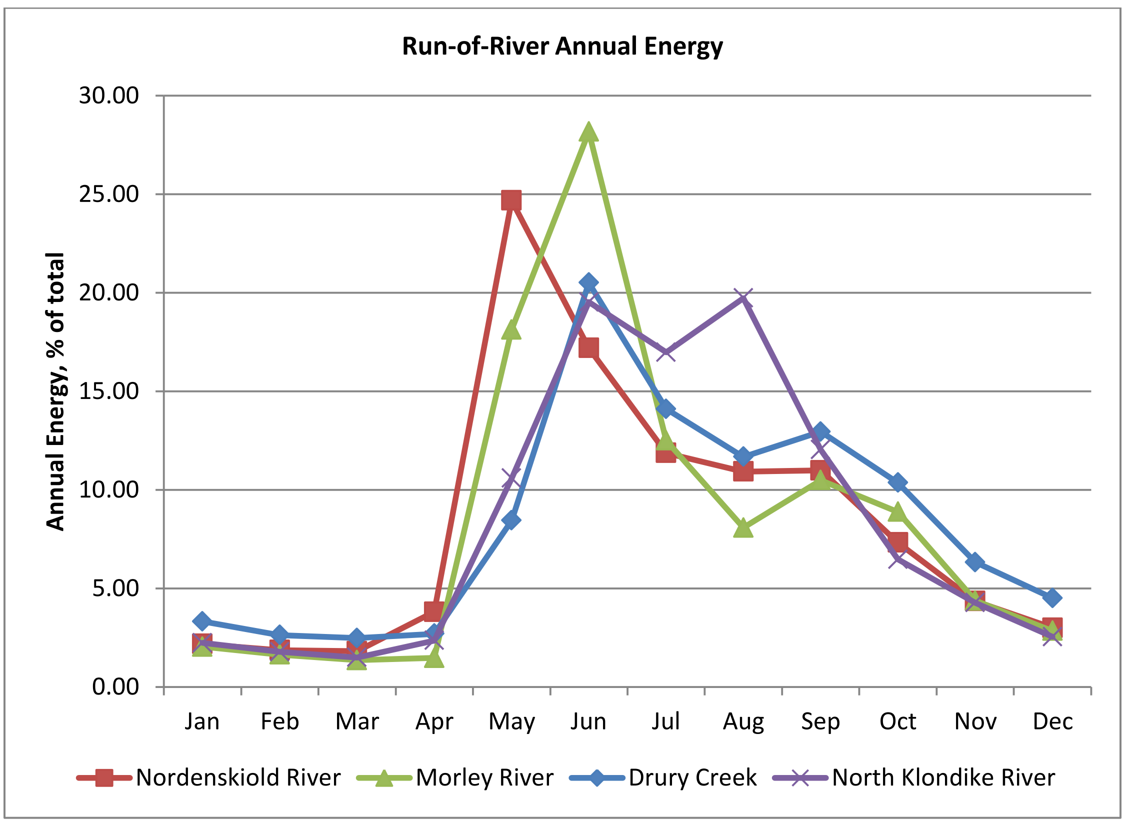
Appendix E: Hydro – Run-of-River

E.1 Yukon Potential

The Yukon has a variety of streams and mountainous terrain, making it a candidate for run-of-river hydro development. Unfortunately, stream flows in the Yukon are highly seasonally variable, with a freshet (snowmelt) high flow period starting in May and June, and a low flow winter period starting in November wherein smaller rivers freeze up. As a result of this seasonal pattern, the availability of run-of-river resources in the territory is reduced, and the period of greatest generation potential (summer) is also the period of lowest electricity demand. The monthly water flows, and hence available energy of representative Yukon rivers is shown in Figure 73[108].

- Nordenskiold River, a relatively small river
- Morley River, a medium size river
- Drury Creek, a creek with an upstream lake and hence an attenuated freshet and higher winter flows
- North Klondike River, a river in the northern watershed with later summer flows

Figure 73: Sample Yukon River Flows[109]



[108] The streams are shown for illustrative and modeling purposes, and are not necessarily locations for hydroelectric development.

[109] Source: Environment Canada, 2015.

Another major challenge for Run-of-River projects is the remoteness of many potential sites that necessitate the construction of long access roads and transmission lines when connecting a project to the Yukon grid.

E.2 Maximum Capacity

The maximum theoretical capacity of run-of-river hydro projects in the Yukon is theoretically limited only by the number of project sites. Given the size of the territory and the number of streams available, the maximum theoretical supply of run-of-river hydro projects is larger than the Yukon could utilize.

However, there are several factors which make the practical realization of run-of-river hydro in the Yukon challenging. First and most relevant is the seasonal variability of the water resource, wherein the available energy from a run-of-river hydro project with no water storage is mostly realized during the summer months when supply of water is highest and electricity demand is lowest.

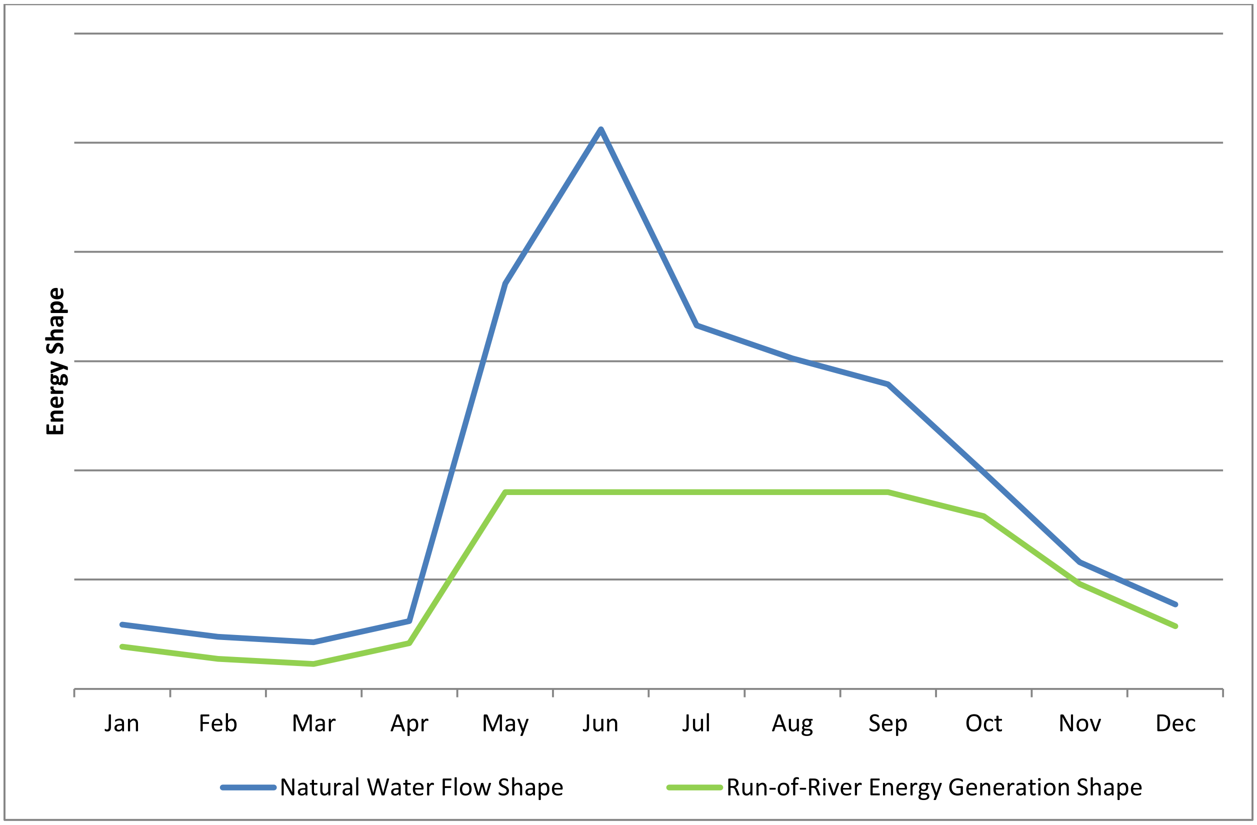
The economics of a run-of-river hydro project are also challenging because the costs of transmission and road access for remote projects are significant. By way of example, the small hydro resource in British Columbia was extensively surveyed and documented in the BC Hydro *2013 Resource Options Report Update*. This study identified over 7,000 potentially viable project sites in the province, yet only 11 of these were estimated to have a unit energy cost (LCOE) of less than $100/MWh.[110] Despite the development challenges, it has been assumed that potentially viable run-of-river hydro projects with rated capacities between 1-15MW can be found. Further survey and research work needs to be done to identify specific potential project sites.

E.3 Maximum Energy

The energy produced by a run-of-river hydro project follows the seasonal variation of stream flows. The average of the four representative Yukon streams in Figure 73 above gives a picture of the annual energy production which might be seen for a Yukon project (see Figure 74). It is acknowledged that this is a simplified representation which does not account for site specific conditions, but it is intended to provide a sense of typical run-of-river production.

[110] Source: "*2013 Resource Options Report Update*". BC Hydro, 2013.

Figure 74: Run-of-River Hydro Energy Generation Shape



As seen in Figure 74, the run-of-river generation shape is different from the natural water flow shape for a "typical" Yukon river. The differences are primarily attributable to two factors:

1) Instream Flow Requirements (IFR): Flows that are reserved to protect the aquatic environment and are not available for generation. Sample IFR flows are listed in Table 80.
2) Maximum Installed Capacity: The maximum size of the facility limits the maximum output of the facility, and correspondingly the maximum water used by the facility.

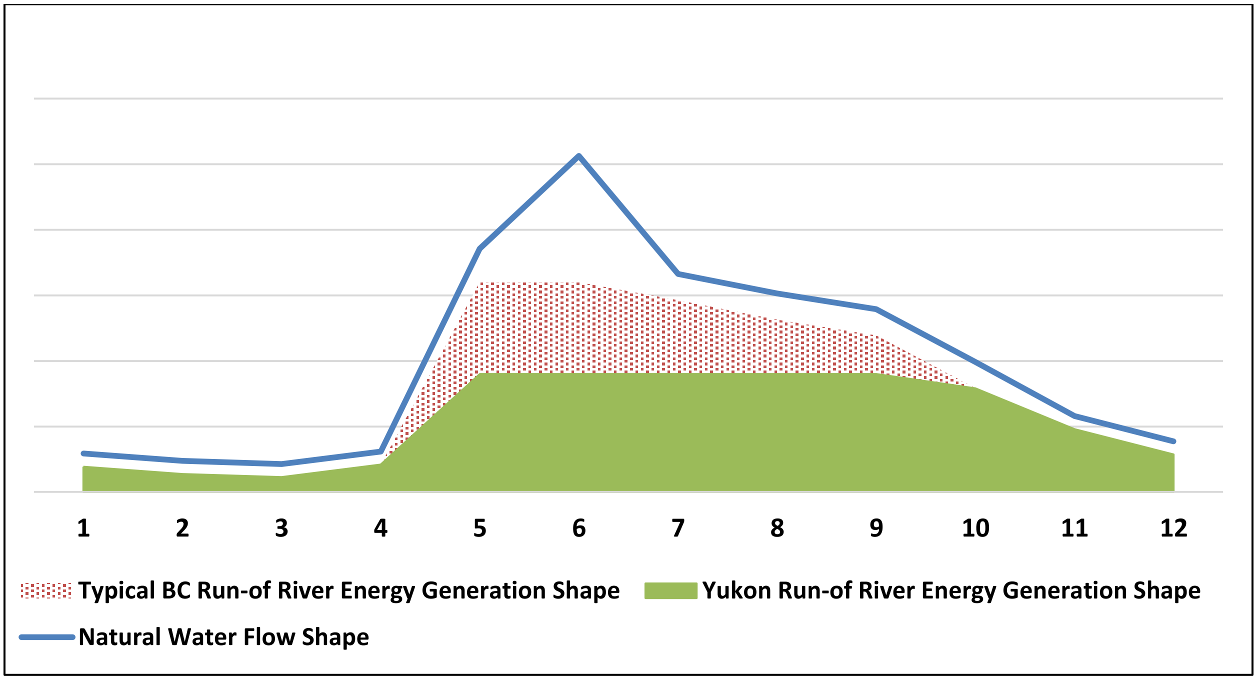
Table 80: Instream Flow Requirements (IFR) Assumption

Month	IFR
January	10% of MAD
February	10% of MAD
March	10% of MAD
April	10% of MAD
May	20% of MAD
June	20% of MAD

Month	IFR
July	20% of MAD
August	20% of MAD
September	20% of MAD
October	20% of MAD
November	10% of MAD
December	10% of MAD

Midgard has sized the "typical" Yukon run-of-river hydro project so that it emphasizes the production of winter energy rather than maximizing annual energy because the Yukon has a need for winter generation and little/no need for additional summer generation. As a result, it is assumed that a typical project has an installed capacity of approximately 0.9 x MAD (Mean Annual Discharge), rather than the 1.5-1.7 x MAD that is more typical for projects that value summer energy more highly than in the Yukon context (see Figure 75 for a graphical comparison).

Figure 75: Yukon ROR Energy Shape Comparison (Yukon = 0.9xMAD, BC = 1.5xMAD)



The monthly energy production for a typical Yukon run-of-river hydro project sized at 4.7 MW (corresponding to 0.9 X MAD), after provisions for IFR requirements is as shown in the Table 82 below. The annual energy generation adds up to 23.4 GWh/year in an average water year.

Table 81: Yukon Typical Run-of River Monthly Energy Production

Month	Monthly Energy Production (MWh)
January	673
February	479
March	397
April	730
May	3,133
June	3,133
July	3,133
August	3,133
September	3,133
October	2,754
November	1,670
December	998

E.4 LCOE

Using assumptions for capital cost, operating cost, transmission and project lifetimes detailed below, Midgard estimates the current full utilization LCOE for a representative small hydro project in the Yukon at **$116+/MWh** for the first few run-of-river projects built in the Yukon. Beyond the first few projects, costs will increase as the "best" few projects are developed.

Over the course of small hydro development in British Columbia, a wide range of energy costs have been realized. There are approximately 50 operating small hydro assets in British Columbia, with LCOE values ranging widely. Estimates for energy costs at point of interconnection range from $93-500/MWh[111]. This represents a bracketing range for the full utilization LCOE of small hydro energy. In the Yukon, higher seasonal variability, remoteness and construction challenges would likely combine to make small hydro energy somewhat more expensive than in BC.

The BC average forecast capital cost for potential new small hydro projects is $4M/MW, with fixed annual O&M costs averaging 1.8% of direct capital costs.[112] The cost of construction in the Yukon will be higher than in BC, and is estimated at $5.75M/MW. Given an assumed 40-year project life and 3.38% real discount rate, the total full utilization LCOE is estimated at $116+/MWh.

[111] Source: *"2013 Resource Options Report Update"*. BC Hydro, 2013.

[112] Based on an average of 55 potential projects in BC. Source: BC Hydro RODAT, 2013.

Table 82: Run-of-River LCOE Estimates

Cost Component ($ / MWh)	Levelized Capital Cost	Fixed O&M	Variable O&M (including fuel)	Total LCOE
BC Projects Range	-	-	-	93-500
Yukon Estimate Range	-	-	-	65-300
Midgard Estimate, based on Yukon Conditions for preferred (least cost) projects	97	19	0	116

E.5 Land Use Footprint

The direct land-use footprints of run-of-river developments are typically smaller than storage hydro developments because run-of-river projects do not require a water storage reservoir. The direct land-use requirements for run-of-river projects includes the land-use associated with the diversion weir and headpond, penstock (water conveyance), and powerhouse. The National Renewable Energy Laboratory estimates the direct land-use impact of run-of river as 0.1 hectares/MW.[113]

The total land-use requirements for run-of-river plants are greater than the direct land-use because run-of-river hydro plants are often sited in remote locations, necessitating the construction of longer access roads and transmission lines. The incremental land-use impacts associated with these rights-of-way are site-dependent and are not easy to generalize. However, most economical run-of-river projects are located less than 50km from a point of interconnection and the best sites are typically less than 30 km from point of interconnection.[114] Assuming that a 10MW project would require a transmission line with a 30m right-of-way, an additional 90 hectares of land would be impacted due to transmission[115]. Given a road width allowance of 6m, a further 18 hectares of land would be required for the access road.[116]

Table 83: Land-Use Requirements of Run-of-River Hydro

Best sites, including transmission and roads (hectares/MW)	11

[113] Source: "*Renewable Electricity Futures Study".* National Renewable Energy Laboratory (NREL), 2012.

[114] Source: Kerr Wood Leidal (2015). *Run-of-River Hydroelectric Potential for British Columbia, Summary of 2015 Updates.* For BC Hydro.

[115] Given a 69kV or 138kV interconnection. Source: AEP Ohio (2009). *Encroachments on Transmission Rights of Way.*

[116] Source: British Columbia Ministry of Forests (2002). *Forest Practices Code of British Columbia.*

E.6 GHG Emissions

The GHG emissions associated with a run-of-river facility are those related to construction, maintenance and decommissioning. The most recent IPCC estimates for run-of-river life-cycle emissions are from 4.5-14 gCO_2e/kWh, with a median of around 7 gCO_2e/kWh.[117]

The direct electricity production emissions associated with run-of-river hydropower are zero.

[117] Source: *"IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation".* IPCC, 2011.

Appendix F: Hydro - Pumped Storage

F.1 Yukon Potential

Pumped storage installations are often used to smooth out hourly or daily variations in electrical grid demand/supply balance by consuming or producing power as necessary to compensate for changes in intermittent (wind, solar, run-of-river) generation and changes in demand. For example, pumped storage can generate when wind generation declines and consume energy (by storing water) when wind generation increases. Pumped storage can also be used for the seasonal storage of water, utilizing surplus (e.g. Yukon summer surplus) electricity to pump and store water, and then releasing it during a period of higher (e.g. winter in the Yukon) need.

The Yukon has potential for the development of pumped storage hydro because it has some mountainous topography and a number of lakes and streams at different elevations. Preliminary work has been done investigating the potential of specific sites for pumped storage in the Yukon, but further work needs to be done to accurately identify the full potential in the territory.

Studies in neighboring BC have identified thousands of megawatts of potential pumped storage, and it is likely that the Yukon potential mirrors this potential to some extent. Seasonal energy storage would allow for a greater penetration of intermittent energy sources such as wind, solar and run-of-river hydro because seasonal pumped storage uses otherwise wasted surplus summer energy to pump water into storage reservoirs for use in the winter when demand is highest.

F.2 Maximum Capacity

The theoretical potential for pumped storage hydro in Yukon exceeds the grid's ability to absorb capacity, but the economically feasible potential is likely significantly smaller. Because pumped storage facilities are not common (there is only a single pumped storage project in operation in Canada[118] and another in development[119]), it is assumed that no more than one potential site would be developed in the Yukon over the planning horizon. For this report it was assumed that a representative pumped storage project would be in the 10-20 MW range with the modelled value sitting at 20 MW.

F.3 Maximum Energy

An important feature of pumped storage is that it does not produce *additional* energy for use on the electricity grid; rather it is a *net consumer of energy*. Pumped storage serves as a storage reservoir for electricity produced by other assets when it pumps water from a lower to upper reservoir. Although stream

[118] Ontario Power Generation's Sir Adam Beck Station

[119] Northland Power's Marmora Pumped Storage

inflows may contribute to filling the upper reservoir and thereby lead to net energy production, this is generally not the target design feature and primary objective of a pumped storage project.

The maximum annual energy storage of pumped storage scheme is highly dependent on the site characteristics as well as the operating regime of the project (i.e. whether it is used for hourly, daily or seasonal storage). For the purposes of this study it will be assumed that a site with 40 GWh of seasonal storage could be developed.

Assuming that the water balance for the year must be maintained (i.e. the reservoir must be operated sustainably, with no more water being withdrawn during the winter than can be replaced during the summer), a 20 MW pumped storage project with 40 GWh of seasonal storage would be able to release/store no more than 15 GWh/month, with a total maximum of 40 GWh for each season.

To achieve 40GWh of seasonal storage, 50GWh of surplus summer energy will need to be available to pump water into the storage reservoir for 40GWh of winter generation. The loss of 10GWh of energy is due to actual capacity/availability factors and the round trip efficiency of the process (which we assume will be 80% efficiency[120]). This report will assume a maximum of 10 GWh/month of actual generation potential for modeling purposes.

F.4 LCOE

The full utilization LCOE for pumped storage is calculated differently than for other resources because it is not a *source* of energy. Rather, the LCOE is calculated as the cost of energy *storage* produced from other resources. Midgard estimates that the single best pumped storage site that could be developed in the Yukon would cost **$183/MWh.**

Estimates for the LCOE of electricity produced from a pumped storage project, from various sources and locations, are shown below. However, these generalized estimates typically assume the use of pumped storage as a diurnal (daily) resource – with pumping and generating being alternated on a daily basis in order to take advantage of low energy prices at night and higher prices during the day. Pumped storage operations that would most benefit the Yukon are *seasonal* storage operations (i.e. storing surplus summer water for use in winter generation).

120 Sources: Alstom, 2015. Chi-Jen Yang (2014). *Pumped Hydroelectric Storage*. Duke University, NC.
Jonah G. Levine (2007). *Pumped Hydroelectric Energy Storage and Spatial Diversity of Wind Resources as Methods of Improving Utilization of Renewable Energy Sources.* University of Colorado.

A study of pumped storage on a seasonal basis in BC has been performed; however, this estimate assumed the use of a pre-existing dam.[121] This study estimated capital costs of around $1250/kW, $9/kW of annual fixed O&M, and variable O&M at $0.90/MWh. The total capacity cost was forecast at $100/kW-yr.

The BC average capital cost for potential pumped storage is $1.25M/MW, with fixed annual O&M costs averaging 1% of direct capital costs, or $12,470/MW[122] and variable O&M costs of $0.90/MWh. Given an assumed 65-year project life, and including the cost of taxes and transmission, the average is estimated at $131/kW-yr. However, these estimates were for very large (1000MW) projects, which lead to an underestimation of the expected cost of a smaller (e.g. 20MW) pumped storage project in Yukon.

A pumped storage cost estimate was developed given an approximate capital cost of $10.8M/MW,[123] based on Midgard's experience with pumped storage projects and representative *Next Generation Hydro* projects, and with fixed annual O&M costs of 0.8% of capital costs. Based on the assumed representative pumped storage project of 20MW and 40 GWh of pumped water storage (plus natural watershed inflows of 14GWh), an estimated full utilization LCOE of $183/MWh as shown in Table 84:

Table 84: Pumped Storage Hydro LCOE Estimates

Cost Component ($ / MWh)	Levelized Capital Cost ($/MWh)	Fixed O&M ($/MWh)	Variable O&M (including fuel) ($/MWh)	Total LCOE ($/MWh)
International Energy Agency, 2014[124]	-	-	-	90-150
Bath County Pumped Storage, US[125]	-	-	-	130
Midgard Estimate	149	34	-	183

F.5 Land Use Footprint

Pumped storage schemes which operate on an hourly or daily basis can have a lower land-use footprint than traditional hydro reservoirs because these daily reservoirs need only store half a day, or slightly more than a day, worth of water. For example, some pumped storage projects with artificially constructed upper reservoirs have a relatively small land-use footprint because they only store 8 hours of generation at full

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[121] Source: "*Pumped Storage at Mica Generating Station, Preliminary Cost Estimate*". Hatch, 2010.

[122] Source: BC Hydro RODAT, 2013.

[123] Midgard estimate of Moon Lake Pumped Storage project

[124] Source: "*Technology Roadmap: Energy Storage*". IEA, 2014.

[125] Source: *"Bath County Pumped Storage Station – Case Study".* Clean Energy Action Project. http://www.cleanenergyactionproject.com/CleanEnergyActionProject/CS.Bath_County_Pumped_Storage_Station___Pumped_Storage_Hydropower_Case_Studies.html

output. Projects utilizing a large body of water (e.g. large lake) as the lower reservoir can have an even smaller land-use impact because the lake fluctuations due to pumped storage activity can be small.

Figure 76: An artificially constructed storage reservoir[126]

The use of pumped storage on a seasonal basis, however, requires the storage of larger amounts of water because there is effectively only one storage/discharge cycle per year. As a result, for seasonal pumped storage the upper reservoir must be large enough to accommodate the entire stored water requirement so that it can be released throughout the winter without additional inflows. For the purposes of this report, land footprint was estimated based on previous pumped storage studies[127].

Table 85: Land-Use Requirements of Pumped Storage Hydro

Large Hydro assumption including transmission and roads (hectares/MW)	145

F.6 GHG Emissions

Although pumped storage hydro is not completely analogous to traditional hydro, the requirement for impoundment and flooding of a reservoir exists in both technologies. It is therefore assumed that the life-cycle GHG emissions resulting from pumped storage hydro are comparable to those associated with traditional storage hydro. In both cases, the GHG emissions associated with direct energy production are zero.

[126] Image Source: Wikimedia Commons.

[127] Midgard pumped storage studies and "Seasonal and Pumped Storage Hydro Opportunity Search in the Carmacks to Faro Road and Power Line Corridor", John F. Maissan, June 2015.

Appendix G: Natural Gas

G.1 Yukon Potential

Natural gas generation is a dispatchable, highly scalable technology, appropriate for use to meet the Yukon's energy and capacity needs (primarily in the winter). The first natural gas generation facility in the Yukon was completed in 2015 near the Whitehorse Rapids hydro facility as a replacement for existing diesel capacity. The expansion of natural gas as an energy source in the Yukon is dependent on social acceptability, as well as a reliable supply of fuel. Since the Yukon does not currently process natural gas or have natural gas supply pipelines, liquefied natural gas brought in by truck is used as fuel for power generation.

G.2 Maximum Capacity

The maximum installed capacity of natural gas is limited only by its social acceptability and the availability of a secure fuel supply. Natural Gas generation is a non-intermittent and scalable technology, and it is less site specific than wind, solar, and hydro (run-of-river, storage, pumped storage) because it does not rely on natural endowments of fuel (wind, sun, water) and topography (suitable natural land features). The currently installed diesel generation capacity on the Yukon interconnected grid is 39 MW[128] (not considering remote communities currently served by diesel).

Table 86: Assumed Maximum Natural Gas Capacity

Year	Assumed Peak Demand (MW)	Installed Capacity (MW)	Maximum Natural Gas Penetration (% of Peak Demand)
2015	84	39	46%
2035	109	Unlimited	Unlimited
2065	141	Unlimited	Unlimited

G.3 Maximum Energy

The maximum energy produced by natural gas is limited only by the installed generation capacity and the availability of fuel for these assets. Capacity factors for base load natural gas generation are assumed to be as high as 85%.[129] Therefore, if the full 2065 energy gap were filled by natural gas, the total annual energy production from natural gas could theoretically, be as much as 265 GWh/year.

[128] Source: Yukon Energy Corporation

[129] Yukon Energy Corporation estimate

Table 87: Assumed Maximum Natural Gas Energy

Year	Total Assumed Energy Demand (GWh)	Existing Hydro Generation (GWh)	Energy Gap (GWh)	Maximum Natural Gas Installed Capacity (MW)	Assumed Capacity Factor	Maximum Annual Natural Gas Energy (GWh)[130]
2035	547	443	103	Unlimited	85%	103
2065	710	443	265	Unlimited	85%	265

G.4 LCOE

The full utilization LCOE of natural gas energy production is highly dependent on fuel costs, in much the same way as for diesel generation. Current fuel cost estimates of $180/MWh[131] delivered for LNG justify the fuel's use as a less expensive alternative to diesel. The commodity value of natural gas in North America has been lower than diesel in recent years due to an abundant supply relative to demand, and current market forecasts indicate that the price of natural gas will continue to be low for several years. However, these trends are not a guarantee of future availability or affordability.

Full utilization LCOE is equivalent to the use of natural gas for "base load" energy, that is, it represents the cost of energy when the natural gas facility is used to produce power on a continuous basis with an 85% capacity factor. The full utilization LCOE for natural gas energy in the Yukon is currently estimated at **$229/MWh**[132], compared to $290/MWh for diesel.

Table 88: Natural Gas LCOE Estimates

Cost Component ($ / MWh)	Levelized Capital Cost	Fixed O&M	Variable O&M (fuel)	LCOE
YEC Estimate	34	15	180	229

G.5 Land Use Footprint

The Whitehorse LNG storage and natural gas generation facility will be used as an example of the direct land-use footprint of natural gas generation. The Whitehorse LNG facility currently has an installed capacity of 8.8 MW but is designed to accommodate an additional 4.4 MW of capacity.[133] The range of land use impacts for this facility is between 0.28-0.42 hectares/MW depending on the capacity assumed. For the purposes of modeling, the smaller land use impact case, assuming full development of the site's installed capacity, will be

[130] Only the energy required to meet the forecast energy gap will be generated regardless of the installed capacity.

[131] Source: Yukon Energy Corporation, 2015.

[132] Source: Yukon Energy Corporation, 2015.

[133] Source: Yukon Energy Corporation

used. This estimate does not include any external land use impacts such as upstream production or transportation.

Table 89: Land-Use Requirements of Natural Gas

Direct Impact (hectares/MW)	0.28-0.42

G.6 GHG Emissions

The direct GHG emission of natural gas combustion as would be utilized in the Yukon is estimated at 710 gCO_2e/kWh[134].

Beyond the GHG emissions associated with developing a natural gas generation facility, a full life-cycle GHG inventory of natural gas generation includes the emissions associated acquiring the natural gas fuel. These fuel related emissions include emissions from upstream natural gas production (e.g. drilling and preparing for pipeline transport), fugitive emissions, pipeline transport, natural gas liquefaction, transporting the liquefied gas into the territory. Depending on the energy source used for these purposes (e.g. using coal-fired electricity), these indirect emissions can be substantial. Fugitive emissions result in the atmospheric release of methane through the fuel production and delivery process. A full inventory of natural gas emissions are outside the scope of this report.

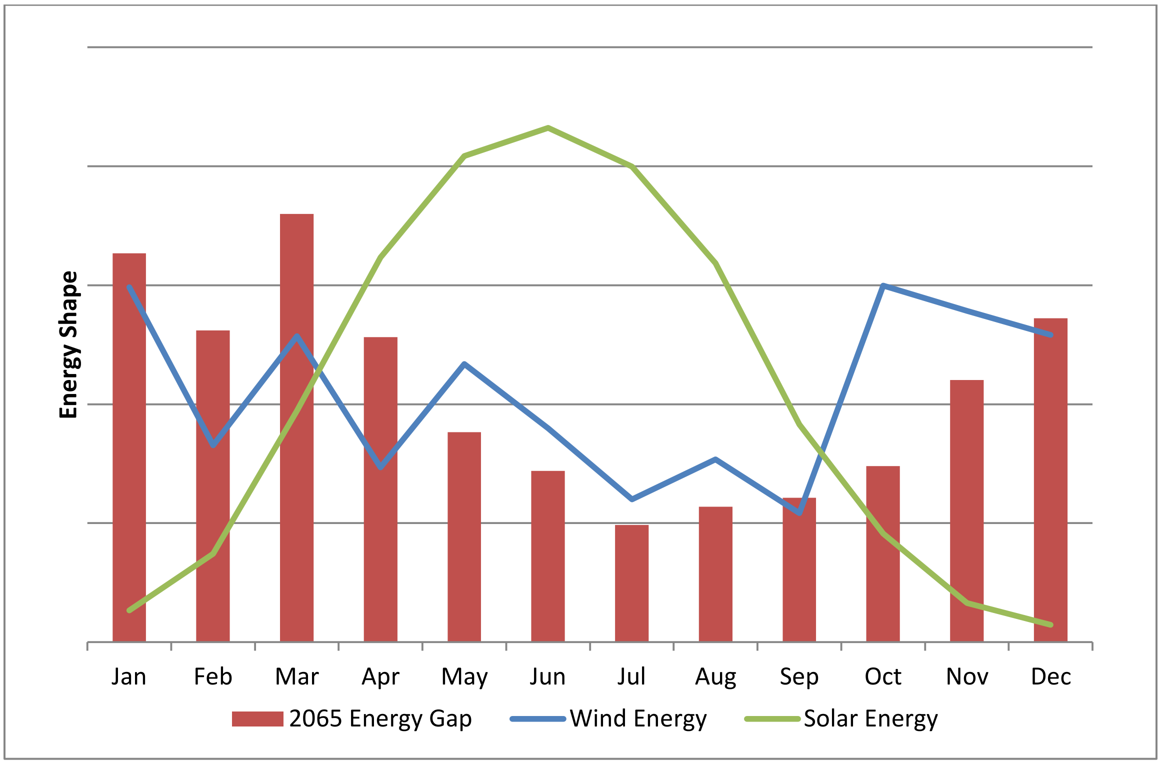
[134] Source: FortisBC, 2015.

Appendix H: Wind + Solar Resource Interactions

The maximum integration of wind power on the Yukon grid, as a percentage of peak demand, has been estimated at 15% without grid scale battery support and 20% with grid scale battery support. Similarly, the integration limit for solar power has been assumed to be 10%. A mix of wind and solar energy would result in a different energy profile than either wind or solar alone.

The energy supply curve of wind energy matches the forecast energy gap much more closely than solar on a month-by-month basis, as shown in Figure 77 below:

Figure 77: Wind and Solar Energy Shape vs. Energy Gap



Some studies have suggested that the energy curves of wind and solar energy sources complement each other somewhat – that is to say, the combination of wind and solar power is less intermittent than an equivalent amount of wind or solar alone. This is primarily because wind power availability is somewhat higher during the winter, the same period during which solar output is lowest in the Northern Hemisphere. Combined, the maximum practical integration of a mix of wind and solar power on a large grid may be as much as 30%.[135]

[135] Source: "*The optimum mix of electricity from wind- and solar-sources in conventional power systems: Evaluating the case for New York State*". Nikolakakis, T. and Fthenakis, V, 2001. Energy Policy 39, pp.6972-6980.

Unfortunately, this limit may not be practically realizable in the Yukon, as it is an islanded grid and much more susceptible to intermittency than large interconnected grids. There is also much less potential in the Yukon for the "geographical smoothing" effect of wind power seen in large grids with widely dispersed wind farms where it is highly likely that wind speeds are sufficient for energy production at one or more sites. The overall intermittency of wind is "smoothed" because drops in wind speed at one location are likely to be counterbalanced by increases in wind speed at other locations. The Yukon grid at present can only support one (or possibly two) wind farm(s), and is therefore exposed to the full intermittency of wind speed at a particular site. Several experiments on operating the island of Bornholm, Denmark as an isolated system concluded that the upper limit on intermittent generation was 15%, given a peak load of 55MW for some 41,000 residents.[136] This small system serves as a good proxy for the Yukon electrical grid. Due to these complications, it is assumed that the Yukon grid can handle no more than 15% *total* intermittent generation without grid scale battery support, and 20% *total* intermittent generation with grid scale battery support.

Given a "fixed budget" of intermittent generation including wind and solar, the energy development scenarios in this report have prioritized utility-scale wind energy over utility-scale solar energy when utilizing this budget. Given the same amount of installed capacity, wind generation is less expensive and produces more energy than solar generation because the monthly generation shape of wind power being a better fit for the forecast demand gap than solar power. Solar resources in the Yukon also have lower capacity factors than wind resources.

However, despite the potential interactions between solar and wind that could limit the quantities of these generation resource, for the purpose of simplifying modelling wind and solar generation, it is assumed that the maximum integration limit for solar as part of the Yukon's Micro Generation Program will be 5MW in 2065, and 20% of peak load for wind.

[136] Source: Jean Kumagi. *The Smartest, Greenest Grid*. IEEE Spectrum, 2013.

Appendix I: Small Hydro with Storage

I.1 Yukon Potential

Similar to run-of-river hydro, small (typically <15MW) hydro storage projects can also be found across the Yukon. These small hydro storage projects are found in areas with suitable topography and generally divide into two types of hydro storage projects; those that modify lakes using a dam, and those that dam rivers. From the perspective of informing what a "typical" Yukon small hydro storage project looks like, Midgard reviewed past studies of small hydro storage projects and developed an "average" project to use for illustration purposes. Table 90 lists the small hydro with storage options previously studied.

Table 90: Previously Studied Small Hydro Options

Small Hydro Site	Installed Capacity (MW)	Annual Energy (GWh)	Capital Cost per MW ($2015/MW)	Area of Reservoir (ha)
Drury	2.4	19.8	30	2650
Ethel Lake	2	13.5	16	4600
Finlayson	17	129	-	4200
Homan Lake	4.2	26	-	890
McNaughton Creek	9.5	76	7	2240
Moon Lake (Without P/S)	5.8	32.9	15.6	530
Reid Lakes and Lake Creek	4	22.1	15.1	1830
Surprise	8.5	50	6.7	3200
Tootsee River with Storage	4	23	13.1	450
Tutshi River	4.3	30.3	23.7	5800
Tutshi Windy Arm	5.9	39.4	21.8	4200
Upper Primrose	12.4	71	25	1400 in total
Lower Primrose	3.7	21	19	
Watson Lake & McDonald	1	6	17.9	1400

I.2 Maximum Capacity

For the purposes of this study it is assumed that the maximum number of small hydro sites available is larger than the Yukon could utilize. However, practical limits such a project economics and distance from the Yukon grid would limit the number of small hydro storage projects that could reasonably be developed in practice. Table 91 below describes a typical small hydro project in the Yukon which is comparable in installed capacity to the existing Mayo A hydro facility that dams the Mayo Lake.

Table 91: Typical Yukon Small Hydro Storage Project

Typical Small Hydro with Storage Installed Capacity (MW)	Firm Capacity (MW)	Annual Energy (GWh)
6.5	4.2	43

I.3 Maximum Energy

A typical small hydro storage project is based on the average of the previously studied projects listed in Table 90, resulting in an annual energy production of 43 GWh (see Table 91). Although the energy generation shape for a typical small hydro storage project (see Figure 78) shows that more energy is generated in the summer and less energy in the winter energy, small hydro storage projects are a reasonable source of winter energy. Table 92 shows the monthly energy production of a typical small hydro with storage plant.

Figure 78: Small Hydro Generic Shape

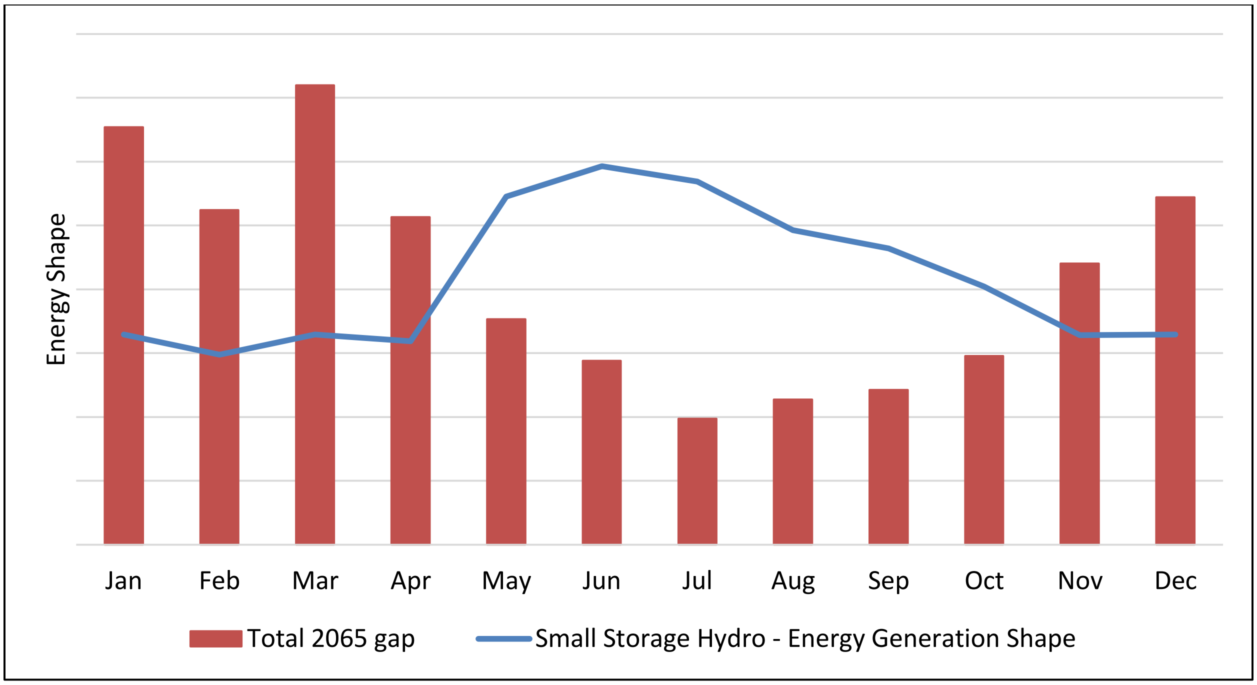


Table 92: Typical Small Hydro Monthly Energy Production

Month	Typical Small Hydro Monthly Energy Production (MWh)
January	2,832
February	2,558
March	2,832
April	2,741

Month	Typical Small Hydro Monthly Energy Production (MWh)
May	4,690
June	5,098
July	4,891
August	4,235
September	3,989
October	3,479
November	2,823
December	2,832

I.4 LCOE

Midgard estimated the weighted average capital cost of small hydro storage projects to be approximately $16M/MW based on projects ranging in size from 1 MW to 12 MW and capital costs ranging from $6.7M/MW to $30M/MW. With annual operating costs similar to NGH at 0.8% of capital costs, 3.38% real discount rate, and 40 year life span, the full utilization LCOE of a typical small hydro with storage project was estimated at $126+/MWh.

Table 93: Small Hydro LCOE

Levelized Capital Cost ($/MWh)	**Fixed O&M** ($/MWh)	**Fuel Cost** ($/MWh)	**Total Full Utilization LCOE** ($/MWh)
106	20	0	126+

I.5 Land Use Footprint

The median land use footprint of a typical small hydro storage projects was estimated to be 390 hectares/MW. Similar to Next Generation Hydro, this estimated value includes the land use for transmission lines, access roads, powerhouse, water conveyance (penstock), and reservoir flooding (including the impact on lakes. The median value for land use footprint was used to estimate typical land use because some of the previously studied projects had very large footprints relative to project size (see Table 90); therefore using the median area (instead of average area) eliminated the impact these outliers on a typical footprint area calculation.

Table 94: Land-Use Requirements of Storage Hydro

Direct Impact (hectares/MW)	390 Ha/MW

I.6 GHG Emissions

The GHG emissions associated with a small hydro storage facility are those related to construction, maintenance and decommissioning. The most recent IPCC estimates for small hydro storage life-cycle emissions are from 4-35 gCO_2e/kWh, with a median of around 18 gCO_2e/kWh.[137]

The direct electricity production emissions associated with small hydro storage are zero.

[137] Source: *"IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation".* IPCC, 2011.