Executive Summary

Alaska's Railbelt Electric System: Decarbonization Scenarios For 2050

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1 Executive Summary

1.1 Introduction

The Railbelt is the largest regional electric grid in Alaska, spanning approximately 700 miles from Fairbanks to Homer, as seen in Figure 1.1.

The goal of this study is to explore and quantify decarbonization scenarios of Alaska's Railbelt electric grid by the year 2050. This study evaluates these decarbonization scenarios for reliability and affordability. These decarbonization scenarios are designed to be illustrative of potential 2050 decarbonized futures, and are not predictions of the future or suggestions of optimal pathways. This project has the scope of a pre-feasibility study, which is an early stage of analysis valuable for evaluating the technical viability of the decarbonization scenarios proposed.

This project aims to provide valuable information to the Alaskan public and decision makers on the economic and reliability implications of several decarbonization scenarios and to demonstrate methods for evaluating Railbelt energy transitions. Additionally, a key intention of this work has been to build capacity within Alaska to perform the types of analyses needed to evaluate energy transitions. The information generated from this study includes general information such as resource availability and load forecasts, and information specific to the developed decarbonization scenarios such as stability and reliability of the system, and the impact to rates.

The outcomes of this study include:

- Evaluate various resource mixes and quantities necessary to meet high-decarbonization objectives in the Railbelt,
- Quantify the electric load impacts of electrification, including high electric vehicle and heat pump adoption,
- Characterize the operational and reliability implications of decarbonization scenarios,
- Quantify the potential capital costs and operational costs of a decarbonized power system,
- Create information for Railbelt planning discussions and future studies, such as an Integrated Resource Plan,
- Train students, staff, and faculty at the University of Alaska Fairbanks in the tools and methods to study energy transitions, including through the mentorship and collaboration of national and local industry experts.

1.2 Overview of Methods

To evaluate the changes to power system operations and grid stability with increasing renewable energy and electrification, this analysis leveraged detailed power system simulation and modeling software. In total, four scenarios were evaluated, identified in Section 3, to represent potential future power systems with increased clean energy. Grid configurations were evaluated with additions of wind, solar, tidal, battery energy storage, hydro, and nuclear technologies as well as corresponding fossil-fuel generator retirements and additions and increased electrification from vehicles and heat pumps. The software tools used in this analysis are available from third-party software vendors heavily used throughout the industry, and are the same ones leveraged by the Railbelt utilities and other global utilities. These grid planning tools allow for evaluation and simulation of a future power system using the same methods and processes used to operate and control today's grid to isolate the effects of integrating renewable energy, new technology, and operational changes. When it comes to power system modeling, no one tool can provide a comprehensive analysis across the generation, transmission, and distribution segments of utility planning. In addition, no one tool can properly evaluate all the timescales of planning, which range from sub-seconds to an entire year, or years, of operation. To overcome this limitation, this study leveraged multiple power system planning tools with tight coupling between the different stages. This allows for each tool to properly evaluate its domain, while linking inputs, assumptions, and outputs between the tools to overcome seams in the analysis typically found between the generation and transmission analyses.

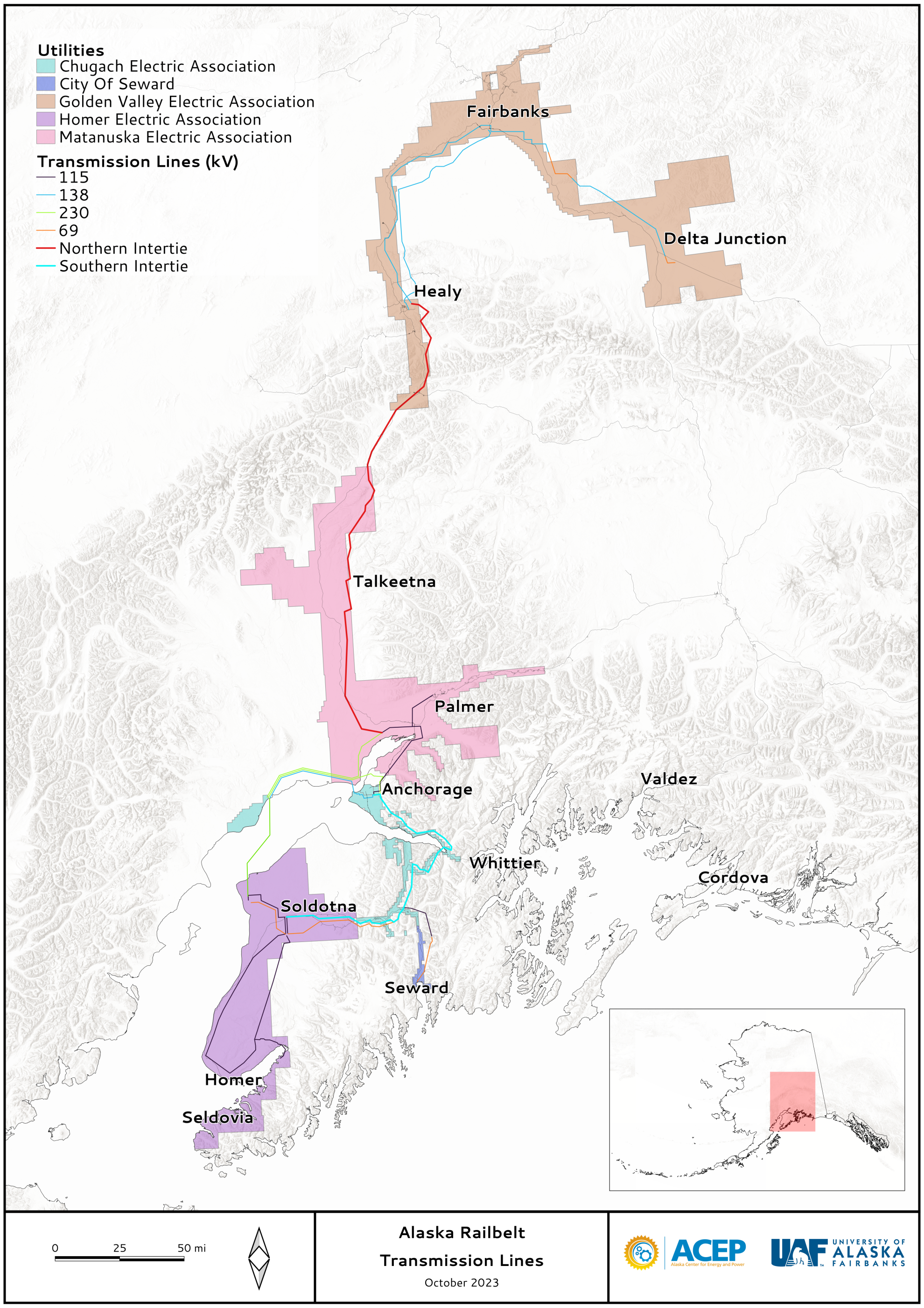

Figure 1.1. Alaska Railbelt transmission, load regions, and electric utility territories

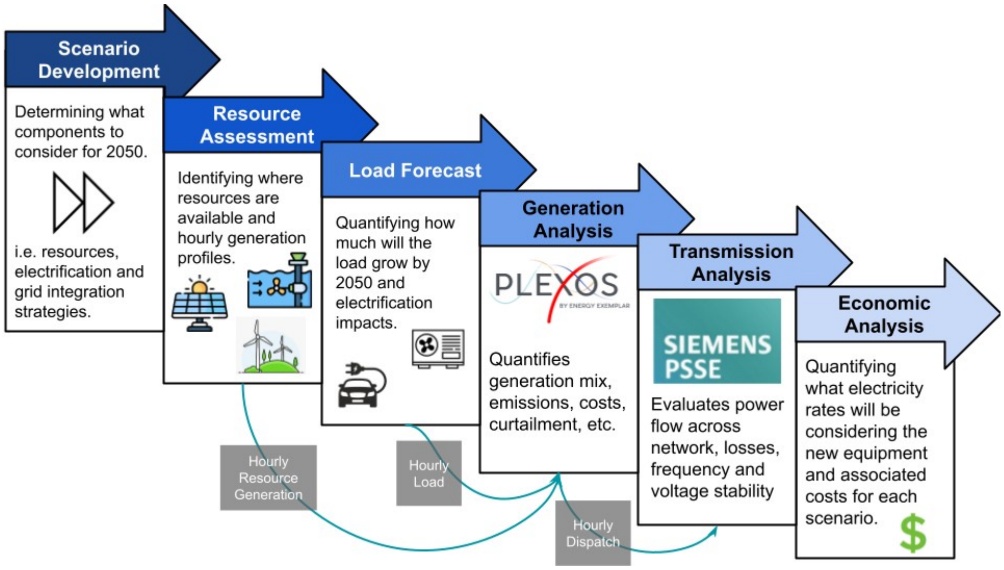

Figure 1.2. Project components flowchart

The study utilized a six-step, interconnected process, as outlined in Figure 1.2:

1. **Scenario Development:** Several scenarios were identified that highlighted different energy resources while including significant integration of wind and solar energy, to illustrate unique pathways to decarbonization. These scenarios were refined through public engagement and feedback during the early stages of the project.

2. **Resource Assessment:** The energy resources considered in this study were identified by high resource availability near the existing Railbelt transmission system. The hourly availability of each new energy resource was collected for many locations of new generation.

3. **Load Forecasting and Electrification:** The Alaska Center for Energy and Power project team developed a load forecast for the Alaska Railbelt following current trends for electric load growth and the impact of electrification of other energy sectors, namely transportation and heating. Following best industry practice, the load forecast was developed for multiple layers, including an underlying economic forecast, rooftop solar photovoltaics, electric vehicles, and heat pump adoption. This allowed for multiple forecasts to be developed to represent different levels of end use electrification.

4. **Generation Analysis:** Generation analysis involves both portfolio optimization and production cost analysis.

   - **Portfolio Optimization:** Using the load forecast developed in Step 1, future generation portfolios were developed with a custom-built portfolio optimization tool that selected resource combinations of wind, solar, battery storage, tidal and nuclear resources to meet future demand.

   - **Production Cost Analysis:** The analysis utilized Energy Exemplar's PLEXOS production cost model to quantify hour-to-hour operation of the grid to match load and generation in a least cost manner while meeting reliability constraints like regulation reserves, contingency reserves, and transmission constraints based on the initial economic capacity sizing, load forecasts, and energy resource information including availability and operating costs. The model incorporated reserves requirements specified in the Alaska Reliability Standards[1] which were modified to account for high penetrations of variable renewable resources based on methods employed in other regions of the United States that currently have greater penetrations of variable renewable energy resources.[2] The output from the model used in this study is an

[1] *The Intertie Management Committees' Railbelt Operating and Reliability Standards*. Oct. 2017. URL: https://www.akenergyauthority.org/Portals/0/Programs/Railbelt%20Energy/Alaska%20Inertie/RailbeltOpratingRlbilityStndardsFinal2017.pdf?ver=2019-06-19-135947-740 (visited on 10/29/2023).

[2] Bartlett, Drake and Parks, Keith. *2020 Study of the Levels of Flex Reserve and Regulating Reserve Necessary for Reliable System Operation*

hourly time series of the dispatch of existing and new generation resources in the system. It is important to note that the generation dispatch created assumed a single load balancing entity or transmission system operator, resulting in optimal dispatch for the system as a whole.

5. **Transmission Stability Analysis:** The analysis utilized Siemens' Power System Simulator for Engineering (PSS®E) power flow modeling software to evaluate steady-state and dynamic stability on the transmission network (from 69 kV to 230 kV voltage levels). This was built from the current PSS®E model of the Railbelt, representing the present-day system. The existing PSS®E model was adapted to represent each of the scenarios using the resource sizes and locations, load forecasts, and economic dispatch generated in earlier steps. Stability and reliability analyses were performed in PSS®Efollowing key provisions of the Alaska Reliability Standard AKTPL-001-2. Grid upgrades, including transmission, grid-forming inverter batteries, shunt capacitors, and synchronous condensers were identified to maintain voltage and frequency stability.

6. **Economic Analysis:** The cost of service to provide electricity on the Railbelt was determined for the system build for each scenario based on 1) the capital cost of new generation, transmission upgrades, and additional equipment or system upgrades necessary for system stability; and 2) the operating costs (fuel, variable and fixed operations and maintenance) of executing the hourly dispatch determined by the PLEXOS production cost model. The average cost per MWh of distribution and general and administrative was assumed to remain constant at current levels. Margins were included as an element of the cost of service to determine average revenue requirements per MWh.

1.3 Methodology Limitations

The analysis performed in this study has several methodology limitations discussed here. These kinds of limitations are inherent to a pre-feasibility study, which is only as good as the input assumptions and simplifications.

- **Load Forecast and Cost Assumptions:** The load forecast is generated using the best available data and information at the time of this study. Similarly, the generation analysis and rate analysis are performed using cost assumptions based on the best available data and information at the time of this study. The assumptions made in this study are outlined throughout the report and appendices. However, as policies change and new data becomes available both the load forecast and cost assumptions will be out of date. Future work will need to reevaluate and generate a new load forecast and cost assumptions.

- **Stability Analysis Tool (PSS®E)**: The power system simulation tool used in this study is PSS®E. This is a common type of a power system simulator for evaluating large power systems at the level of detail for a planning study. This tool can accurately identify key stability challenges that are likely to create issues and that will require mitigation. For detailed implementation studies and for small sections of electric grids with high amounts of inverter-based resources, electromagnetic transient simulations are necessary, such simulations were beyond the scope of this report. For the level of analysis needed for this study, the simulation tool PSS®Eprovides informative results that identify key stability challenges. Additional details on the limitations and uses of the analysis tools and models employed are provided in Section 6.

while Accommodating the Uncertainty of Wind and Solar Generation at Varying Levels of Installed Wind and Solar Generation Capacity within the Public Service Company of Colorado Balancing Area Authority. en. Tech. rep. Public Service Company of Colorado, May 2022, p. 26. URL: https://www.xcelenergy.com/staticfiles/xe-responsive/Company/Rates%20&%20Regulations/Resource%20Plans/Clean%20Energy%20Plan/HE_114-KLS-3-Flex_Reserve_Study.pdf; Paul Denholm et al. "Summary of Market Opportunities for Electric Vehicles and Dispatchable Load in Electrolyzers". In: (May 2015). DOI: 10.2172/1215243. URL: https://www.osti.gov/biblio/1215243.

Scenarios

This study evaluated four scenarios, each of which considers large, fundamentally different resource mixes to achieve similar decarbonization objectives. Scenarios are based on a target 2050 study year and are summarized in Figure 1.3.

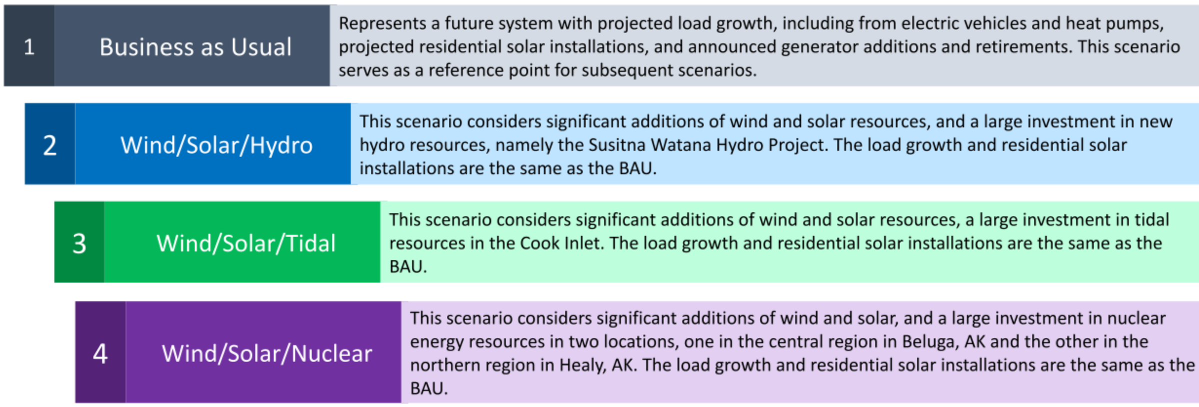

Figure 1.3. Scenario overview

1.4 Key Findings

The key findings from each type of analysis, as outlined in Figure 1.2, are provided below.

Generation Analysis

- **Wind and solar are the cheapest sources of energy, but the cost of curtailment and energy storage limited their installed capacity.** For the range of costs considered in the system sizing sensitivity analysis, wind and solar resources provided the lowest cost energy. However, they were not able to supply the full load and reliability needs of the system. In all scenarios, some amount of curtailment of wind and solar energy was necessary. In cases with high levels of curtailment the capital costs of wind and solar generation become prohibitively expensive. While lithium-ion batteries can mitigate some curtailment for use later, it is a relatively expensive upgrade.

- **Fossil-fuel and hydro power generation are more flexible and operate alongside variable wind and solar generation, while nuclear generation is better suited to supply baseload power.** Our analysis showed that the system could not be decarbonized using only variable renewable resources, such as wind and solar power. Some amount of a firm source of generation is still required for sufficient generation to be available. With the technologies considered in this study, fossil-fuel and hydro power generation were the most cost effective firm sources to pair with variable renewables. When nuclear generation was built into system sizing sensitivity analysis scenarios, it displaced both renewable and fossil-fuel sources of generation and was more expensive.

- **Inclusion of nuclear or tidal generation in system sizing sensitivity analysis scenarios depended on their cost projections.** Nuclear and tidal generation were not built in all system sizing sensitivity analysis scenarios due to their projected costs. There is significant uncertainty in the projected costs and future commercial availability of these technologies.

- **In the low-carbon scenarios, 70 - 96% of generation came from zero-carbon sources.** The rest came from fossil-fuel sources of generation. With the technologies and cost projections considered in this study, achieving 100% fossil-free generation would have been more expensive than the low-carbon scenarios. Carbon capture and storage are not 100% effective, and including it would still not result in 100% decarbonization. Other potential options for this could include repowering with hydrogen, biofuels, synthetic fuels, or using direct air capture all of which have similar challenges.

- **The low-carbon scenarios represent a significant change in system operation compared to the Business-as-Usual scenario and current day operation.** Due to the variable nature of wind, solar, and tidal energy, a high degree of flexibility must be readily available from firm sources of power. Fossil-fuel, hydropower, battery storage, and nuclear sources are leveraged to various degrees to meet this need. This results in a significant increase in the flexibility required from fossil-fuel sources to be able to serve unscheduled load compared to the Business-as-Usual scenario and what is possible in the current system. This flexibility from thermal generators will also increase the flexibility needed from natural gas fuel production and transportation. The flexibility to be expected from a liquefied natural gas import scenario in 2050 is not known and may be more than is in the current gas system on the Railbelt. This flexibility in natural gas production and transportation does not exist under current natural gas tariffs.

- **Increased transmission capacity allows greater power sharing between regions.** The capacities of the Alaska and Kenai Interties were increased to allow 300 MW in the low-carbon scenarios from 140 MW and 78 MW in the Business-as-Usual scenario. The increased transmission allowed large projects such as Susitna-Watana hydro, nuclear power plants, and Cook Inlet tidal to power loads across the Railbelt. It also allowed variable wind, solar, and tidal resource sites of wind, solar, and tidal, spread over the hundreds of miles of the Railbelt grid, to help balance each other and deliver net generation with a lower degree of variability in each region. However, the economic value of transmission upgrades was not analyzed in this study to determine if they resulted in a lower cost system compared to a low-carbon scenario without the upgrades.

1.4.1 Transmission Analysis

- **Grid reliability services must be provided by inverter-based resources as well as the remaining synchronous machinery.** The reliability services like inertia and grid strength that have historically been supplied by online synchronous machinery must still be provided for the grid to be stable and reliable. With inverter-based resources displacing the synchronous resources for thousands of hours each year in the future scenarios, it is critical that inverter-based resources provide sufficient levels of these services to enable the decommitment and/or retirement of fossil-fuel plants. Section 6 analyzes how to use battery storage and other resources to maintain system stability during different contingencies.

- **Improvements in inverter algorithms used on the Railbelt grid will be essential for future grid stability.** The grid-forming inverter technology applied to battery energy storage system resources plays a critical role in the stability of the future system. It is important that the grid-forming inverter battery energy storage system resources are sized and distributed appropriately throughout the future system. The use of grid-forming inverter technology on battery energy storage systems in combination with the most advanced grid-following inverter technology for utility-scale wind and solar plants is instrumental in providing stability to the grid. These technologies enable the system to survive not only separation events, but also to reduce reliance on the under-frequency load-shedding scheme, resulting in a more resilient grid. Grid-forming inverter technology is an emerging technology and more deployments, testing, and incremental grid-forming inverter technology additions would need to be made to enable the successful broad deployment of this technology in the Railbelt as simulated in this study.

- **System stability is more difficult to achieve in low-carbon scenarios.** This is due to the displacement of much of the thermal synchronous generators by inverter-based resources and/or the addition of particularly large plants that could constitute a new most severe single contingency, such as Susitna-Watana hydro.

- **The losses of the interties were the most severe contingencies.** This is because the losses of the interties results in either the Northern or Southern regions being synchronously or fully isolated from the rest of the system, with all generation in the isolated region being required to respond fast enough and with enough system strength for the region to operate independently. The high-voltage direct current line allows power transfer between the Central and Southern regions, but does not synchronously connect the two regions. Therefore, when the Kenai Intertie is lost, only the high voltage direct current line connects the Southern and Central regions, and that does not transfer the inertia or system strength from the Central region to the South region. The ability of the Northern and Southern regions to operate isolated from the rest of the system is critical, and is limited by the inertia and system strength available in those regions.

- **Significant steady-state voltage issues in low-carbon scenarios.** These voltage violations were due to 1) an increased load, 2) new locations of large resources (such as wind, hydro, and/or nuclear) increasing power flows across the two main interties and other transmission lines across the system, and 3) reduction in power generation from fossil-fuel generators near load centers reducing the available reactive power injection. These voltage violations were mitigated with the addition of shunt capacitors and batteries to provide reactive power; however other measures could be considered to reduce the demand for reactive power and voltage support, for instance, reducing the size of Homer Wind or distributing it to two different points of interconnection.

- **Stability considerations must be included when siting new generation.** For example, the large wind facility at Homer Wind was the main cause of the voltage and thermal violations in the Southern region for all low-carbon scenarios. Reducing the size of Homer Wind or locating the wind facility in the Southern region closer to the 230kV Kenai Intertie could have resolved or reduced this issue.

1.4.2 Economic Analysis

- **The required capital investment to implement the low-carbon scenarios, after application of allowed investment tax credit amounts, ranges from about 8 billion to about 12 billion in 2023 dollars under base case assumptions.** These are large amounts, in part because significantly higher Alaska-specific capital and operations and maintenance costs were assumed, and in part because some specific high-cost projects were added to scenarios without first passing an economic screening test. These high up-front costs would be repaid through rates over the economic life of each project. For example, the annualized capital cost of the most capital-intensive scenario (Wind/Solar/Hydro) in 2050 would be about $630 million (for generation). By comparison, the annual fuel expense in 2050 under the Business-as-Usual scenario is $745 million.

- **The cost of service for the low-carbon scenarios, after application of allowed investment tax credit subsidies, differs by -5% to 25% from the Business-as-Usual scenario depending on varying fuel costs, hydro and nuclear capital costs, and interest rates.** Table 1.1 provides a numerical summary of the economic analysis. Under base case assumptions, which include a year 2050 natural gas price of $14/MMBtu (in 2023 dollars) and Alaska-specific (thus relatively high) capital and fixed operations and maintenance costs, the generation and transmission cost of service for the low-carbon scenarios ranges from 7% to 12% higher than for the Business-as-Usual scenario. However, if fuel prices were 20% higher (case S2), the low-carbon scenarios would cost from 5% less to the same as Business-as-Usual, all else being equal. Similarly, if the interest rate and capital costs of the hydro, tidal, and nuclear projects were 20% lower (case S4), the low-carbon scenarios would cost from 3% less to 1% more than the Business-as-Usual scenario.

Table 1.1. Summary of generation and transmission cost of service relative to Business-as-Usual scenario

Cost Sensitivity Scenario	Wind/Solar/Hydro	Wind/Solar/Tidal	Wind/Solar/Nuclear
Base	12%	8%	7%
S1 High Fuel	0%	-1%	-5%
S2 High interest	18%	10%	12%
S3 High-cost renewables	25%	14%	18%
S4 Low-cost renewables	1%	1%	-3%

However, if interest rates and/or the capital costs of renewables were 20% higher than base case levels, the generation and transmission cost of the low-carbon scenarios could exceed that of Business-as-Usual by 18% to 25%[3].

1.5 Conclusion

This study evaluates several decarbonization scenarios of the Railbelt electric grid in Alaska for the year 2050. The scenarios are meant to be illustrative examples as a pre-feasibility study, highlighting the ability of certain resources and resource mixes to create a low-carbon electric grid for evaluation based on affordability and reliability.

[3]When considering these percentages, it is important to remember that a 25% percent increase in the cost of generation and transmission would not result in a 25% increase in the overall cost of service, because other cost components (distribution, customer accounts, administration) would likely remain constant across all four scenarios).

Additional analysis is necessary for implementation of new resources, technologies, and transmission. What is presented in this work is neither a prediction of the future or a suggestion of an optimal low-carbon future.

This project provides valuable information to the Alaskan public and decision makers on the economic and reliability implications of several decarbonization scenarios and to demonstrate methods for evaluation of Railbelt energy transitions. Additionally, a key intention of this work has been to build capacity within Alaska to perform the types of analysis needed to evaluate energy transitions. The information generated from this study includes general information such as resource availability and load forecasts, information specific to the developed decarbonization scenarios such as stability and reliability of the system, and the impact to rates.

Through a multi-stage analysis process the project performed resource analysis to determine availability and sizing, load forecasting, economic dispatch of generation, stability analysis, and economic analysis. The accumulation of this analysis results in a set of resources for each scenario. The complete collection of resources in each of the scenarios is compiled in Table 1.2.

Economic analysis, including the assessment of capital costs, fuel costs, operations and maintenance costs, and financing, provides insight into the potential cost implications of these scenarios. The cost of service for each scenario was calculated, and is presented in Figure 1.4.

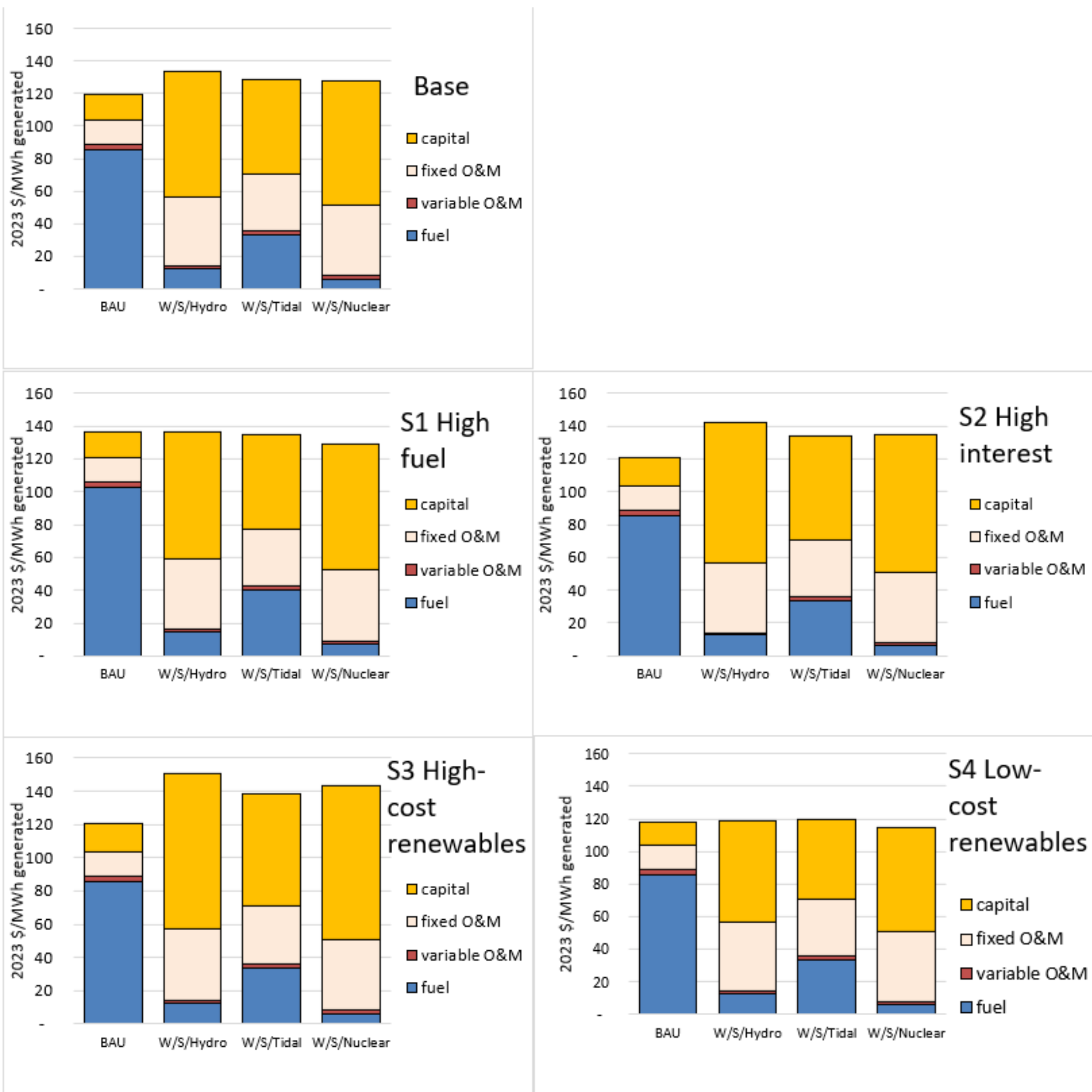

Figure 1.4. Summary of the cost of service, by component and scenario, under four sensitivity cases, in 2023 $ per MWh generated.

Table 1.2. Summary of Resources in the Current System and the Scenarios developed in this Study

Resource Type	Resource	Current System	BAU	Wind/Solar/ Hydro	Wind/Solar/ Tidal	Wind/Solar/ Nuclear*
Hydro	Susitna-Watana	–	–	459-608 ****	–	–
	Grant Lake	–	–	5	5	5
	Bradley Lake	120	120	120	120	120
	Eklutna Lake	40	40	40	40	40
	Cooper Lake	19.4	19.4	19.4	19.4	19.4
Wind	Delta	1.9	1.9	50	7	50
	Eva Creek	24.6	24.6	74	132	160
	Fire Island	18	18	36	18	36
	Homer	–	–	213	231	285
	Houston	–	–	185	165	49
	Little Mount Susitna	–	30	315	214	265
	Shovel Creek	–	–	223	231	285
Solar PV	Fairbanks	0.56	1	1	1	1
	Houston	8.5	8.5	45	33	30
	Nenana	–	–	45	66	60
	Point Mackenzie	–	–	90	33	30
	Sterling	–	–	255	33	96
	Willow	1.20	–	45	33	30
Residential Solar PV	Northern	∼5**	43.3	43.3	43.3	43.3
	Central	∼10**	139.9	139.9	139.9	139.9
	Southern	∼4**	44.3	44.3	44.3	44.3
Tidal	Cook Inlet	–	–	–	400	–
Nuclear	Healy	–	–	–	–	231
	Beluga	–	–	–	–	308
Fossil-Fuel	Coal	114	54	-	-	-
	Natural Gas/Naphtha powered Combined Cycle (CC)	495	1,095	495	495	495
	Natural Gas powered internal combustion (IC)	171	171	171	171	171
	Natural Gas powered combustion turbines (CT)	468	568	468	872	468
	Oil power generation	198	198	198	198	198
Li-ion Batteries	30-minute	27	50	808	390	1,117
	2-hr	46.5	146.5	282	227	287
	4-hr	-	70	70	70	70
	6-hr	-	-	300	280	261
Synchronous Condensers		***	-	-	358	90
Shunt Capacitors		***	-	91	75	185

* The Wind/Solar/Nuclear scenario assumes that naphtha, or an equivalent priced fuel, replaces natural gas.

** Estimated by the 2020 number of net meter customers and scaled by estimated growth from U.S. Energy Information Agency Form 861.

*** Reactive power compensation equipment such as shunt capacitors exist in the current system, but are not tabulated in this study. The scenarios in the study list the synchronous condensers and shunts added to the system, in addition to what is already present.

**** The Susitna-Watana hydro maximum power capability depends on the level of water in its reservoir.

Inspection of the charts in Figure 1.4 reveal the many ways in which the scenarios differ and how their differing reliance on fuel, operations and maintenance, and capital inputs translate into changes in the cost of service.

These results are specific to the scenarios studied in this project, for the year 2050. These scenarios are illustrative and do not attempt to identify the lowest cost scenario for 2050. Additionally, this study did not evaluate the cost-effectiveness of near-term renewable additions. Instead it evaluated illustrative future high-decarbonization portfolios. The cumulative cost of achieving high levels of renewable penetration is non-linear, due to increased transmission and storage requirements. Additionally, from now until at least 2030, low-carbon projects will qualify for investment tax credits of 40-50%[4] of project capital costs. This creates an additional incentive to install renewable energy projects early. The values estimated here for 2050 should not be used to quantify the cost effectiveness of near-term wind and solar resource additions.

This study provides value through demonstrating the process of evaluating decarbonization scenarios, illustrating the types of stability challenges and mitigations that can arise with the integration of inverter-based resources such as wind, solar, and tidal energy, providing an example of how scenarios can be quantified in terms of cost of service, and developing valuable information that can be used by Railbelt stakeholders in future studies of real implementations of new resources and technologies.

[4] All of Alaska qualifies as an energy community as defined by the US Department of Energy, which increases the investment tax credit from 30% to 40%. Projects that use domestically produced products qualify for an additional 10% for a total of 50%. The major wind manufacturers are producing enough components in the US to qualify for domestic content. Major solar and battery manufacturers are also qualifying for domestic content.

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