RENEWABLE ENERGY DEVELOPMENT IN ALASKA:

POLICY IMPLICATIONS FOR THE DEVELOPMENT OF RENEWABLE ENERGY FOR REMOTE AREAS OF THE CIRCUMPOLAR ARCTIC

By

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Abstract

The territories that comprise the Arctic region are part of some of wealthiest and most advanced countries on the planet; yet, rural Alaska, northern Canada, the Russian Far East and Greenland—characterized by off-grid communities, regional grids, and higher degrees of energy insecurity—have more in common with the developing world than the southern regions of their own country. This thesis explains this paradox of energy development in the Circumpolar North and tackles the issue of developing renewable energy in remote areas where technical and socio-economic barriers are significant. The primary research questions are two-fold: 1) Why did the Alaska electrical system develop as a non-integrated patchwork of regional and isolated grids? and 2) What are the major factors in Alaska that have resulted in a greater uptake of renewable energy systems for remote communities, compared to other similar places in the Arctic?

This thesis demonstrates that state-building theory provides a cogent framework to understand the context of electrical build-out in the Circumpolar North. A major finding of this thesis is that the buildout of electric infrastructure in the non-Nordic countries, including Alaska, exemplifies a process of incomplete nation-building. Interconnected regional grids, where they exist, are largely due to the twin national priorities in infrastructure development in the north: extracting natural resources and enhancing national security. This thesis also draws on socio-technical transition theory to explain why Alaska exhibits such high levels of energy innovation when compared to other similar regions across the Arctic. This research concludes that drivers such as extremely high energy costs, a highly deregulated utility market with dozens of certificated utilities, state investment in infrastructure, and modest subsidies that create a technological niche where renewable energy projects are cost-competitive at current market prices have spurred energy innovation throughout Alaska's communities, remote or otherwise.

Many of the evolving technical strategies and lessons learned from renewable integration projects in Alaska's remote islanded microgrids are directly applicable to project development in other markets. Despite differences in climate and geography, lessons learned in Alaska could prove invaluable in increasing resiliency and driving down energy costs in remote communities world-wide.

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I would like to thank my children, Leif, Marais, and Lael Anderson for always supporting me, for *trying* to play more quietly when I worked on this thesis, and for cooking many family breakfasts so I could write.

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Chapter 2. Poelzer, G., Holdmann, G. and Pride, D. State-Building and Electrical Energy – a comparative view of Norway, Alaska and the Circumpolar Arctic. I completed the section on Alaska, which is included in whole in this thesis, as well as contributing to other sections relevant to the Alaska case.

Chapter 3. Holdmann, G., Wies, R.W. and Vandermeer, J.D. Renewable Energy Integration in Alaska's Remote Islanded Microgrids: economic drivers, technical strategies, niche market development, and policy implications. I was involved with developing all section, especially the background, niche market development, and lessons learned. My co-authors contributed significantly to the technical strategies section, and in developing Table 3.1.

Dedication

To my children Leif, Marais and Lael – thank you for all of the joy you bring into my life, and for telling me that you are proud of me.

Chapter 1

Introduction

1.0 Overview

Over the past two decades scholars have focused increasing attention on the current, global transition toward low carbon economies and societies. Most research to date has focused on the industrialized countries of the OECD[1], particularly on utility-scale renewable energy integration, decentralized ownership models, and smart grids. There also is an increasingly rich literature emerging that focuses on energy security and energy transitions in the developing world. However, as a research community, we have a much poorer understanding of a geographically large part of our planet, the Circumpolar North. The Circumpolar North represents a paradox: On the one hand, the region straddles portions of eight states who are among the wealthiest on the planet, and whose continental areas have among the most robust and integrated grid systems anywhere. On the other hand, Canada, Alaska, Russia, and Greenland, have enormous expanses that have more in common with the developing world, characterized by off-grid communities, regional grids, and higher degrees of energy insecurity. Notwithstanding these realities, the Arctic region has in general high levels of renewable energy use, though there is high variability in its distribution. The Arctic also exhibits high levels of energy innovation, including integration of renewable energy with diesel generation in remote areas, and local ownership models. This raises the following questions such as, why have the various energy systems across the Circumpolar North emerged the way they have? Are there empirical lessons from the Circumpolar North that may be instructive and insightful for understanding other regions of the world? How well do current theoretical approaches equip us to understand energy systems and transitions in the Circumpolar North? Can an empirical investigation of the Circumpolar North inform, amend, or add to the current conceptual tool kits used by scholars of energy transitions?

Current theoretical approaches can help us address these questions, most notably socio-technical transition literature (Geels, Schot), which provides a firm grounding in current approaches to technology transitions, including the shift from carbon intensive fossil energy resources, to renewable energy sources with a much lower carbon footprint. This literature provides a wealth of research and case studies on how innovations occur and why they fail, which has helped inform this thesis. However, socio-technical transition theory falls short in explaining how and why existing

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[1] The OECD is the Organization for Economic Development and Cooperation. It is comprised of 36 member states with market economies that together account for about 2/3 of the world's GDP.

socio-economic-political frameworks came to be in the first place, especially when considering variations within a single nation state. This gap in understanding is particularly noticeable for more peripheral areas of some nations such as the far north, where underlying motivations and historical context can be quite different than that experienced by more populous or central areas of the same country. To uncover some of the historical context that grounds technology transitions, this study turns to state-building literature (Tilly, Poggi, Skocpol and Giddens). Understanding these differences can help uncover some of the differences in how different regions experience technological transitions, and provide important context for how technological niche markets such as the one in Alaska arise.

This thesis focuses predominantly on the Alaska case study, with some contextualization from the broader Arctic region, and, more specifically, territorial Canada which shares many historical, cultural, geographic, and socio-economic features with Alaska. Alaska is an important case to study because of its non-integrated electric grid, lack of statewide energy policy, and disaggregated and private energy market with decisions often being made at the local level by many different actors. There is also a vast amount of both quantitative and qualitative data available about Alaska communities, utilities, and individual projects that make a robust empirical study possible.

This chapter now turns to the background of the case study.

1.2 Background

The Arctic region as a whole is a leader in renewable energy technology (RET) development, with an estimated ~60% of grid-connected electric power derived from renewable resources (see Figure 1), compared to the global average of 22.8% (REN21). However, incorporating RETs is more challenging for the roughly half of the Arctic population residing in communities not connected to central energy infrastructure such as a natural gas pipeline or statewide electricity grid. In many of these communities, living conditions more closely resemble the developing world than more urban areas of their respective countries (Poppel et al.). It is a tremendous challenge to build, operate and manage electric utility services in remote areas of the Arctic due to a wide range of factors including the harsh climate, remoteness, limited construction season, and dispersed population (Colt et al.). As a result, the construction, operation, and maintenance costs associated with these systems are much higher than in more populous areas of the same country.

No nation in the Arctic has found a "magic bullet" by which to overcome the problems of high cost, remoteness, and lack of economic base for its remote regions. The disparity in infrastructure is magnified by the fact that the eight Arctic nations are each affluent, highly developed countries that score as high or very high on the Human Development Index (HDI 2015). In fact, 4 of the top 10 countries ranked through the HDI are Arctic nations, and 7 of the top 251. As a result of this inequity, the people living in these remote communities as well as their respective regional and national governments have placed a high priority on development in the form of capital infrastructure build out, direct subsidies, and transfer payments. Energy has been a primary target for this investment, but with the exception of some common experience among the Nordic countries, each nation has independently developed strategies to deliver electric power services (and subsidize those services to make them more affordable) to its remote communities. This has resulted in numerous independent policy experiments that present an ideal opportunity to compare and contrast each experience in order to better understand which factors best promote the adoption of RETs.

The U.S. state of Alaska has a vast territory with a relatively modest population and limited infrastructure. Over 200 communities in the state, including the capital of Juneau, are not road or grid connected to the rest of the state, or to Canada. Therefore, many rural communities across the state are defined as 'remote', or not connected to central energy infrastructure (e.g. natural gas pipeline or statewide electricity grid). This typically results in a high reliance on easily transportable liquid fuels, lower quality energy supply, and higher energy costs (Rickerson, et al.). In most places in Alaska, rural communities are too far apart and too sparsely populated to justify the cost of building roads or interties between them. Instead, these communities are served by local, remote microgrids.

A "microgrid," in its most basic form, is just a small-scale version of the electricity grid that the vast majority of electricity consumers in North America and other developed parts of the world rely on for power service today. Like these transmission networks, microgrids include generation facilities, distribution lines, and voltage regulators – but these all exist in close proximity to customers or loads, or are co-located with them. They can be networked with one another (and the central grid) in order to boost capacity, efficiency, and reliability – or can function as autonomous islands of power. Microgrids are formally defined by the U.S. Department of Energy as "a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode" (Ton and Smith). In 2018, this definition was updated to include remote microgrids that are permanently islanded, in recognition of the important role microgrids serve in supplying electric power to consumers in rural Alaska and other remote areas (Holdmann and Asmus).

Microgrids have the ability to improve grid resilience and therefore have economic and social value. A resilient grid is more responsive to a disruption – whether anthropogenic or natural – since it serves a small, discrete geographic area. The current electric grid in the U.S. is a highly interdependent collection of generation and distribution nodes, and disruptions in service in critical infrastructure can have broad ripple effects far from the epicenter of the disruption itself. If the U.S. grid was converted to a series of interlinked microgrids, it would become highly resilient to disruptive events since power would mostly be produced and distributed at the local area. Like the internet, which does not exist in any one location but rather is an interlinked network of computers, servers, and users, an electric grid based on a series of interlinking microgrids rather than centralized power stations and a lengthy transmission network would be able to contain threats to a smaller geographic area, and be more flexible in response to real or potential threats (Holdmann and Asmus).

Alaska and Hawaii are unique in the U.S. in that they do not have contiguous electric grids. Instead, they rely on local microgrids to distribute electric power services to local customers. Both states also struggle with economies of scale in developing electric infrastructure, but this is a greater challenge for Alaska because of the vast territory the state encompasses. This is further exacerbated by the fact that while Hawaii has two utilities[2], Alaska has over 100 certificated utilities, and of these over 80% of rural utilities have generating capacities of less than 2.5 megawatts (MW) (Fay and Schwörer)[3]. Unsubsidized electricity rates in these rural Alaska communities are two to ten times more expensive per kWh than in urban areas of the state and in some cases over $1 per kWh (AEA). While this situation is unusual for the United States, it is the norm across the circumpolar north outside of the European Arctic, with an

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[2] Kauai Electric Association, and Hawaiian Electric Company.

[3] In comparison, a large utility in the continental U.S. such as Pacific Gas and Electric in California might have over 7500 MW of generating assets.

estimated 1,400 communities and 1.4 million residents defined as off-grid in Russia, Canada, Greenland, and Alaska (Holdmann and Poelzer).

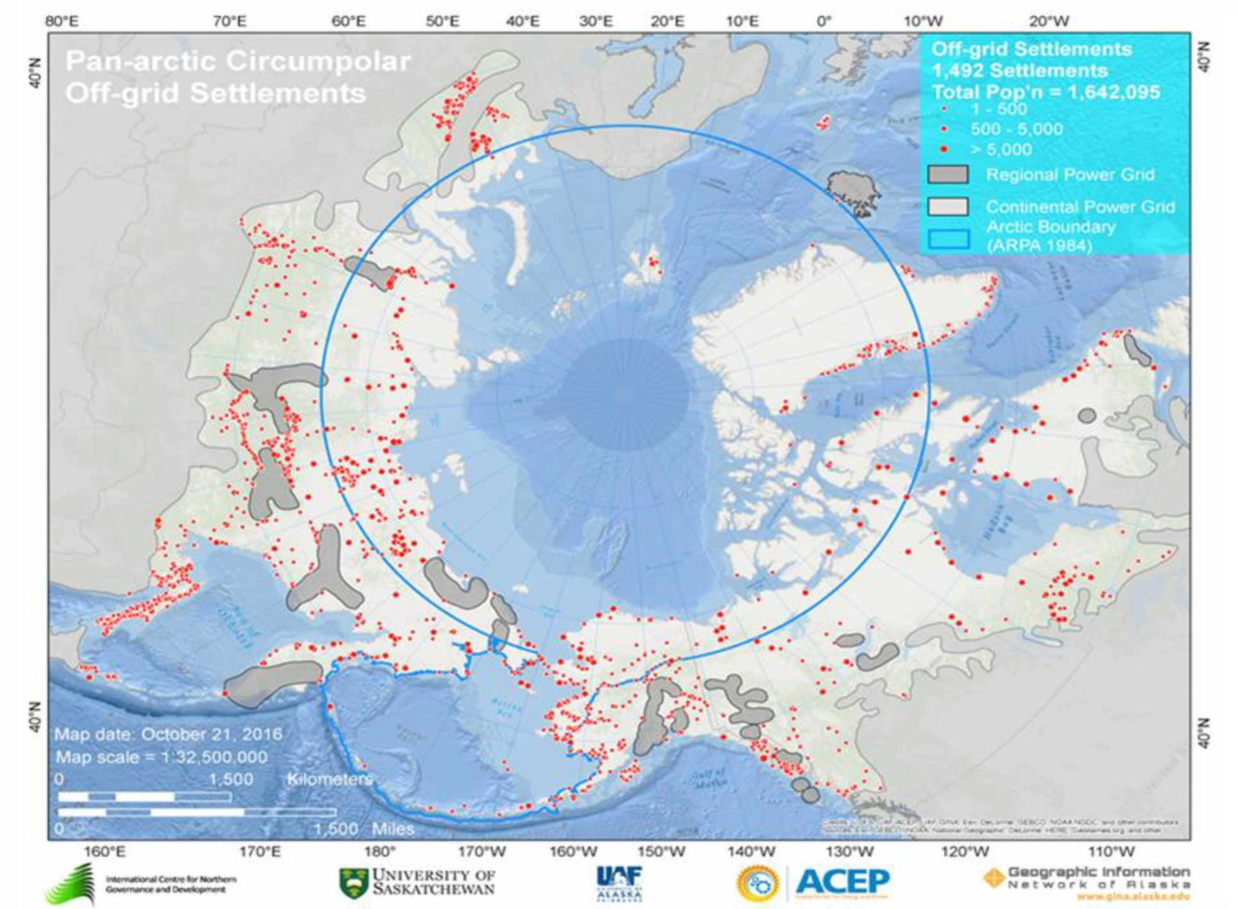

Figure 1.1. Map depicting remote communities in the Circumpolar Arctic (Holdmann and Poelzer). Light grey area roughly delineates the northern boundary of the continental electric grids in North America and Eurasia. Darker grey areas show regional grids that are interconnected via transmission linkages, but are not connected to the continental grids or are only weakly connected. The red dots represent an estimated 1,492 remote settlements in the circumpolar north, the vast majority of which rely on imported diesel fuel for power generation, and in many cases also for space heating.

According to a white paper co-authored with Navigant Research[4] and using data from their Microgrid tracker[5] (which has been updated every quarter for the past decade), Alaska is

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[5] Navigant's microgrid tracker is not publicly available, but is available for purchase at https://www.navigantresearch.com/reports/microgrid-deployment-tracker-2q19

home to roughly half of the remote communities in the circumpolar Arctic with community-scale renewable energy projects (Holdmann and Asmus). It also leads the Arctic and the U.S. states in the total installed capacity of microgrids, with 2,362 MW. This includes both remote microgrids, as well as interconnected, nested and linked microgrids such as Alaska's Railbelt grid[6]. The Railbelt grid extends for over 600 miles and links three distinct service areas: the greater Fairbanks area, the Matanuska-Susitna valley and Anchorage metropolitan area, and the Kenai Peninsula. Each service area is capable of islanding via a transmission backbone. In addition, the Railbelt grid contains a number of nested microgrids, such as the University of Alaska Fairbanks campus and several military bases.

There are several factors to take into consideration regarding the data collected by Navigant Research. Navigant's definition of microgrids is narrow and requires the incorporation of a renewable energy resource or co-generation (heat plus electric power). In addition, they include both existing and planned projects in their tracker, which tends to overestimate the number of projects now and in the future, because not all planned projects are eventually completed. Navigant also does not discriminate between remote microgrids, and other sorts of grid-connected microgrids. While this does not impact the absolute number of microgrids too much (the vast majority of microgrids in the Arctic are remote), it does impact the installed capacity since non-remote grids are often serving areas of higher population density, and thus have a higher installed capacity that most remote systems. This issue of population highlights another caveat – countries cannot be compared directly due to variation in population. A country like Greenland with a total population of 35,000 will never compete with Alaska on the number of installed systems, let alone on an installed kW basis.

Nonetheless, as Figure 3 illustrates, Alaska has by far the largest number of qualifying microgrids according to the Navigant Tracker, representing roughly half of microgrids deployed in the circumpolar Arctic with 122, followed by Canada with 73, Russia with 46, and Greenland with nine. This raises the obvious question – why?

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[6] Definitions various microgrid-related terms can be found in the article "What is an Advanced Microgrid Today" published in Distributed Energy Magazine and available at: https://www.distributedenergy.com/microgrids/article/21110541/what-is-a-microgrid-today

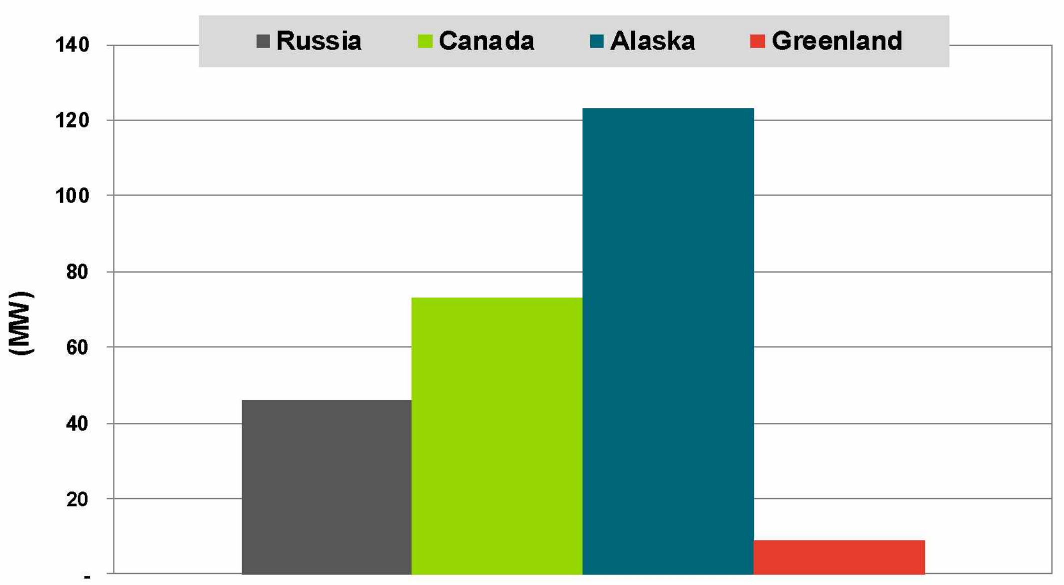

Figure 1.2. Total installed capacity of microgrids in Arctic countries. Reproduced from "Microgrid Innovation in the Circumpolar Arctic - Lessons for Developing Global Markets" by Navigant Research, using date from the Q2 2019 tracker (Holdmann and Asmus).

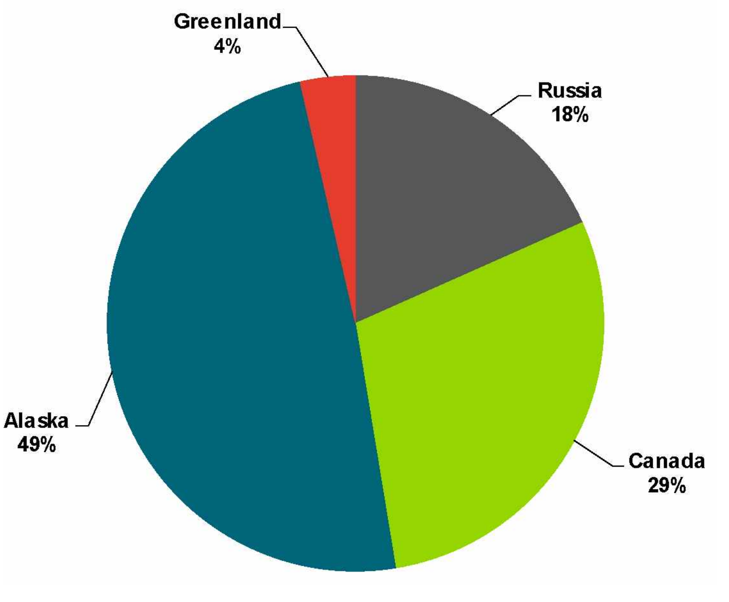

Figure 1.3. Circumpolar Arctic microgrid market share by total number of microgrids deployed in each country or state, reproduced from "Microgrid Innovation in the Circumpolar Arctic - Lessons for Developing Global Markets" by Navigant Research, using date from the Q2 2019 tracker (Holdmann and Asmus).

1.3 Research Questions

This research seeks to identify the major variables that affect the adoption of renewable energy systems for remote communities in the Arctic, including historical, institutional, regulatory, and economic factors. It also seeks to better characterize technical approaches and lessons learned for projects developed in Alaska, in order to disseminate this information to other regions in the Arctic, and beyond. Specifically, this thesis aims to answer the following primary research questions:

1. What are the major factors in Alaska that have resulted in a greater uptake of renewable energy systems for remote communities, compared to other similar places in the Arctic?
2. What lessons can we learn from Alaska as an early adopter/niche market in the development of renewable energy that is relevant to other areas of the Arctic, and globally?

1.4 Literature Review

There is very little prior scholarship on remote energy supply in the Arctic, and what exists is generally confined to a single country or region. For example, there is a large volume of published reports and papers on Alaska some of which include analysis of various utility structures, community sizes or compositions, and the impacts of developing renewable energy on energy price structure. These are drawn upon heavily, specifically prior work completed by the Institute for Social and Economic Research (Colt, Fay), and data and analyses in reports published through the Alaska Energy Authority (AEA). A more cross-sectional comparative assessment of energy projects and policies for remote regions in the Arctic was completed by the 2016 Arctic Fulbright Program's Energy Group, "Developing Renewable Energy in Arctic and Sub-Arctic Regions and Communities – Working Recommendation of the Fulbright Arctic Initiative Energy Group" (Poelzer et al.). This report included an initial effort to quantify off-grid communities in the circumpolar Arctic (Figure 1), and a series of recommendations for increasing renewable energy development for remote communities in the North.

In addition, this thesis is informed by a wide range of existing academic literature and theory, including State-building literature (Tilly, Poggi, Skocpol and Giddens). This is particularly relevant to the argument presented in Chapter 2 – that state building, or rather incomplete state-building in the case of the northern periphery of North America, is a major explanatory factor for why the electric grid was never fully developed in the north.

Socio-Technological Transition literature (Geels, Schot) provides a firm grounding in current approaches to technology transitions, and provides a wealth of research and case studies on how innovations occur and why they fail. This literature contributes broadly to the full paper excerpted in Chapter 2, and is also drawn upon in Chapter 3, with an emphasis on socio-technological niches as a key feature of transformation pathways (within Socio-technical Transitions). Chapter 3 closes with a discussion of whether microgrid development in Alaska is an example of such a niche.

Finally, although not included in the narrative of this thesis, a broad overview of renewable energy policy (Beck and Martinot) and specific development barriers for small island developing states (Weisser) was completed in order to gain a broad understanding of what has been successful in similar markets outside the Arctic region. In addition to the academic literature, reports produced by the International Energy Agency (IEA), Renewable Energy Policy Network for 21st Century (REN21), and the International Renewable Energy Agency (IRENA) have been particularly helpful in drawing comparisons internationally.

1.5 Data

There is limited use of specific data sets in this thesis, since it is presented as more qualitative than quantitative. However, the information regarding specific Alaska renewable energy projects presented in Table 1 of Chapter 3 was gathered from data reported to the Alaska Energy Authority's Power Cost Equalization Program (PCE), the Alaska Energy Data Gateway (curated by ISER and the Alaska Center for Energy and Power at the University of Alaska), and conversations with individual utility managers.

1.5 Contribution of Research

This research contributes to the larger body of work investigating pathways to carbon neutral energy source transitions. The Circumpolar North provides a unique window into some of the factors inhibiting or promoting the adoption of renewable energy. Communities in this region share many similarities geographically and culturally. They also have similar challenges related to remoteness, including logistical challenges, local capacity, high cost of infrastructure development, and high energy demand due to the cold climate. Nonetheless, there are significant differences in history, particularly the experience of nation building, and the resulting institutions of governance and economy. Whatever the reasons, there have been vastly different trajectories taken in the development of renewable energy across the North. If the underlying factors can be uncovered to explain these varying experiences and outcomes, it could provide powerful insights to help guide the development of renewable energy by people in other similarly remote areas, as well as to guide future policy decisions within the Arctic region itself.

1.6 Chapter Overview

This thesis is organized into four distinct chapters. Chapter 1 introduces the research questions and provides context in which to understand the research. Chapter 2 represents a case study of the historical build-out of the electric grid in Alaska, focusing on the historical and socio-political context. This chapter is an excerpt from an unpublished paper co-authored with Dr. Greg Poelzer and Dr. Dominique Pride titled “State-Building and Electrical Energy. A Comparative View of Norway, Alaska, and the Circumpolar Arctic.” The larger paper argues that the state often instigates and drives massive technological transitions, not with the aim of fostering innovation and competitive markets, but rather to succeed in politico-military competition. The measure of success in energy transitions is not the extent of diffusion of new technologies, but rather the continued existence of the political regime. Technology and technological transitions, including energy transitions, are a means, not an end. This perspective on the buildout of the electrical grid is a significant departure from contemporary approaches to energy transitions. In the paper, we focus on two case studies which represent opposite ends of the spectrum of complete and incomplete state-building in the Circumpolar North – Alaska and Norway – and analyze specific socio-political histories of these nations with a specific focus on events that resulted in the state and infrastructure buildout apparent in the modern era. Included in this thesis is the excerpted section on Alaska.

I further consider niche market development and explore technical, socio-political, economic, and policy issues associated with the implementation of renewable-diesel hybrid microgrids in Alaska in Chapter 3. This Chapter represents the full manuscript of a paper published in a special issue of Proceedings of the IEEE titled “Renewable Energy Integration in Alaska’s Remote Islanded Microgrids: Economic Drivers, Technical Strategies, Technological Niche Development, and Policy Implications”, along with co-authors Dr. Richard Wies and Mr. Jeremy Vandermeer. The article explores technical challenges and associated mitigation strategies of renewable energy integration, including lessons learned from the implementation of renewable-diesel hybrid microgrids in Alaska. This article also reviews the underlying socio-political and economic landscape that has allowed Alaska to emerge as an early adopter of microgrid-enabling technologies and includes a discussion of Alaska’s energy programs and policies and how they impact project development.

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Chapter 2

State Building and Electrification in Alaska[7]

Alaska, as well as territorial Canada, represent paradoxes of incomplete state-building at the periphery of otherwise highly developed states and extremely wealthy societies. State-building as a specific term in social sciences is the political and historical processes of creation, institutional consolidation, stabilization and sustainable development of states, from the earliest emergence of statehood up to the modern times (Scott). The buildout of electric infrastructure in the north exemplifies a process of incomplete nation-building, with the northern edge of the contiguous electric grid ending somewhere in the northern portion of Canada's provincial norths. Regional grids[8], where they exist, are largely a legacy that reflects the twin national priorities in infrastructure development in the north: extracting natural resources or enhancing national security.

The following chapter explores the history of electrification in Alaska as an example of incomplete state-building in northern peripheral areas of North America. Alaska's electrification story is similar to Canada's, though the timing is offset by several decades due to the challenges of accessing and developing Canada's remote interior prior to wide-spread air transport. The differences between Alaska and Canada's electrification histories are mainly a reflection of different state-society relations. Historically, the Canadian government played a larger role in the

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[7] Prepared for submission. This Chapter is excerpted from an unpublished paper titled: "State-Building and Electrical Energy – a Comparative View of Norway, Alaska, and the Circumpolar Arctic," co-authored with Greg Poelzer and Dominique Pride. It presents a historical narrative of the build-out of Alaska's energy infrastructure from the perspective of state-building.

[8] A regional grid in this context is defined as "a high voltage transmission network connecting multiple distribution nodes/load centers and power stations, but that is either entirely isolated from a larger national or continental central grid or is only weakly connected" (Holdmann and Asmus)

national economy than in the U.S., and thus had a greater role in the buildout and management of electric power infrastructure (McCannon).

There are four primary eras of state building in Alaska. The first era follows a colonial trajectory centered on resource extraction, largely driven by private interests, beginning with the fur trade industry and, later, the mining industry. The second era is the war-time buildout of infrastructure, coupled with population influx and traditional state-building concerns of securing borders and surveillance, culminating with statehood in 1959. The third era begins with the Cold War, which changed the emphasis of development in Alaska based on shifting geopolitical threats to the nation and ultimately resulted in a greater emphasis on internal state-building and build-out of infrastructure to benefit existing communities and industries, usually at the local or quasi-regional level. This parochial emphasis on development extends into the modern (fourth) era, and is still evident in the lack of macro-scale infrastructure in Alaska and the distributed and deregulated nature of the industry compared to other parts of the U.S. However, during the last three decades there has been an increased emphasis on providing reliable power to communities and residents in all areas of the state, exemplified by electrification and, to a lesser extent, interconnection of remote and rural areas.

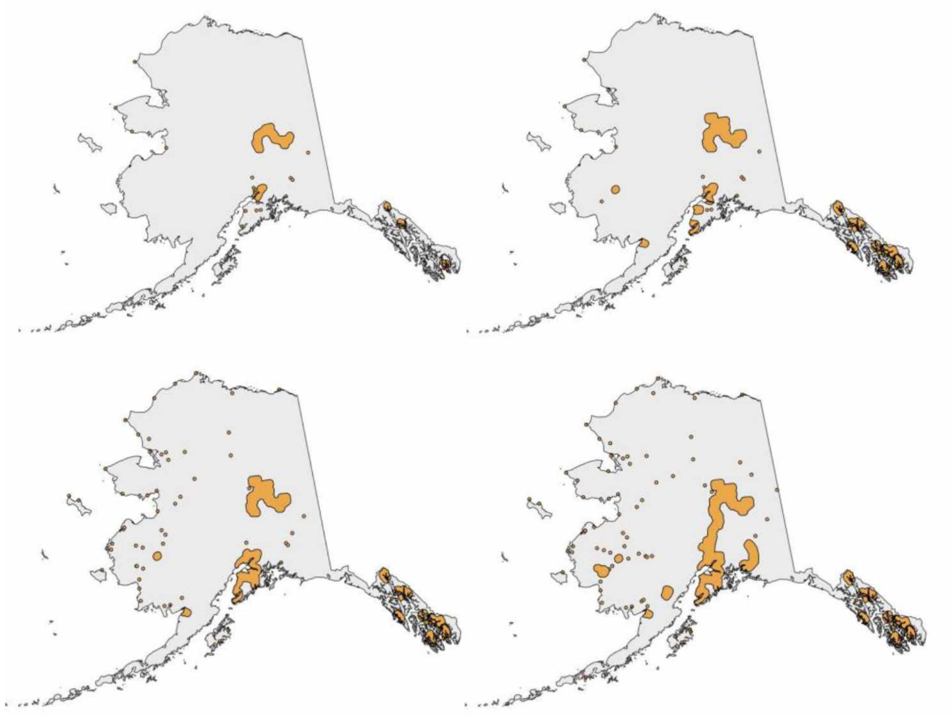

Figure 2.1. Electric grid build-out in Alaska. From upper left going clockwise: 2a) Alaska electric grid infrastructure in 1930; 2b) Alaska electric grid infrastructure in 1950; 2c) Alaska grid infrastructure in 1970; 2d) Alaska electric grid infrastructure present day. Source: Alaska Center for Energy and Power, UAF.

2.1 Early electrification in Alaska (1893–1930)

Early electrification in Alaska supported the intensive energy needs of the mining industry. As a frontier area far from political and economic centers of influence, it is inaccurate to assume that peripheral areas such as Alaska are always societal and cultural backwaters. With the dramatic growth in population during the Gold Rush era and the high proportion of personal wealth, many settlements in Alaska quickly grew to resemble slightly rougher-around-the-edges versions of modern cities further south, including early adoption of electric power. Less than a decade after Pearl Street Station in Manhattan became the first commercial power plant in the U.S. in 1882, and while the vast majority of the nation remained in the dark electrically, central power was being brought to Alaska. Alaska Electric Light and Power was incorporated in 1893 as a private for-profit company in order to construct and operate several hydroelectric facilities to supply power for the Juneau mining district and a few local businesses (AEL&P). By 1904, the city of Nome boomed to a population of 20,000 residents and had a privately-owned light and power plant[9] to support the growing number of businesses, schools, churches, newspapers, saloons, a hospital and a post office (Cornwall and McBeath). Nome also was home to the first wireless telegraph in the U.S., which could transmit over 100 miles, relaying messages to Seattle via St. Michael[10]. That this form of communication was available in Alaska is of interest because telegraph stations—called signal stations in Canada—required significant amounts of electric power to operate and would thus create a demand for rural power generation in the coming decades (Roberts). The Nome Gold Rush ultimately proved lucrative but short-lived, and Nome has dwindled significantly in size since its heyday.

Another example of early electrification in Alaska is Fairbanks, which was electrified by the Northern Commercial Company in 1905, using a wood-fired steam heat and power plant located in the downtown area[11]. These early power plants supported mining and other commercial activities as well as some private housing and public facilities. Over time, some of these early utilities expanded their footprint to incorporate outlying areas and eventually to connect to other population centers within their geographic area to form regional grids. A map showing Alaska's energy infrastructure circa 1930 is shown in Map 2a; note that the majority of development was co-located with established mining districts.

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[9] Alaska and Polar Regions Collections, University of Alaska. Map of Nome City ca. 1904. Shows sand spit and electric light power plant

[10] Information from website www.akhistorycourse.org. Alaska History and Cultural Studies – Northwest and Arctic – 1897–1920 GOLD, retrieved 2017-11-21.

[11] Based on an oral history of the NC Company provided by George Preston, "lead agent" for the company during its final years of operation in Fairbanks.

2.2 Securing borders, infrastructure buildout, and statehood (1930–1950)

In the late 19th and early 20th centuries, nation-building in both Canada and the U.S. reached its zenith, driven by a desire to establish sovereignty and consolidate control over territory. Development initially centered on civilian needs, but this was rapidly superseded by national security concerns instigated by the U.S. entry into World War II, reinforced by the Japanese invasion of the Aleutian Islands, and then protracted by the Cold War.

On the civilian power front, no single program had a larger impact on electrification in rural parts of the U.S., including Alaska, than the executive order signed by President Franklin Delano Roosevelt in 1935 that formed the 1936 Rural Electrification Administration (REA). The REA was part of Roosevelt's New Deal – a grand vision for nation building intended to bring the country out of the recession, implementing radical programs that would transform U.S. social and infrastructure programs in many ways that still impact us today (Skocpol and Finegold). The REA was designed to bring electrification to farms and small communities across the U.S. through the 1940s and 50s by offering low-interest loans to any organization willing to build and operate the electrical infrastructure needed to serve these rural areas (Owen 6–17). Most of these organizations were non-profit, member-owned cooperatives that were formed to serve as distribution utilities, purchasing wholesale power from larger utilities and distributing it to member-consumers. Except for in the state's largest population centers, cooperatives quickly became the dominant model for electrification in Alaska. The first attempt at forming a cooperative in Alaska was initiated by farmers near Palmer in 1937, who asked for REA assistance in organizing a co-op (ARECA). This effort led to the formation of the Matanuska Electric Association (MEA), which began distributing power purchased from the Eklutna hydroelectric facility to 127 members in 1942 (ARECA).

The onset of World War II (WWII) greatly enhanced the geopolitical importance of Alaska. The proximity of the state to Japan, coupled with its key strategic location enabled it to pay a central communications and logistics role in the war effort, such as the Lend-Lease program with Russia[12] (Kimball). This contributed to the accelerated buildout of infrastructure that shaped the future direction of the territory and its relationship with the nation as a whole. Massive infrastructure projects were undertaken, such as the Alaska Highway, a 1,420-mile road built over a 9-month period, connecting Alaska through Canada to the rest of the U.S. for the first time. Other construction projects included telephone lines, oil pipelines, railways, and roughly 300 military installations throughout Alaska (Naske and Slotnick).

As a result of WWII, thousands of men and women moved to the sparsely populated territory and many stayed. In 1940, just over 72,000 people called Alaska home. By 1950, the population nearly doubled to 129,000. Anchorage saw the largest influx, with its population ballooning from 3,000 to 47,000 in just a decade (Hollinger), while Fairbanks grew from 4,000 to nearly 20,000 residents. This growth in population would significantly tax Alaska's power infrastructure and result in severe power shortages, particularly in Anchorage, calling for creative means to add to the city's limited local generating capacity. For example, in 1947 the steam generator on-board a wrecked ship at the mouth of Ship Creek was temporarily utilized by the City of Anchorage to alleviate severe power shortages (Chugach)[13]. Over time, infrastructure around population centers and military installations were gradually expanded to meet the growing localized demand (map 2b).

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[12] The Lend-Lease policy, formally titled "An Act to Promote the Defense of the United States", was a program under which the U.S. supplied allied nations, including the Soviet Union with airplanes and other critically need war infrastructure during World War II. Alaska served as a critical transfer point for airplanes and other supplies sent to Russia along what was called the "Northwest Staging Route."

[13] The Ocean-going tanker, the Sackett's Harbor, was beached at the mouth of Ship Creek, and the boilers and generating equipment were used to provide 42% of Anchorage Public Utilities' power until decommissioned a year later due to high operating costs and other available alternatives.

2.3 Post-WWII emphasis on nation-building in the north (1950–1970)

Following WWII, Alaska and the Yukon were on the cusp of a recession due to a steep decrease in military spending. Nonetheless, the geostrategic importance of the region remained evident as the World transitioned from an active war fought on many fronts, to a lengthy and uneasy global stalemate - the Cold War. The Cold War era marked a time of continued state-building to protect borders, including the buildout of infrastructure along strategic frontiers, such as the north. To secure control and sovereignty over their northern territories, both the U.S. and Canadian governments considered pre-emptive approaches to bring new industry to the north. One of these approaches was to reduce the high cost of power by building large hydroelectric facilities (Naske and Hunt). The idea of using hydropower to support economic development in the north was hardly new, and in these decades several mega-projects were proposed in both the Yukon and Alaska. These projects included the Rampart Dam, which was proposed by the U.S. Army Corps of Engineers in 1954 and would have created the largest constructed reservoir in the world by flooding an area the size of Lake Erie. Despite ambitious plans, only two projects were completed during this era. The Eklutna hydroelectric dam still provides power to the Matanuska-Susitna Valley, and the Snettisham hydroelectric dam continues to serve Juneau.

Despite these grand plans for large scale development, Alaska was still heavily dependent on the federal government and in particular, expenditures related to national defense. According to the Alaskan economist George Rogers, “by the 50s and 60s Alaska had become primarily an ‘exporter’ of military defense” … and that the military had become “the major industry in the state” (Rogers). In effect, Alaska was exporting defense to the rest of the nation, receiving in return economic benefit. During the Cold War era, the Distant Early Warning (DEW) Line was created to detect incoming Soviet aircraft and provide early warning of any sea-and-land invasion. The DEW Line network became operational in 1957 and included dozens of radar stations strategically placed along the Aleutian Islands, the Arctic Ocean coast in Alaska and Canada, and the Faroe Islands, Greenland, and Iceland (Naske and Slotnick). A short time later, the Cuban Missile Crisis in 1961 ended the existential threat of a land-based invasion using conventional forces and made the DEW Line obsolete. In place of this threat, intercontinental ballistic missiles and the doctrine of mutually assured destruction (MAD) held force to the end of the 20th century. No longer was there a need for large-scale connective infrastructure investments in the north such as roads, ports, and electric grids to ensure sovereignty over the land, and thus the trajectory of investment and nation-building in the north changed again. Nonetheless, because of the North's strategic geographic importance both in monitoring activities (ranging from nuclear testing to submarine activity) and deployment of military resources, Alaska has retained a place of prominence in national defense throughout these geopolitical and technological transitions.

Two major events in the late 1950s and 60s permanently altered the future trajectory Alaska: the achievement of statehood in 1959 and the massive North Slope oil discovery on state-selected lands in 1968. Alaska moved from a frontier territory to a self-governing state with the necessary resources for creating a self-sufficient economy, albeit one still dependant on resource extraction. A major precursor to the development of Alaska's newfound oil wealth was the settlement of Native land claims, which was signed into law in 1971 as the Alaska Native Claims Settlement Act (ANCSA). At the time of signing it was the largest land claims settlement in U.S. history. ANCSA was unique in that it not only to resolved issues surrounding aboriginal land claims, but also created Alaska Native corporations at the regional and village level, thereby stimulating economic development throughout Alaska. With the promise of future oil revenues, the young state focused on infrastructure buildout to support local communities and economic activity statewide, rather than rely on federal investment to serve national interests. (Naske)

2.4 Power to the people – village electrification (1970–1985)

While urban centers in Alaska and their outlying areas gradually became electrified in the 1950s and 1960s, rural villages did not benefit similarly. The REA model depended strongly on the assumption of a local cash economy and customers that could pay for electric services if provided. Rural Alaska with its mostly barter economy, did not fit the REA model. An early exception was the community of Kodiak, which formed a cooperative in 1942. After purchasing the existing power company, the cooperative extended service to meet the new demands of a rapidly expanding post-war community (ARECA).

In 1963, the REA enlisted the help of Alaska's first cooperative utility, MEA, to assist the village of Unalakleet in western Alaska in creating an electric utility. The State of Alaska's operating certificate was listed in MEA's name, as were the REA loans needed for power plant construction, fuel tank construction, and line distribution (Towarak). This experiment proved successful, but existing Alaska cooperatives could not be expected to take on the debt burden and corresponding risk, for electrifying rural villages. A new entity was needed whose primary focus would be on rural Alaska electrification.

The formation of the Alaska Village Electric Cooperative (AVEC) in 1967 represented a major breakthrough in rural electrification in Alaska. The creation of AVEC came about through the coordinated efforts of the REA, key federal and state agencies, and rural leaders and coincided with federal efforts at reducing poverty. In order to participate in AVEC, villages interested in service had to guarantee that 80% of homes would hook up and that each village would make land available for the power plant and provide donated labor. In exchange, the REA agreed to provide capital in the form of a $5.2 million loan for equipment and construction. The AVEC charter explicitly noted its function as “a means of increasing Native involvement” in rural development. Between 1968 and 1985, community-wide power generation was brought to over 200 villages throughout rural Alaska (ARECA, Kohler). While the formation of AVEC was a major contributor to widespread electrification in rural Alaska[14], a variety of municipally owned, privately owned, and smaller cooperatives were also formed to supply power to rural communities. Today, there are over 100 certificated utilities in Alaska, most of which serve rural Alaska (AEA, *PCE*). This contrasts with Canadian utility models, where the vast majority of electric power services are supplied by Government-owned utilities. The electrification of rural Alaska is evident in Map 2c, and was largely completed by 1970.

2.5 1970–present

The discovery of oil on Alaska’s North Slope and the construction of the Trans-Alaska Pipeline resulted in new wealth for the young state and the ability to invest in infrastructure to support its population and industries. Thus, investment in energy infrastructure shifted from the federal government to the state. This included the continued build-out of rural powerhouses and the construction of a number of hydropower facilities such as the “Four Dam Pool” projects built by the State of Alaska in the early 1980s to serve Kodiak, Valdez/Glennallen, Ketchikan, and Wrangell/Petersburg, and the Bradley Lake hydropower project in 1991 (Davis). In addition, the state and utilities invested in transmission infrastructure to tie together local grids into larger

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[14] In 2019, AVEC served 58 villages via 49 individual power plants.

regional grids. The largest is the Railbelt electric grid, the only true regional transmission network in Alaska, connecting service areas in Anchorage, the Kenai Peninsula, and Fairbanks. The primary source of energy producing electric power for the Railbelt Grid is natural gas from a stranded resource in Cook Inlet near Anchorage, which was first developed in 1964 and is also used for local heating. This energy source is complemented by hydropower, a small amount of coal and oil residuals, and 45 MW of installed wind capacity from three individual wind farms (AEA, *Atlas*). A large battery system, GVEA's 27 MW (approximately 8MWh) Battery Energy Storage System (BESS) was installed in 2003 to anchor the northern end of the Railbelt intertie and improve reliability of service in the Fairbanks market. At the time of construction was the largest battery system in the world, and is still operational today (GVEA). The State of Alaska in partnership with the utility industry built transmission lines to connect existing local grids and newly developed resources., including projects like the Willow - Healy Intertie, completed in 1986 and representing the final link to connect the service areas of the six Railbelt electrical utilities. Most of these state investments benefitted from federally available grant and loan programs or tax credits. This continued incremental buildout of transmission infrastructure is evident in Map 2d.

2.6 Discussion

Understanding the history of electrification in Alaska in the context of national priorities and within broader geopolitical landscape is important context to understanding how Alaska has progressed with development of renewable energy over the last two decades. Much of the explanatory factors in why Alaska has been at the forefront of renewable energy development is rooted in this historical narrative. The next Chapter further contextualizes development in the modern era, including a more detailed description of the underlying socio-political and economic landscape that has allowed Alaska to emerge as an early adopter of microgrid-enabling technologies. A discussion of Alaska's energy programs and policies and how they impact project development both historically and in the future is also included, as well as technical challenges and lessons learned from the implementation of renewable-diesel hybrid microgrids in Alaska.

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Chapter 3

Renewable Energy Integration in Alaska's Remote Islanded Microgrids: Economic Drivers, Technical Strategies, Niche Market Development, and Policy Implications[15]

3.1 Abstract

Alaska has over 200 communities operating remote islanded microgrids that are not connected to each other or to the North American electric grid. These communities range in size from a few dozen to a few thousand residents and rely heavily on fossil fuels—primarily imported diesel—to generate electricity. This has resulted in some of the highest energy costs in the nation (over \$1/kWh in some locations) and a strong incentive to invest in renewable energy as a strategy for reducing these costs. This paper explores technical challenges and associated mitigation strategies of renewable energy integration, including lessons learned from implementation of over 70 renewable-diesel hybrid microgrids in Alaska utilizing a wide range of resource and technology solutions. This paper also reviews the underlying socio-political and economic landscape that has allowed Alaska to emerge as an early adopter of microgrid-enabling technologies and includes a discussion of Alaska's energy programs and policies and how they impact project development. The results of our study show that the primary technical hurdles for renewable energy integration in Alaska's remote islanded microgrids include management of distributed energy resources and design for reliable and resilient operation with intermittent high-penetration renewable generation. Additionally, economic drivers include extremely high energy costs, a highly deregulated utility market with dozens of certificated utilities, state investment in infrastructure, and modest subsidies that create a technological niche where renewable energy projects are cost-competitive at current market prices. Many of the evolving technical strategies and lessons learned from renewable integration projects in Alaska's remote islanded microgrids could help inform project development in other markets, despite differences in climate and geography.

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3.2 Introduction

Alaska is a pioneer in the integration of high-penetration renewable energy from variable renewable resources such as wind energy, as well as an early adopter of microgrid-enabling technologies. Approximately one third of Alaska's 200 remote communities that operate remote islanded microgrids (not grid connected) have developed community-scale renewable energy systems over the past two decades. In addition, the regional "Railbelt" electric grid that serves the majority of Alaska's population and extends from the interior to south-central Alaska, contains several independent nested and interconnected microgrids (Allen, et al.). When aggregated, Alaska has one of the highest adoption rates for microgrids in the world, with approximately 12% of the world's total installed capacity (Holdmann and Asmus). This paper explores particular features of Alaska's socio-technical landscape and energy market, including a range of economic, institutional/policy, and technical characteristics that have encouraged experimentation and novel solutions.

Microgrids can be used to support distributed renewable generation, improve grid resiliency and reliability, offer opportunities for demand charge abatement, or provide other ancillary services. Many of the technical approaches and programs supporting microgrid development in Alaska as a whole could be relevant to other markets pursuing microgrid development as part of a broader energy management strategy. However, Alaska's experience with using renewable-diesel hybrid systems to support cost reductions in rural electrification is perhaps the most interesting and is the primary focus of this paper. This experience is also the most directly transferrable to developing parts of the world without reliable access to affordable energy. This is because, in many ways, rural (and often remote) parts of Alaska resemble the developing world more than other parts of the U.S. when considering indicators such as access to clean water and sanitation infrastructure, communications, and energy. It is estimated that 80% of people in the world without access to any electric power live in rural areas, many of them with no nearby grid. The International Energy Agency, in its World Energy Outlook Report has concluded "for the large rural population that is distant from power grids, mini-grids or off-grid systems provide the most viable means of access to electricity." This report goes on to anticipate that approximately 70% of new electrification in rural areas will come from non-centralized grids (IEA).

The high cost of energy in remote parts of Alaska is exacerbated by relatively low median household incomes, with few local opportunities for cash-based employment and a strong emphasis on local subsistence activities. Alaska's investment in renewably-powered microgrids is largely driven by a desire to extend affordable, reliable energy to these remote communities where it is not economically or technically feasible to extend grid services. However, Alaska's success in maintaining and incrementally improving these systems over more than a decade lies partly in non-technical considerations critical for long-term project success. This paper will consider both the technical solutions and the overarching socio-political and economic landscape that have allowed Alaska to emerge as an early adopter of microgrid-enabling technologies through the development of what socio-technical theory literature calls a technological niche (Schot and Geels, Geels).

The remainder of this paper is organized as follows. In order to understand the development of electricity grids and integration of renewable energy in Alaska, a general overview of Alaska electricity infrastructure including grids and generation sources, is presented in Section 3.3. In Section 3.4, the scope of Alaska's energy portfolio and economic drivers for renewable energy development are discussed. Technical strategies and project examples for integrating renewable energy systems in Alaska's remote islanded microgrids are described in Section 3.5. Section 3.6 describes the underlying characteristics present in Alaska's socio-political landscape that have facilitated creation of a technological niche in remote microgrids, followed by policy implications for remote microgrid development in Section 3.7. Lessons learned from Alaska's experience with integrating renewable energy in remote islanded microgrids are detailed in Section 3.8. Finally, conclusions are summarized in Section 3.9.

3.3 Alaska's Electricity Infrastructure

When considering energy provision in North America, there is a natural division in how services are delivered, demarcated by the northern edge of the North American electric grid. This grid gradually fades out in Canada's provincial norths and does not extend into the Yukon, Northwest Territories, Nunavut, or Alaska. Within this northern region, a number of small regional grids have been developed to serve population or industrial load centers. These grids are not connected to the North American electric grid, or only weakly connected. In Alaska, the primary example in the Railbelt electric grid (see area marked by solid oval in Figure 3.1). This grid resembles other regional grids in the circumpolar north, which are geographically and capacity limited and generally connect major population centers to one or more stranded energy resources, sometimes coupled with major industrial or military loads.

Beyond these regional grids, a high proportion of remote communities are not connected to any form of central energy infrastructure such as a regional electricity grid or natural gas pipeline. In many cases, communities are not road accessible and receive provisions only through barge service or air transport. For example, Alaska's capital, located in Juneau, is the only state capital in the U.S. not accessible by road. Juneau represents one example of a hydro-power based microgrid, which has access to a firm source of baseload power through stored hydro. This enables Juneau, like many other hydro-power based microgrids in the north, to be able to produce close to 100% of its electric power from renewable resources, maintaining diesel generators only for backup power, peak load generation, or supplemental power during periods of low rain or snowfall.

For communities without access to hydropower resources, reliance on diesel generation remains high. Developing renewable energy is generally limited to non-firm sources of energy, complicated by the limited geographic extent of local distribution networks that lack entirely a transmission backbone that could send excess electricity to more distant markets. Power must be consumed locally and at the time of production. The remainder of this section provides additional detail related to these three microgrid paradigms in Alaska, including historic context related to the electric power industry, current energy infrastructure, and underlying policies that are important to understanding Alaska's experience in renewable energy development.

3.3.1 Alaska's Railbelt Electric Grid

The largest example of a regional grid in Alaska is the Railbelt electric grid; it serves approximately three-quarters of Alaska's approximately 740,000 residents and follows the Alaska Railroad for over 500 miles from Fairbanks through Anchorage to the Kenai Peninsula (see Figure 3.1). In total, over 2,000 MW of installed power generation capacity exists along the Railbelt to serve an average annual load of approximately 600 MW and a peak load of over 800 MW (AEA, *Atlas*). Approximately 70% of the power generated on the Railbelt electric grid is produced from a stranded natural gas resource in Cook Inlet, near Anchorage, with other major sources including hydropower (~20%), and coal (~8%) (Fay, et al.).

The Railbelt electric grid became a regional grid through the interconnection of several independent utility service areas. For example, the State of Alaska-owned Willow-Healy intertie was completed in 1986 to connect the Golden Valley Electric Association (GVEA) grid in Fairbanks to inexpensive hydroelectric and natural gas power produced further south. As a result, the Railbelt electric grid, is actually a conglomeration of numerous interconnected and nested microgrids (see Figure 3.2). For example, in the Fairbanks area, two local military bases and the University of Alaska Fairbanks (UAF) operate small, ~20 MW combined heat and power coal plants, and are nested microgrids that can island from the GVEA grid. The UAF grid typically operates independently from the larger grid, while the two bases typically operate in grid-connected mode. The GVEA grid, in turn, can be isolated from the rest of the Railbelt and is

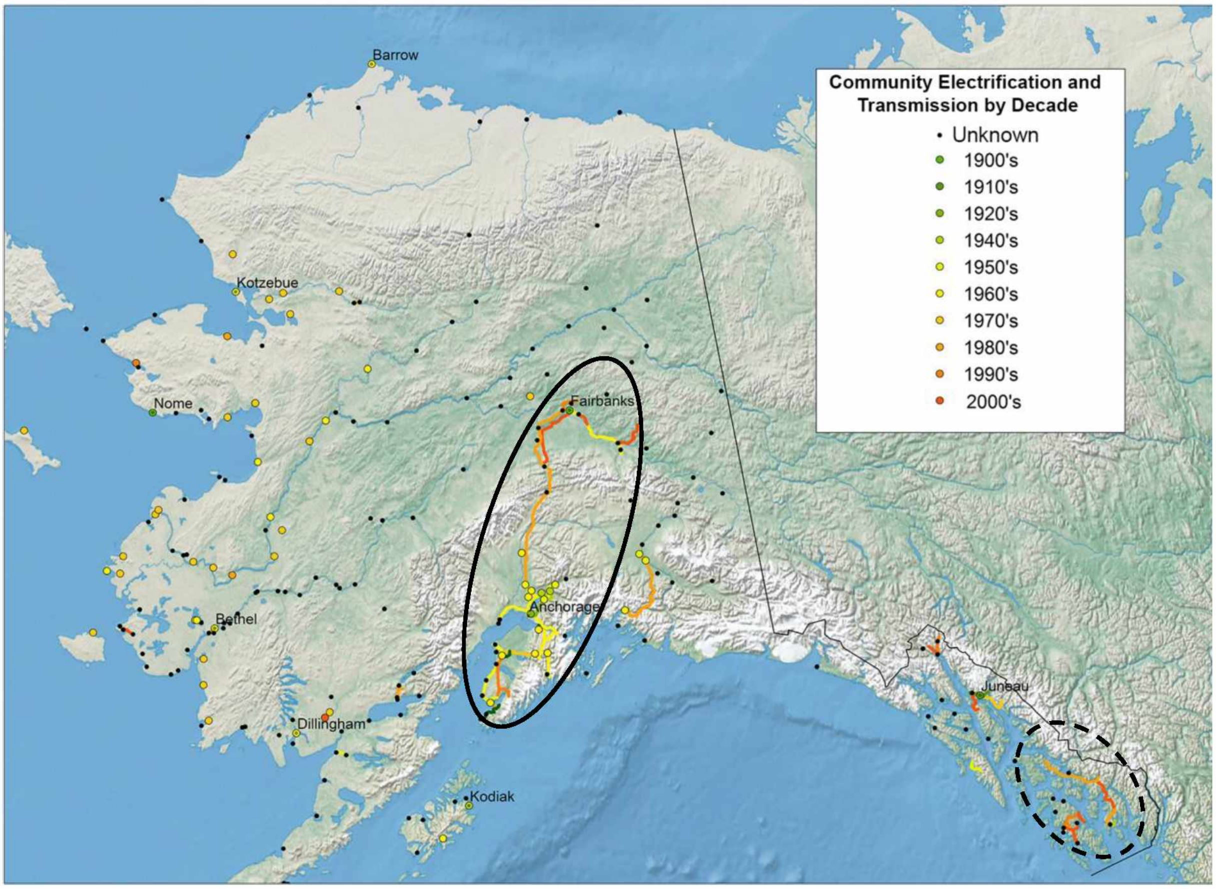

Figure 3.1. Map depicting local and regional electric grids in Alaska and decade of construction. Source: Alaska Center for Energy and Power, University of Alaska Fairbanks.

supported by a battery energy storage system (BESS) that can provide 27 megawatts of power for 15 minutes in the event of a generation- or transmission-related outage. In total, the Railbelt grid incorporates the service areas of six independent electric utilities that each operate and manage its own generation sources, and sometimes its own transmission assets as well. Some basic forms of economic dispatch are voluntarily practiced by these utilities, mainly through adhoc power sales, though no formal supervisory system operator manages grid operation. In addition, there are some communities at the margin of the grid where interruption in service is common, and these communities also have their own local generation sources that allow them to operate independently of the larger grid if necessary.

3.3.2 Hydropower-based Grids in Alaska

Early in statehood, Alaska invested substantial resources in hydroelectric generation to serve communities in southcentral and southeast parts of the state where resources were most abundant. Hydropower remains an important contributor to Alaska's total energy portfolio, though without a statewide grid its benefit is generally localized. Early hydroelectric projects were mainly privately owned and operated, often in conjunction with mining operations. The first community in Alaska to receive electric power services was Juneau. The Alaska Electric Light and Power (AEL&P) Company was incorporated in 1893 (and still exists today) to construct and operate several hydroelectric facilities to supply power to the Juneau mining district, along with a few local businesses. After achieving statehood in 1959, the discovery and subsequent development of oil fields on the North Slope resulted in new wealth for the young state, and Alaska invested in a number of hydroelectric facilities. The most notable were the "4 Dam Pool" projects with a total generating capacity of 76 MW constructed in the early 1980s to serve Ketchikan, Kodiak, Petersburg, Valdez, and Wrangell. The state also later invested in 175 miles of transmission lines connecting the municipalities of Ketchikan, Wrangell, and Petersburg, which is now operated by the Southeast Alaska Power Agency (SEAPA), a generation and transmission utility that sells power wholesale to local distribution utilities in the communities it serves (see area marked by dashed oval in Figure 3.1). Each of these communities can self-generate and thus represent a series of connected microgrids, but generally receive power from the lowest-cost production assets pooled through the SEAPA grid. Around the same time, the 120 MW Bradley Lake hydro project was also built to serve the Railbelt electric grid, along with transmission to deliver power from southcentral Alaska to Fairbanks.

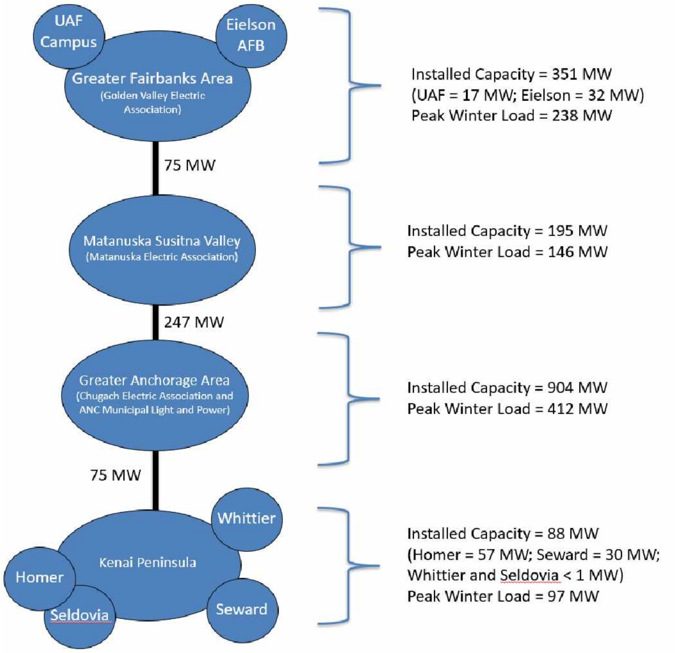

Figure 3.2. Diagram depicting the interconnection of utilities with nested microgrids in the Alaska Railbelt including installed generation and transmission capacity and peak load. Source: Alaska Center for Energy and Power, University of Alaska Fairbanks.

Investments made by the State of Alaska in both hydropower communities and regional grids are important, because without an interconnected grid the benefit is limited to a single community or load center. Communities served by these hydroelectric facilities have the lowest price per kWh in the State of Alaska. For example, Ketchikan's 2019 residential electric rate is \$0.10/kWh. In comparison, the small community of Shungnak in western Alaska relies on diesel fuel flown into the remote community, resulting in current rates of \$0.71/kWh. To equalize this benefit, policies (discussed later) were developed to help make electric power more affordable in other parts of the state that did not benefit from large-scale state-funded infrastructure projects. Nonetheless, the large geographic expanse and sometimes severe weather and environmental conditions has made maintaining local backup generation and the ability to operate independently of a larger grid network prudent and commonplace for Alaska's communities and population centers – both large and small.

3.3.3 Alaska’s Remote Islanded Microgrids

Rural and remote parts of Alaska were some of the last places in the U.S. to become electrified, and electric cooperatives played a major role in this development (U.S. EIA). The first rural cooperative was formed in Naknek in 1960 with hub communities such as Kotzebue, Dillingham and others soon following. A few years later in 1967, the Alaska Village Electric Cooperation (AVEC) was incorporated with the specific goal of village electrification in Alaska. Between 1968 and 1985, community-wide power generation was brought to over 200 villages throughout Alaska in the form of remote islanded microgrids. While AVEC was a major contributor to electrification in remote Alaska, it was not the only mechanism as municipally and privately-owned utilities and smaller cooperatives were also formed to supply power to remote communities. In total, at least 92 independent certificated utilities are operating in remote Alaska today including municipally, tribally, cooperatively, and privately-owned utilities.

Although by 1985 remote parts of the state were electrified, they relied almost entirely on imported fuel and diesel electric generators for baseload power. This is still true today and accounts for Alaska's high per capita generation of electric power from petroleum liquids which at 15% is second only to Hawaii in the U.S. (AEA, *PCE*). As a result costs for power generation are very high, especially when compared with parts of Alaska where state government has made significant investments in hydropower and transmission infrastructure. To create some parity in state investment, the Power Cost Equalization Program (PCE) was established in 1984. Through this program funds were appropriated annually and distributed to eligible utilities to pass through as a subsidy to eligible customers. The precise value of this subsidy is based on a complex formula specified in state statute (AS 42.45.110-150) and is tied to the average price in Alaska’s largest electricity markets of Anchorage, Fairbanks, and Juneau. To better ensure long-term funding for the program, the PCE Endowment Fund was created and capitalized in 2001 with funds from the Constitutional Budget Reserve and proceeds from the sale of Four Dam Pool Project assets, and now totals around $1B. Recently, the legislature has approved the use of additional earnings from this fund to capitalize the Alaska Renewable Energy Fund (REF) to continue to invest in the buildout of remote Alaska infrastructure. The PCE program only subsidizes electricity for residential customers and public facilities in remote Alaska communities which accounts for an average of one-third of the electricity consumed in these communities. Commercial and government consumers who are the major users of electric power are not eligible for this subsidy and thus pay the full weighted cost for electric power generation which ranged from $0.08/kWh to $1.80/kWh in 2016 (AEA, *PCE*; AEA, *Status Report*).

Given the high energy costs associated with Alaska's remote islanded microgrids there is a need to find cheaper alternatives for power generation. The quest to reduce the cost of energy for electric power in these grids has led to the wide-spread adoption of renewable energy, often driven by the communities themselves. The economic drivers, technical strategies, technological niche development, and policy implications of renewable integration in Alaska's remote islanded microgrids are the primary focus of this paper.

3.4 Alaska's Energy Portfolio and Economic Drivers for Renewable Energy Development

According to the U.S. Energy Information Agency, Alaska's electricity is generated from 47% natural gas, 39% hydroelectric, 10% petroleum-fired, and 4% non-hydroelectric renewables (U.S. EIA). However, metrics aggregated at the state level do not tell the whole story when an interconnected grid is not present. While hydroelectric, natural gas, oil, and some coal dominate much of the Alaska energy mix, many communities throughout Alaska rely on 100% diesel-based power generation which results in much higher electric energy costs as described previously. In order to abate the high cost of energy in remote communities, Alaska has invested significantly in renewable energy projects (see Figure 3.3), many of which have been funded through the Alaska Renewable Energy Fund (REF), established in 2008 (AEA, *Status Report*).

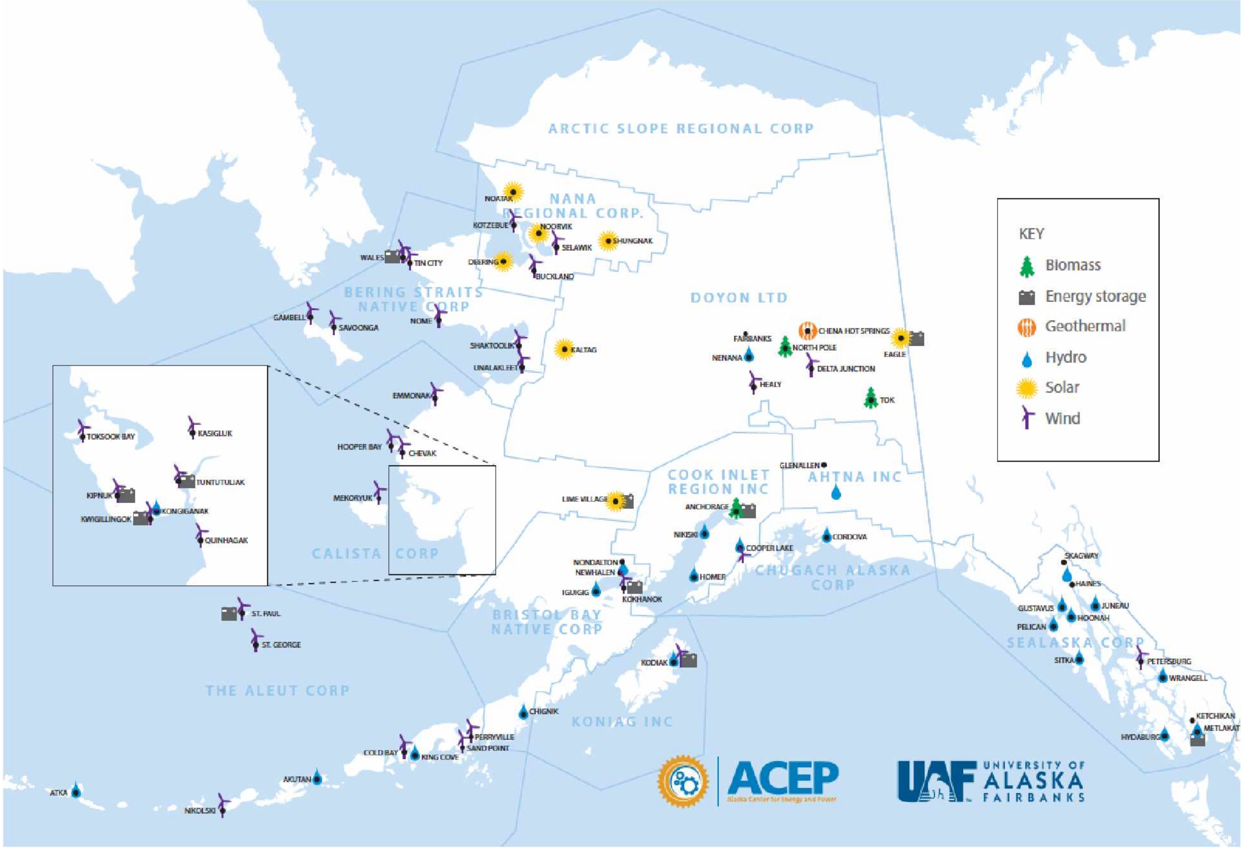

Figure 3.3. Map depicting renewable energy projects developed in Alaska based on technology. Source: Alaska Center for Energy and Power, University of Alaska Fairbanks.

Because this grant fund has prioritized high energy cost areas of the state, many of the projects funded are small community-based systems that contribute little to Alaska's overall energy portfolio but make a substantial difference at the local level.

The non-hydroelectric renewables portion of Alaska's energy portfolio includes more than 60 MW of installed wind capacity consisting of two large wind farms supplying the Railbelt electric grid and 24 smaller community-based systems ranging from 100 kW to 9 MW. Wind turbines are installed mostly in coastal villages of the western and southwestern portions of the state where good wind sites are more prevalent, typically class 3 to 5 (Vandermeer et al.). Due to the relatively high penetration of wind in the small microgrids, wind power often exceeds the local load and is diverted for other purposes such as heat. This, and delay in repairs due to remoteness, results in relatively low capacity factors (for electrical generation) that are typically between 10

Figure 3.4. Biomass boilers use locally harvested wood resources for district heating in Tanana Alaska. Source: Alaska Center for Energy and Power, University of Alaska Fairbanks.

Figure 3.5. A10 kW solar PV array installation on the water treatment facility in Shungnak, Alaska in the Northwest Arctic Borough. Source: Rob Bensin, Bering Straits Development Corporation.

and 25% (AEDG). Solar energy use is increasing rapidly in Alaska ’s western and interior regions (see Figure 3.5), and biomass fuels are commonly used for heating and sometimes small-scale power generation in forested areas of the state (see Figure 3.4). The bulk of energy from solar power is in the summer, when in some cases the sun never sets but travels a circle above the horizon. In many systems, panels are installed as a multidirectional array to achieve a more constant power output. Bifacial arrays also show promise for high latitude installations. Tracking systems have been used to a much lesser extent due to the greater operational complexity and challenges with operation in the harsh environmental conditions. Installing panels in a multidirectional array also contributes to lower capacity factors, often between 5 to 15% over a year, but a more usable power output (Whitney and Pike). Alaska also has invested in emerging technologies including low-temperature geothermal, seawater and ground-source heat pumps, biomass combined heat and power, river hydrokinetics, landfill-derived natural gas, and fish oil as a replacement for boiler fuel. Many of these emerging technology projects have been funded through the Alaska Emerging Energy Technology Fund (EETF), established in 2010 to complement the REF program described earlier in Section 3.3.3. In total, over 70 of the communities in Alaska have developed commercial-scale renewable energy projects (see Figure 3.3).

The primary motivation for adopting renewable energy systems in remote Alaska communities is the displacement of imported fossil fuels—for both heat and power—in order to reduce local energy costs within the constraints of a remote islanded microgrid. Fuel costs comprise roughly half of the cost of power generation in remote Alaska, including the transportation of fuel via barge or by air over long distances (see Figure 3.6). Depending on the remoteness and size of the village, utility fuel costs range from around $0.50 to $2.50 USD/liter (AEDG). Because energy cost is the main driver, potential solutions must be economically viable and replicable. Generally speaking, Alaskans are not interested in pilot or demonstration projects, although incorporating innovative system components is a common practice. Instead, these systems are expected to operate as the status quo, must be self-supporting financially, and robust enough to operate reliably in a remote area with minimal on-site technical expertise. These requirements are somewhat unusual compared to a grid-connected microgrid, including

Figure 3.6. The Kongiganak, Alaska bulk fuel storage facility stores 1,317,200 liters (348,000 gallons) of diesel and gasoline. Source: Alaska Center for Energy and Power, University of Alaska Fairbanks.

some of those in other parts of Alaska. In most cases, when a grid-connected microgrid islands itself or disconnects from the larger grid, it is in response to some sort of external disruption in service and higher costs are acceptable to maintain service within the boundaries of the microgrid. Alaska's remote islanded microgrids need to perform as efficiently and economically as possible at all times because islanded mode is the norm, not the exception.

In addition, because Alaska's remote microgrids are permanently islanded, there is no option for sending excess renewable generation to users in other locations. All of the generation must be used locally or it is wasted, which creates additional challenges with maximizing the economic performance of installed equipment.

3.5 Technical Strategies and Project Examples for Integrating Renewable Energy Systems in Alaska

Alaskans have had to solve the challenge of capturing maximum economic value from integrating variable renewable generation in small grids with very little inertia while maintaining grid reliability. This situation is inherently more challenging than in a larger interconnected grid. Within the framework of a larger grid, as long as the percentage of intermittent resources is relatively low, the system can absorb fluctuations. Achieving this balance becomes more difficult as systems become smaller. In small grids, all typical loads are much greater relative to generation capacity and/or total demand level than in large grids. Starting a 1 kW appliance (e.g., a small electric oven) in a 100 kW system is an immediate 1% load change, which requires ramping of the load-following generation. In contrast, the same 1 kW load is lost in the noise on a 100 MW grid. The same is true with generation. If a wind farm experiences a sudden gust or drop-off in wind speed, the potential impact will be much more dramatic on a small grid, and Alaskans have employed a variety of strategies to cope with this and other grid integration challenges.

Alaska utilities have adopted several general strategies to achieve their renewable energy integration goals such as centralized and distributed dispatchable thermal loads, strategic use of energy storage including flywheels and battery systems, and innovative grid-forming systems. Examples of renewable integration in Alaska are outlined in Table 1 based on data found in the

Alaska Energy Data Gateway or reported to the Alaska Energy Authority under the REF and discussed in the following sections.

3.5.1 Dispatchable Thermal Loads—Centralized

Using a dispatchable load to increase the instantaneous load on a local grid has become a go-to strategy for Alaska utilities, employed in over 20 systems to date. Often, this dispatchable load is located in the powerhouse and connected to an existing space-heating loop that utilizes rejected heat from the diesel generator to heat the power plant and nearby community buildings such as a school, tribal hall, or washeteria. For example, the Alaska Village Electric Cooperative (AVEC) provides power to 58 remote communities across Alaska. These communities are not connected to a regional grid and, with few exceptions, are not interconnected. As in most remote Alaska communities, diesel generators provide the bulk of electrical generation. Eleven of these communities also have wind power installed. The average load ranges between 100 and 400 kW, and the installed wind power capacity ranges between 80% and 170% of the average load. Due to the small size of the communities and the relatively high wind power capacity, most of the utilities have installed a controllable thermal load to absorb fast fluctuations in wind and use on the grid and take power set-points to utilize excess wind power.

In other cases, the dispatchable load is located away from the powerhouse and provides heat to critical infrastructure. For example, in Kotzebue, the dispatchable load is an electric boiler installed in the community's hospital, resulting in the displacement of a significant amount of the facility's heating oil requirements. Due to the success with the hospital, plans are being made to install another electric boiler in the National Parks Service headquarters. Kotzebue has an average load of 2.5 MW and an installed wind power capacity of 3 MW (Janssen).

Dispatchable loads are sized up to 100% of the installed wind capacity, use excess wind power generation, and help stabilize the grid in response to fluctuations in wind power. Note that in most other systems, dispatchable or interruptible loads are primarily used to decrease system load, whereas in Alaska they are primarily used to add load to the grid, which is necessary to maintain grid stability in these relatively low-power-capacity systems with intermittent renewable generation.

Table 1. Alaskan examples of renewable energy integration

		Installed Renewable Capacity				
Community	Ave. Load [kW] 0	Wind Power [kW]	Hydro Power [kW] [25]	Energy Storage/ Thermal Loads	RE Penetration [%] 0	Commission Year(s)
Kokhanok	50	180	-	SC, CT, B	18	2011
St Paul industrial and airport complex	70	675	-	SC, CT	55 0	2006-2008
St. George	77	95	-	CT	36* 0	2015
Deering	80	100	-	CT	33* 0	2015
Mekoryuk	104	200	-	CT	25	2011
Shaktoolik	118	200	-	CT	29	2012
Tuntutuliak	121	475	-	DT	30 0	2012
Kwigillingok	134	475	-	DT, B	50* 0	2013
Kongiganak	139	475	-	DT, B	35 0	2012
Buckland	200	200	-	CT	28* **Error! Reference**	2015
Quinhagak	231	300	-	CT	28	2010
Gambell	232	300	-	CT	24	2010
Savoonga	246	200	-	CT	16	2008
Chevak	287	400	-	CT	32	2010
Kasigluk	339	300	-	CT	19	2006
Toksook	359	400	-	CT	18	2006- 2010
Unalakleet	495	600	-	CT	23	2009
St Mary's and Mountain Village	693	900	-	CT**, B**	30-40* 0	2018-2020
Metlakatla	2,326	-	4,900	B	100	1997
Kotzebue	2,447	2,965	-	B	16	1997-2012
Cordova	3,239	-	7,125	B	68	2019
Nome	3,738	2,970	-	CT	7 0	2010-2013
Kodiak	15,538	9,000	30,475	B, FW, DT 0	100	2009-2012
Chugach Electric*** 0	64,977	17,600	33,300	B, FW	14	2012-2017
GVEA *** 0	142,000	26,400	20,000	B	10	2003-2012

Examples of communities in Alaska with installed renewable energy and the integration hardware that was used. CT = centralized thermal load, DT = distributed thermal load, B = battery, FW = flywheel and SC = synchronous condenser. The year(s) that the wind power, energy storage and/or thermal loads were commissioned is given. Multiple years indicate they were installed in multiple stages.

* Expected value based on the feasibility study performed prior to installation. This is either for systems that have not yet or recently been installed, or where operational information is not available.

** Not yet installed.

*** On the Railbelt electric grid.

3.5.2 Dispatchable Thermal Loads—Distributed

Some communities have installed dispatchable thermal loads in individual residences. This strategy has primarily been pioneered by communities in the Chaninik Wind Group (Kongiganak, Kwigillingok, and Tuntutuliak), in collaboration with the Alaska-based developer Intelligent Energy Systems (IES). These communities have populations of around 450 people and average loads of around 130 kW. At each location, 475 kW of wind power capacity has been installed, over 3 times the average electrical load (see Figure 3.8). These wind systems with distributed electric thermal loads were modelled and assessed for frequency regulation capabilities in (Janssen et al.) and (Janssen).

Figure 3.7. Community member sits in front of the electric thermal stove installed in his home (top) and local workers prepare ceramic bricks for installation in a electric thermal stove in another residence (bottom) in Kongiganak, Alaska. Electric thermal stoves are used to store excess wind energy as heat in ceramic bricks which displaces a portion of oil heating in individual residences. Source: Alaska Center for Energy and Power, University of Alaska Fairbanks.

The high level of wind power means that often more energy is generated than can be used by the electrical load. Since heating oil costs around $1.85/liter ($7/gallon), using excess wind power to heat homes results in significant savings. Between 20 and 30 dispatchable thermal loads are installed in each village. These loads respond to grid frequency, communicate with each other and the powerhouse using a mesh radio network, consume up to 9 kW of electrical power, and store up to 24 kWh of thermal energy in ceramic bricks (see Figure 3.7). The heat is released into the homes on demand by blowing air over bricks and into the room. Households are metered separately, and the power is sold at a reduced rate to be cost-competitive with heating oil. Community members have reported a reduction of up to two-thirds of their heating oil consumption based on interviews with Kongiganak residents conducted by ACEP[16].

Figure 3.8. Five 95 kW wind turbines are installed in Kongiganak, Alaska which help to displace a large proportion of more costly diesel electric generation and oil heating in residences through the use of electric thermal stoves. Source: Alaska Center for Energy and Power, University of Alaska Fairbanks.

3.5.3 Energy Storage

Alaska communities have experimented with varying technologies and strategies for integrating energy storage. Alaska has one of the largest battery systems in the world, installed to

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[16] A video developed by the Alaska Center for Energy and Power Amanda Byrd) documenting the project from the community perspective is available at: https://www.youtube.com/watch?v=90n9ga3SOQQ.

support the Golden Valley Electric Association (GVEA) grid located in interior Alaska. This utility is an electrical cooperative that is connected at the far northern end of the Railbelt electric grid and serves an average electrical load of around 142 MW. The main local fuel sources for power generation are oil and coal. Whenever possible, GVEA purchases up to 70 MW of cheaper electricity from natural gas and hydropower over the transmission line (GVEA). The 40 MW NiCad battery came online in 2003 (the largest capacity storage battery in the world at the time) to increase grid reliability by providing a spinning reserve in case a generator drops offline or there is a fault on the transmission line. In 2017, the battery system responded to 72 events preventing over 280,000 member outages (GVEA). Chugach Electric is another electrical cooperative on the Railbelt electric grid; it has installed a hybrid 2 MW/0.5 MWh Li-ion battery and 1 MW flywheel system to help balance the fluctuations from the 17 MW Fire Island wind farm (Chugach Electric, Chugach Electric Association).

Remote Alaska communities that are not connected to a regional grid have used energy storage systems to stabilize islanded grids and provide spinning reserve to help integrate renewable energy and supply large reactive loads. In total, eight remote communities in Alaska have installed battery systems to help integrate renewable resources and several communities are in the process of procuring systems. Kodiak Electric Association has installed a 3 MW Li-ion battery system to help manage variability on its 9 MW wind farm and two 2 MW flywheels, placed "in front of" the battery to manage inrush currents from a large electric crane in the harbor and to protect the battery from excessive charge/discharge cycles. Combined with a storage hydro asset, these systems have allowed Kodiak Electric Association to achieve close to 100% of annual generation from renewable resources (Desroches)

Some remote communities without access to cheap hydropower use large amounts of other renewables such as wind power to offset their diesel consumption. Use of wind energy requires a source of spinning reserve in the event of a drop in wind power. Alaska-based Intelligent Energy Systems has used 250 kW Li-ion batteries in Kongiganak and Kwigillingok, which have installed wind power capacities of 457 kW and average loads of around 135 kW. The batteries help stabilize the grid and provide spinning reserve; they are even able to operate in diesel-off mode with wind power and support from the batteries. Kotzebue is another example, with a 1.2 MW Li-ion battery to help integrate close to 3 MW of wind power onto a grid with an average load of 1.5 MW (see Figure 3.8).

Figure 3.9. Kotzebue, Alaska has close to 3 MW of installed wind power, a 1.2 MW Li-ion battery, and dispatchable loads including thermal electric boilers, absorption chiller for ice-making, and an organic Rankine cycle generator. Source: Alaska Center for Energy and Power, University of Alaska Fairbanks.

3.5.4 Innovative Grid-Forming Strategies

One of the services provided by diesel generators is actually forming the electric grid. “Grid-forming” means a system is able to control frequency and voltage to support operation of an islanded grid. In order to achieve very high penetration levels of renewable energy and turn off the diesel generators, alternative grid-forming approaches are necessary. In systems with energy storage, an inverter can be used as the grid-forming device (Mueller-Stoffels et al., Mastromauro). The inverter serves to supply power with regulated voltage and frequency that would otherwise be supplied by the diesel generators. This type of system is used in Kongiganak and Kwigillingok where during diesel-off operation the wind turbines supply all the necessary power for the communities and a BESS inverter regulates voltage and frequency using normal droop control methods. However, more innovative droop control strategies exist for inverter-based energy storage systems such as real-time droop curve adjustment and nonlinear droop control. Some inverter-based energy storage systems now have the capability to provide virtual inertia which imitates the rotating inertia of the diesel generator through controlled switching of the inverter (Arani and El-Saadany).

In systems without inverter-based energy storage, other approaches are required to balance generation and regulate frequency and voltage. One of the earliest wind-diesel systems capable of diesel-off operation was installed in 1999 to power an industrial facility on the island of St. Paul. This system uses a secondary load with thermal storage to provide real power balance (i.e., regulate frequency) and uses a synchronous condenser (rotating machine) to provide reactive power (i.e., regulate voltage). Although the synchronous condenser approach is reliable, one challenge is the relatively high loss associated with keeping the machine spinning.

3.5.5 Reliable and Resilient Operation

Reliable and resilient operation of remote islanded microgrids in Alaska is critical to energy security and, most importantly, to the survival of communities. In a power grid, reliability is defined as the ability of the system to deliver quality power to meet the demand of the customers (IEEE, *Guide*), while resilience is defined as the ability of the system to recover from disturbances such as faults, sudden load changes, intermittent renewable generation, extreme weather events, or cyber-related incidents (Alexander, Mayunga). Reliability is generally measured by interruption indices, defined by the IEEE Standard 1366 (IEEE, *Guide*), while resiliency is measured based on the ability or effectiveness of the power grid to reduce the magnitude and duration of disruptive events (Alexander).

In order to maintain high reliability in an islanded grid with no external source of power, the system needs to be more resilient to disruptive events. Resiliency is often achieved through the integration of distributed energy resources, including renewables, energy storage systems, fault-tolerant control systems, underground distribution systems, and ultimately the ability to create sub-islands or backup systems within the grid to support critical infrastructure. For example, in Alaska, the communities of Kodiak and Cordova use underground distribution infrastructure to eliminate overhead line maintenance and mechanical failures due to snow, ice, and wind.

Resiliency of a system can be difficult to place a value on, however, improving resiliency of our electric grid infrastructure may be one of the strongest cases to be made for investing in microgrids in more urban markets where reliable, affordable energy is taken for granted. Microgrids can provide an insurance policy against unforeseen and potentially disruptive events, whether based on natural or human causes. In Alaska, the terms reliability and resiliency are often used interchangeably when it comes to the grid. Reliability and resiliency in Alaska's remote microgrids are directly impacted by local capacity and readiness to adopt new technologies, which is enabled by the existence of a socio-technical framework that supports successful technology transitions and market development.

3.6 Technological Niche Development to Support Alaska's Remote Microgrids

While Alaska's non-integrated electric grid is somewhat unusual among highly developed western nations, it is hardly unique on a global basis. By some estimates, over 500 million people worldwide rely on some form of local diesel-based generation, not including the more than one in five of the world's population that do not have access to electricity at all (IEA, Blechinger et al.). Clearly, an opportunity exists for integration of renewable energy with diesel-based microgrids to displace imported fuels in many locations – so why has Alaska proven to be an early adopter in transitioning to these systems? Socio-technical transition theory can help answer this question.

Socio-technical transitions theory has introduced a framework and a set of conceptual tools that can be used to better understand large-scale transitions and compare them systematically across time and across societies (Schot and Geels). It puts a high importance on the "regime" which is the meso level of societies where institutions, cultures, markets, regulation, and so on provide the context and structure of how people utilize technologies. Along with a focus on "regimes", socio-technical theory also directs our attention to "technological niches" which, for a variety of reasons, can emerge within a regime and act as innovation incubators for new technologies and new micro-technology-societal relations (Schot and Geels, Kemp et al.). Following this logic, Alaska is an ideal technological niche that can serve as an "incubation room" protecting a novelty—in this case, renewably-powered microgrids—against mainstream market selections. Many of the strategies utilized in Alaska and described in the previous section push the limits of existing technology and require a willingness to accept risk and the potential for failures. In fact, Alaska projects have not been uniformly successful. However, when challenges have arisen, corrective measures have usually been implemented quickly and lessons learned diffuse rapidly throughout the community of stakeholders. Most of these experiences are shared through direct communications and state-based conferences, workshops, and organized technology working groups rather than through secondary sources such as publications or reports.

A commonly held assumption is that Alaska has been at the forefront of this technology transition because the state has wealth generated from oil exports that can support capital investment in renewable energy infrastructure. However utilities in Alaska began investing in renewable energy before specific programs and financing mechanisms were in place to support this development, and in some cases before it was even clear that the technology would work in the Arctic region. Moreover, the wealthiest region of Alaska and arguably one of the wealthiest sub-governmental regions in the world, the North Slope Borough, has not invested in any renewable energy systems. Instead, it continues to rely entirely on imported diesel fuel for heating and power generation for the six communities in its region that do not have access to local natural gas. Similarly, Alaska's neighbor to the West, Canada, is a wealthy, developed country that heavily subsidizes its northern territories, but to date, has not invested significantly in renewable energy generation in its remote communities[17]. This is especially relevant because the indigenous populations of northern Canada and Alaska have an interrelated history, share many cultural and linguistic similarities, and experience many of the same underlying challenges related to remoteness and coping with a harsh climate. Therefore, other underlying factors must have enabled Alaska, along with a few other regions such as Australia and the Sakha Republic in Russia's Far East,[18] to develop renewably-powered microgrids while others have not. As such,

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[17] This is changing, as the Canadian Government recently made significant commitments to funding renewable energy development for rural and remote communities, including $220 million over 6 years through the Natural Resource Canada's Clean Energy for Rural and Remote Communities program.

[18] Australia has invested heavily in solar-diesel hybrid systems for its remote off-grid communities and regular transfer of knowledge and lessons learned occurs between utilities and developers in Australia and Alaska. The

these markets represent technological niches in the broader microgrid space, where experimentation and novel ideas can be tested and adopted or rejected quickly.

In section 3.7, we will analyze features of Alaska's technological niche in microgrids. However, it is first important to understand how Alaska's socio-technical landscape has enabled the natural emergence of this technological niche in several important ways, when other apparently similar markets have not. In the rest of this section we explore the underlying policy, institutional, and social frameworks in Alaska that have enabled widespread adoption of renewable-diesel hybrid microgrids.

3.6.1 Low Energy Subsidies

Alaska has low state and local subsidies for imported fossil fuels relative to other regions of the Arctic with a high number of remote communities. For industry and government consumers – customers that arguably have more resources to seek alternatives, no subsidy is available at all. This situation appears to have reduced market distortion and allowed renewables to be cost-competitive with the status quo, which is typically diesel-based generation. The nexus in Alaska of low household per capita income, high delivered energy costs, and high energy demand given the cold climate and seasonal darkness, creates significant incentives for shifting to locally sourced power. In contrast, other markets in the circumpolar Arctic region have employed more aggressive subsidy programs for diesel-based generation, ranging from cross-subsidization (Russia), to postage stamp or fixed regional rates[19] (parts of Canada), to preferential subsidization of industry (Greenland). Where subsidies are high, there is little incentive from either the local community or the utility to incorporate renewable energy technologies. In small island communities such as in the Caribbean, the "lock-in" dilemma permeates through the cost of fossil fuels to the end user (Blechinger). In fact, because a reduction in fossil fuel consumption

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Sakha Republic has also invested in solar energy for its off-grid communities through the regional utility company, RAO Energy Systems of the East, primarily as a hedge against phasing out fuel cross-subsidies by the central Russian government. At this time the largest solar installation above the Arctic Circle is located in Batagay, in the Sahka Republic.

[19] Postage stamp rates are a method of cost allocation where any rate class charge is the same for all consumers, even if the service area is not interconnected and thus actual local costs vary widely. The underlying premise is that all customers jointly develop electricity resources and should equally share in the costs.

almost always corresponds to a reduced subsidy (including in Alaska), there is a real disincentive to incorporate renewables.

3.6.2 Decentralized Energy Markets

A decentralized, private energy market dominated by not-for-profit utilities, including municipal and cooperative (member-owned) utilities, means that decisions are often made at the local level, and community members are directly engaged in decisions that impact their own energy provision. In addition, because these electric utilities are deeply embedded in the fabric of the communities served, they often view themselves as "energy utilities" and undertake programs and policies to reduce non-electric energy costs in the communities they serve, such as capturing rejected heat from diesel power plants to provide space heating to nearby facilities, or in one case using it to make ice to support a local fishing industry (Kotzebue). This holistic approach has been critical to achieving high penetration rates of renewable generation since dispatchable thermal loads are a key supporting strategy.

Figure 3.10. Locally trained technicians reset a tip brake on a 95 kW wind turbine after a strong wind caused the brakes to deploy in Kongiganak, Alaska. Source: Alaska Center for Energy and Power, University of Alaska Fairbanks.

3.6.3 Open Access to Community-Level Energy Data

Energy data for Alaska communities spanning several decades are readily available and easily accessible via the Alaska Energy Data Gateway, including consumer price, fuel and nonfuel costs, and production (Vandermeer et al.). These energy data are available because of the reporting requirements of the Power Cost Equalization (PCE) program. The wide-spread accessibility of this information allows consumers to view data relevant not only to their own community or utility, but also to any other community in the state. This creates a certain amount of peer pressure to keep costs contained, which is especially important because most non-privately-owned utilities in remote areas of the state are exempt from economic regulation and have significantly more flexibility in rate-setting than most larger, more regulated markets (including in Alaska).

3.6.4 A Culture of Innovation

Alaskans tend to view themselves as relatively independent and self-reliant. The residents of most remote Alaska communities are Native Alaskans whose ancestors have lived sustainably in one of the harshest places in the world for millennia. When the nearest hardware store is two plane rides and at least a day's journey away, the incentive to figure out solutions locally is significant. This need has fostered an underlying "culture of innovation" that has been critical to keeping equipment operational over time. For example, local operators are often willing to learn new skills such as maintaining wind turbines installed in their community, and thus have been key to long-term project success (see Figure 3.10). In addition, most projects have been designed and implemented by Alaskans within reach of technical assistance when necessary and appropriate.

As a result of this underlying socio-technical landscape, Alaskans tend to view local energy projects favorably and with a sense of pride because locally developed projects inherently benefit their community and, to a large degree, usually their community alone. Concerns about viewshed are largely non-existent as residents see installed equipment such as wind turbines, as emblematic of local energy independence. For this reason, there is also a significant incentive to keep equipment maintained, and many systems have been in operation for over a decade with incremental improvements often enhancing system performance over time.

While economics remains the key driver in the adoption of renewable energy in remote islanded microgrids, a number of policy, institutions and supportive programs have been critical in creating a technological niche to support it.

3.7 Internal Processes Supporting Technological Niche Development in Remote Islanded Microgrids

Alaska's advancements in remote islanded microgrids provides a valuable case study in renewable energy development for two reasons. First, there is an obvious opportunity to benefit from technical strategies and lessons learned, as described in Section 3.5. However, it is also interesting to understand *why* this technological niche has arisen in Alaska in order to inform similar development elsewhere. According to socio-technical transition theory, a successful technological niche often has a number of characteristics or internal processes that have been identified as necessary for the successful development of a technological niche including a clearly articulated vision, building of socio-economic networks to support the niche, and learning processes at multiple dimensions (Schot and Geels, Elzen et al.). Alaska is no exception. What is especially noteworthy is that this market has grown organically, and mainly has been driven by the utility industry and communities themselves. Supportive policy, institutions, and programs, where they exist, are either a pre-existing landscape feature as described in the previous section, or a lagging indicator formed in response to a bottom-up demand for supportive programs. Nonetheless, the internal processes necessary to support and sustain a technological niche are all present, as described below.

3.7.1 Clearly Articulated Vision – Reducing the Cost of Energy

Most technological niches have a clearly articulated vision that drives niche creation and sustainment. This is often defined by policy, such as California's Renewable Portfolio Standard (RPS) that has led it to become a leader in clean energy investments. This is not the case in Alaska, although the vision is equally clear. In Alaska, the overarching goal is to reduce the cost of energy. In fact, this is such a salient objective for Alaska that the mission of the Alaska Energy Authority is to "reduce the cost of energy in Alaska." Reducing energy costs is also a central theme of each and every energy policy and report that has been written for Alaska, dating to before statehood (McMahon). Because the cost of energy in remote Alaska communities is closely tied to the cost of imported diesel fuel, the most obvious path to reducing energy costs is to decrease reliance on these fuels. It is important to note that the diesel fuel being used in remote communities is almost without exception being imported from outside the state, despite the fact that Alaska is an oil-exporting state. Therefore, the price fluctuates with world oil prices; in addition, the cost of transportation also fluctuates since a significant component of shipping costs is the fuel burned by the tanker or tug. For this reason, renewable energy investment in Alaska is a hedge against price variability, as well as long-term price increases.

3.7.2 Building of Socio-economic Networks to Support Microgrid Development

For a successful technological niche to develop, supportive socio-economic networks, including enabling local policies and programs, are critical. In Alaska, these policies and programs were developed largely through grass-roots efforts by stakeholders organized around a non-profit education and advocacy group called the Renewable Energy Alaska Project (REAP). REAP included membership from the utility industry, environmental groups, consumer advocacy groups, Alaska Native corporations and associations, and the private sector, with the goal of increasing the adoption of renewable energy and energy efficiency measures. Because stakeholders had different reasons for supporting renewable energy and energy efficiency, REAP did not initially connect these goals to any broader socio-economic or environmental objectives. Specific programs that REAP, along with other stakeholders, were instrumental in developing include the following:

1. *Alaska Renewable Energy Fund (REF).* As of 2018, about $270 million in grant funds had been appropriated by the state legislature, resulting in numerous studies and over 70 constructed projects since the fund's formation in 2008. State funds have been matched with more than $152 million from other sources.[20]

2. *Emerging Energy Technology Fund (EETF)*, which complements the commercial technologies funded through the REF, and prioritizes new and emerging technologies. Since inception in 2010, this program has funded dozens of innovative technologies in partnership with UAF's Alaska Center for Energy and Power.

3. *Energy Literacy (AK Energy Smart).* REAP has also led the development and implementation of energy literacy curricula across the state, reaching thousands of students and teachers statewide since 2010.

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[20] Over 300 grants have actually been awarded for multiple phases of project development from resources assessment through construction.

In addition to these programs directly impacting renewable energy development, a number of energy efficiency and weatherization programs were created and funded, although interestingly there is still no mandatory state building code for residential structures in Alaska. More than 50,000 Alaska households have taken advantage of the low-income Weatherization Assistance Program and the Alaska Housing Finance Corporation's (AHFC) and Energy Efficiency Rebate Program. These programs were supported with approximately $640M in state legislative appropriations, and the average energy saving per household has been over 30% (Ord). The Power Project Loan Fund (PPLF) was also developed by the State of Alaska in order to help provide loans for energy infrastructure in communities that cannot qualify for traditional loans.

Network actors supporting Alaska's technological niche development are not confined to residency in the state. Generally speaking, social networks are more likely to contribute to successful technological niche development if they are both diverse and broad. In Alaska, national labs, industry advocacy groups such as the National Rural Electric Cooperative Association (NRECA), the U.S. Department of Energy, the U.S. Department of Defense, and private sector actors have been key to both creating and sustaining Alaska's microgrid niche throughout its incubation phase. These external supportive actors have engaged in a range of activities including research, project implementation, technical assistance, and education.

3.7.3 Learning Processes at Multiple Dimensions

In successful technological niches, learning processes to help iterate solutions are focused not only on first-order learning (the accumulation of facts and data), but also second-order learning that includes applying new knowledge to creating new and better solutions (Loorbach

Figure 3.11. ACEP's Power System Integration Laboratory at the University of Alaska Fairbanks is a 0.5 MW hardware-scale emulation of an isolated microgrid. Source: Alaska Center for Energy and Power, University of Alaska Fairbanks.

and van Raak). The programs and policies that have been developed to support renewable energy development in Alaska have not been static; they have been adjusted and continually improved and iterated upon. For example, the REF grant program initially focused on project construction with limits placed on how much funding could be applied to feasibility studies or resource assessments. Later, the program was adjusted to prioritize funding for early, lower-cost, higher risk stages of project development which creates opportunity to leverage significant private investment to carry projects through to completion.

To complement this shift, REAP is now focusing on new efforts that can continue to support the development of renewable energy within a more budget-constrained state government, such as the creation of a green bank based on the Connecticut Green Bank model. REAP's goal for this bank is to incentivize and leverage future private sector investment in Alaska clean energy projects. REAP has also expanded its original focus on energy literacy through the formation of the Alaska Network for Energy Education and Employment (ANEEE) recognizing the need for building human capacity across all sectors to support successful projects and an educated citizenry and creating a common thread between K–12, post-secondary, and vocational energy education in Alaska (McConnell).

Figure 3.12. The Williams-Hatch 200 kW flywheel (large black cylinder) during testing and development at the ACEP Power System Integration Laboratory at the University of Alaska Fairbanks. Source: Alaska Center for Energy and Power, University of Alaska Fairbanks.

The University of Alaska has also been a key player in supporting learning processes at the technical level. The Alaska Center for Energy and Power (ACEP) at UAF, responding to in-state stakeholder demand, developed a research program in power systems integration supporting high-penetration renewable energy systems and developed a full-power testing laboratory to test technologies and strategies (see Figs. 15-17). The ACEP Power Systems Integration Laboratory shown in Figure 3.11 is a 0.5 MW hardware-scale emulation of an isolated microgrid with 320 kWe diesel electric generator (not shown), 100 kW wind turbine simulator (induction), 100 kW solar PV simulator, 313 kW grid-forming inverter, 540 VDC/1000 Ah lead-acid battery bank, two 250 kW, 200 kVar load banks, and 1000+ channel custom data collection system. This testing lab has been important for identifying the most appropriate approaches to achieving high contribution renewables or diesel-off operation. Testing of developing energy technologies for isolated renewable energy-diesel microgrids in the lab included the Williams-Hatch 200 kW flywheel energy storage system (Figure 3.12). Two of the flywheels were later used to levelize demand swings from draglines in a mine in northern Quebec. The Oceana 25 kW in-river hydrokinetic turbine (Figure 3.13) was tested in the field and in the laboratory. The laboratory set up consists of a large steel drum filled with water (cooling) which houses the electrical generator (under yellow support beam), a right angle motor drive (blue box on top of drum) to spin the generator with a variable frequency drive (far left foreground), inverter (light grey cabinet in middle of rack), and a Li-ion battery pack (black box on floor in bottom center). The hydrokinetics turbine is still undergoing development. ACEP also co-hosts the bi-annual Rural Energy Conference with AEA, which brings together utility operators, developers, and community leaders from across the state to share lessons learned in managing and developing energy systems. This event, one of the largest energy conferences in Alaska, compliments several technology-specific working groups managed by AEA, as well as smaller topical workshops hosted by ACEP.

Finally, utilities themselves – sometimes in partnership with state or federal agencies – have developed systems and processes to support community and regional energy planning as well as long-term project maintenance, such as a circuit rider program that allows skilled technicians to assist multiple communities in technology-specific repairs and maintenance.

The creation of policies, institutional frameworks, and training programs to support the integration of renewables in Alaska's microgrids, coupled with economic drivers and technical strategies, has resulted in a knowledge base that effectively supports the development of a technological niche for rural and isolated grids on a global scale. To foster renewable integration in rural and remote microgrids and develop a market worldwide, it is important to document the successes and failures of renewable integration in Alaska.

3.8 Lessons Learned

Socio-technical transitions, by definition, are two-fold: they involve both technological innovations and social systems change. The Alaska case provides both technical and policy lessons. As a result of experimentation to support a transition to local energy resources, Alaska has developed significant experience and expertise in integrating a high proportion of renewable resources into microgrids, especially in remote islanded applications. Evolving technical strategies and lessons learned from the multitude of projects that have been completed in Alaska over the past two decades are relevant to other markets, particularly in developing areas of the world with similar challenges related to remoteness, or other related applications such as forward deployments for military activities where fuel resupply can come at a high price (Whitney). Alaska’s policies and programs have similarly evolved over time, and also offer useful insight into how to enable and support successful market development.

Figure 3.13. The Oceana 25 kW run-of-river hydrokinetic turbine generator during field testing (top) at the Alaska Hydrokinetics Energy Research Center's Tanana River Hydrokinetics test site and laboratory testing (bottom) at the Power System Integration Laboratory at the University of Alaska Fairbanks. Source: Alaska Center for Energy and Power, University of Alaska Fairbanks.

The following sections covers important lessons learned in technical design, environmental considerations, and policy and program development based on the Alaska case study.

3.8.1 Technical Lessons Learned

Over time, Alaska's microgrids have combined various types of energy storage, grid-forming inverters, synchronous condensers, and controllable thermal loads in order to maximize their use of renewable resources. Off-the-shelf products and solutions rarely fit the needs of Alaska communities without modification. The technical successes and failures of renewable energy integration strategies in Alaska's remote islanded microgrids has resulted in a number of lessons learned including:

1. *Consider impacts to diesel generation.* While integrating renewables into diesel-powered microgrids generally results in an increase in overall system efficiency, it can also significantly impact the operation of the diesel electric generator and the stability of the system. Diesel electric generators are designed to operate at a minimum load that is typically 20–30% of rated power capacity. Integrating high penetrations of renewables can reduce the load on the diesel generators which adversely affects their ability to stabilize the grid and increases their maintenance costs. If higher loads are maintained on the diesel generators, then the renewable energy penetration is reduced resulting in lower displacement of diesel fuel and an overall less efficient system.

2. *A holistic approach to energy management.* It is useful to take into account all of the energy needs of the community and develop a system that can address as many of these as possible. For example, in Alaska dispatchable thermal loads are frequently used to help stabilize the grid and take advantage of excess generation. In other locations loads associated with chilling or electric vehicle charging offer similar opportunities for maximizing energy utilization.

3. *Robust and proven designs are preferable.* Given the remoteness of many sites and the lack of available onsite expertise, robust and proven designs that are less likely to experience failures and can be operated by the local workforce are preferable. Full-scale microgrid testbed facilities, such as the one at the Alaska Center for Energy and Power, play a critical role by allowing new technologies and solutions to be fully vetted before deployment in a remote location. By testing equipment and strategies in a controlled laboratory environment that emulates a remote microgrid at full power levels, the rate of success of projects once they are deployed in the field can be improved significantly.

4. *Grid-forming energy storage solutions allow for cost-effective high penetration of renewable energy.* Having an alternative to diesel generators that can form the grid (usually energy storage systems) allows for smaller capacity diesels, and sometimes diesel-off operation, and maximizes the use of the renewable energy. It also minimizes the negative impact that high penetrations of renewable energy can have on the diesel generator as discussed in Section IV. In order to maximize the benefit and minimize costs, the energy storage system needs to be properly sized, specified, and operated. To

accomplish this, the Alaska Center for Energy and Power developed the MiGRIDS open source tool modelling tool[21].

5. *Ensure equipment is appropriate for environmental conditions.* Engineering challenges related to equipment installed in an Arctic environment include: mechanical failures of wind turbines due to high winds, icing of blades, and denser (cold) air; geotechnical challenges of erecting wind turbine towers in permafrost laden soils; coverage of solar photovoltaic systems and overproduction from these same systems due to cold (improving efficiency) and albedo effects; debris for in-river hydrokinetics applications; and large seasonal variation in renewable generation. It is important to ensure equipment has been tested to withstand the particular environmental conditions in which it will operate, and that special attention is given to warranties to understand who is responsible for incurring the costs for repairs, including travel and shipping.

3.8.2 Policy Lessons Learned

In addition to technical lessons learned, there are a number of policy-related lessons that could help inform successful programs elsewhere. Surprisingly, State of Alaska energy policy has been largely absent, or a lagging indicator in cases such as the creation of the REF as discussed in Section II.C. For example, Alaska has no RPS or clearly defined targets or strategy for increasing renewable energy development. However, at the local level, many communities or individual utilities have developed their own goals for incorporating renewable energy into their generation mix. In addition, stakeholder advocacy has played a central role in driving the development of supportive programs, most notably through REAP. No two markets are exactly alike, and Alaska has some unique landscape factors as described in Section 6 that likely have contributed to market development, but we can offer some general lessons that are likely transferrable to other places.

1. *Address the underlying issues first.* Often, high energy costs are due at least in part to inefficient housing or appliances. Addressing these issues through weatherization and energy efficiency programs are often very cost-effective and can be implemented quickly.

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[21] MiGRIDS is available at: https://github.com/acep-uaf/MiGRIDS

2. *Energy literacy is important.* Basic energy literacy is important to helping people understand how they can reduce their energy costs by taking advantage of available programs and services. Programs such as the Alaska Energy Smart program are broadly available and tailored to Alaska-specific issues. While targeted to the youth population, the information is often broadly disseminated across communities.
3. *Community Involvement is Critical to Project Success.* In Alaska, projects are often developed from the bottom up, with the communities themselves driving development. Within communities, there are many different stakeholder groups that are not always aligned in their motivation and perspectives around energy development. Developing a robust energy plan for the community and the region is important to defining shared priorities and a strategy for future development. In Alaska, the Alaska Energy Authority has played a leading role in supporting communities in developing these plans.
4. *Consider project benefits holistically.* It can be difficult to make small projects "pencil out" when taking a traditional approach to cost-benefit analysis. It is important to consider broader societal benefits, such as keeping more resources in the community, creating jobs, and addressing energy costs beyond electricity. These broader benefits are often difficult to quantify but can be very important to long-term project success.
5. *Tailored financing and funding opportunities.* Financing is often a major barrier to project development, and small communities often have limited access to capital through traditional lending sources. Programs such as Alaska's Power Project Loan Fund are important for providing financing mechanisms tailored to the specific market (Holdmann et al.). Grant programs are most successful when they target early, high risk stages of project development first.

3.9 Conclusions

The high cost of fuel has pushed the integration of large amounts of renewable energy in over one-third of Alaska's remote islanded microgrids. While economics was the main driver, local policies, institutions, and culture played a key role in creating a technological niche where these projects could be successful. As a result, innovative technical solutions were developed that allowed a much higher than normal penetration of renewable energy in these remote islanded microgrids that in some instances can be powered by 100% renewable energy.

Many of the technical challenges associated with integrating a high penetration of renewable energy into a remote diesel microgrid are similar regardless of geographical location. With some modification, many of the technical solutions implemented in Alaska could also be implemented in similar systems elsewhere.

While the technical challenges may be similar, the social, institutional and policy frameworks in which remote diesel microgrids exist globally will widely differ. Socio-technical transition theory can be used to understand where these frameworks encourage a transition to a high penetration of renewable energy, and where they discourage it. In Alaska, a clearly articulated vision, the building of supportive socio-economic networks and learning processes at multiple dimensions created a technological niche that encouraged a transition to a high penetration of renewable energy. It is worth exploring whether these apply to other regions of the globe.

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Chapter 4:

Findings and Conclusions

This thesis makes important empirical and theoretical contributions to scholarship on energy transitions, and its sets the foundation for further lines of scholarly inquiry. These contributions also provide important lessons and insights for regions across the Circumpolar North and for regions far from, especially the developing world where more than 2 billion people have no electricity or are electrically islanded.

In regards to empirical contributions, five key findings emerge from this study. First, high electricity price and cost driven by global market prices have created incentives to transition to non-imported fuel sources. While impacts of climate change and environmental concerns are secondary factors, economic factors appear to be the overwhelmingly primary driver to transition to renewable energy resources in the north. Second, utility structure and deregulation in Alaska have permitted many solutions to be propagated, while data accessibility has helped identify the most robust solutions. This explains much of the technological diversity that has arisen in Alaska. Each utility has taken slightly different approaches to integrating renewable energy based on resource availability and interests and acumen of personnel; however data accessibility has supported robust knowledge sharing and interaction among stakeholders to help identify and promote the most effective solutions. Third, relatively low subsidies for status quo (diesel) has limited market distortion and enabled a robust market for renewables *despite* few policy tools. Alaska is somewhat anomalous in that there has fairly aggressive investment in renewable energy systems, despite minimal policy support at the state level. This seems to be largely driven by economics, as relatively modest subsidies have made innovative solutions affordable at current price structures. Fourth, while state policies lack specific targets or goals, numerous supportive programs have been developed to sustain Alaska's niche microgrid market, though many have historically been grant-based. These programs seem to have been successful in developing a self-sustaining market as the level of activity has not decreased, despite significant declines in available funding. Finally, socioeconomic and demographic factors have played a role, including project champions and community capacity as important supportive factors. Most, if not all projects that have been successful have had strong support at the local level, and in many cases, that local support has centered on one or a small number of key community leaders. These leaders are rarely technical experts, but rather individuals invested in the long-term success of the community. Supporting these local "projects champions" may be key to successful project development elsewhere.

Why does this matter? Alaska is an early adopter and technology niche market in using renewable energy to displace imported fossil fuels for remote, islanded microgrids. As a result, there have been a number of interesting technological approaches and a high degree of experimentation, which have collectively honed in on several best practices. Based on this experience, there are exportable lessons to be learned from the development of microgrids in Alaska that could benefit future development not only in the Arctic, but in other areas of the world that has similar challenges related to small populations, high cost of energy, and high reliance on imported sources of energy. In addition, as grid reliability becomes an increasing concern in even our urban centers, microgrids are gaining in popularity as a method of increasing grid reliance and ability to recover from unexpected events whether these are man-made, or related to extreme weather impacts.

This thesis also makes important theoretical contributions. As the second chapter demonstrates, historical context, including an understanding of the history of state building within a particular jurisdiction, is important to achieving a full understanding how nations cope with major socio-technological transitions, including switching to renewable sources of energy. State-building matters. Socio-technical transition theory, like any theoretical approach has limitations. It has been powerful in understanding universals in energy transitions, but not energy transitions universally. Alone, it cannot explain the high variation within and across highly industrialized countries that are exemplified in the Arctic states. The case study of Alaska shows that state-building theory is an important tool to understanding patterns for energy transitions, the institutional legacies of these patterns, how these may shape the future energy transitions of the 21st century.

As the thesis outlined, the history of electrification in Alaska in the context of national priorities and within broader geopolitical landscape is important context to understanding how Alaska has progressed with development of renewable energy over the last two decades. State-building helps explain the pattern of electricity sector development. Electrical grid development in Alaska and indeed all the eight Arctic states provide a critical check on theoretical approaches to understanding energy transitions. All eight Arctic states are among the richest and most economically advanced nations on Earth. All eight states have been on the forefront of technological innovation over the past century and have been among the world's largest consumers of electrical energy. If we should see common and robust electrical grid buildout anywhere, we should see it here. But, we do not. What we see instead is a high degree of variability of electrical grids connection on a territorial basis. State-building theory provides the conceptual tools to explain why this is so and underscores the importance of understanding political institutions as critical and essential variable shaping the outcomes of energy transitions with their logic, independent and distinct from economic or technological variables. If we ignore political institutions and processes of state-building, we will fail to have a complete understanding of energy transitions at best and risk to have erroneous explanations at worst.