Introduction

Research into the cause and effect of increased thawing in permafrost areas and rising sea level has led to the conclusion that without extensive decrease in carbon emissions, future generations may be presented with severely different global conditions (IPCC, n.d.). This condition could make populated areas uninhabitable and leave others with limited possibilities for agriculture and other activities vital for human survival.

However, the increasing melt rate of Greenland’s glacier may present an opportunity to harness more energy for electrical generation than is currently being done today. Such a project could prove beneficial for Greenland’s economy and may possibly attract the interest of various energy demanding industries, which may in turn present various employment opportunities and infrastructure investments for the benefit of the indigenous people of Greenland.

Hans Stauber studied the potential of the glacial meltwater of Greenland’s glacier in the 1930’s (Alther et al., 1981). His study outlines the methodology for harnessing the meltwater by using the elevation difference of the glacier, utilising the Nunataks for creating reservoirs and transporting the energy.

This research paper will focus on the feasibility of a large-scale hydropower project in Greenland, presenting examples from Iceland and Norway, and paying careful attention to the current global conditions, modern applicable parameters, and the potential benefits of large-scale hydropower investments in Greenland.

Hydropower Background

Since the development of the Francis, Pelton and Kaplan turbine, hydropower has been a vital contributor to economic growth. The world’s first large scale alternating current hydropower plant was built in the USA. It harnessed the energy from the Niagara Falls in New York, coming into production in 1895. By the beginning of the 20th century, hundreds of small hydropower plants were installed across the world. In 1940, the United States accounted for around 40% of the electric generation after completion of The Hoover Dam and the Grand Coulee dam finishing in 1942. The Itaipu dam in Brazil was finished in 1984 and was the world largest hydro power plant until the Three Gorges dam power plant was finished in 2012 (“History of Hydropower”, 2018) (Bank, 2013) .

Hydropower in Norway

The power production in Norway is divided among hydropower, wind, and thermal power, with the vast majority coming from hydropower. The total annual energy production on an average wet year is 151 trillion watt hours (TWh), with hydropower production at 90%, wind power around 7.5% and thermal power producing the rest. Currently, Norway has around 1671 hydropower plants, 52 wind power plants, and 30 thermal power plants across the country, with the majority situated along the coast (NVE, 2019). Norway’s history of producing electricity by hydropower dates back to the 19th century as plants were built to energize chemical and metallic production. This heralded the start of economic and technological growth in Norway. The majority of the hydropower plants built during the 20th century are still running today, with only maintenance and minor modifications required. The oldest hydropower plant currently running is Hammeren which was built in the year 1900.

Hydropower in Iceland

Iceland’s terrain and position offers the unique opportunity of being able to utilise both geothermal and hydropower energy sources. Geothermal energy contributes 28.9% of the total energy generation, hydropower contributes 71%, and 0.3% are gained from wind energy (NEA, n.d.). Iceland’s location on the Mid-Atlantic ridge offers geothermal possibilities, but not without some complications. Iceland has multiple active volcanoes and a history of violent eruptions which have had severe effects both inland and abroad. For example, the Eyjafjallajökull eruption in 2010 disrupted a large portion of the air traffic in Europe.

In 2015, Iceland’s electricity generation was 18.798 GWh (GI, n.d.), but a recent study by David Finger points out that there is still unexploited hydropower potential in Iceland (Finger, 2018).Hydropower electrical energy in Iceland began in the 20th century when the main power station located in Elliðaár was built in the year 1921. This power station is still in partial use today. A further complication is that Iceland’s glaciers cover around 11% of the land, with Vatnajökull covering 7900km2 (NI, n.d.). Because Iceland’s glaciers hold a mass of 3600 km3, they could raise the global sea level by around 10 mm if melted (of Earth

Sciences, 2020).

Hydropower in Greenland

Greenland is the largest island in the world. Located 740 km from the North Pole, with Kap Farvel having the same latitude as Oslo. Greenland's total area is 2.166.086 km2 with 81% permanently covered by icecap (Nunatsiaq, 2016). Buksefjord, Greenland's first hydropower plant was constructed in 1993. Today, Greenland utilises five hydropower plants which supply six towns with electricity used for domestic use and heating (Nunatsiaq, 2016). Greenland relies partly on imported oil, even though they are increasing self-production and utilising heat from waste incineration. The Co2 emission of Greenland in 2013 reaching 555Kt with 94% of the emission originating from energy consumption (Nunatsiaq, 2016).

Indigenous People

Greenland is part of Denmark's kingdom, but has had a self-government since 2009 and "has had exclusive responsibility regarding extractive projects on the territory and in surrounding maritime zones" (Johnstone and Hansen, 2020). A great deal of attention is currently being paid internationally to Greenland's pursuit of independence from Denmark as a sovereign state (Johnstone and Hansen, 2020). The Indigenous people of Greenland view extractive industries as a means to increased stability, improved living conditions, and good employment opportunities which among other factors could lead to an increased standard of living. From an outsider's perspective, enabling extractive industries in Greenland is a stepping stone towards independence from Denmark. But as the study depicts, the Indigenous people place more importance on the benefits of increasing economic independence by allowing the extractive industries, rather than seeking political independence. "Exploration and exploitation of natural resources is known to contribute to major changes at individual, community and national levels" (Johnstone and Hansen, 2020). Greenland's Mineral Resources Act states how developers are required to conduct an environmental impact and social impact assessment (SIA). The government often requires a social sustainability agreement, i.e. Impact and Benefit Agreement (IBA), to promote equitable development. "The provisions in the Mineral Resources Act on EIA and SIA are brief, but are developed further in a number of topic-specific Guidelines. Although the latter are not legally binding in a formal sense, it is unlikely that the government will grant a license in cases where the developer has not met, if not exceeded the requirements in the Guidelines." (Johnstone and Hansen, 2020).

Technical details
Greenland's glaciers theoretical energy potential is, according to the Geological Survey of Greenland (GEUS), 470 Twh per year. "This estimation gives results far from the real available hydropower energy, which can be applied only when the water comes into hydrological catchment areas where hydropower plants in reality can be constructed" (Nunatsiaq, 2016).

Figure 1: Hydropower potential locations in west Greenland (Højmark, 1996). "Blue areas indicate hydropower basins, black squares possible localities for hydropower plants and black circles are observation localities for water flow estimates operated by GEUS. (Geological Survey)" (Nunatsiaq, 2016).

An estimate based on multiple years of research work determines 16 catchments areas with a combined energy of 14 Twh in the western of Greenland (Nunatsiaq, 2016).

Energy Exportation
Exporting the energy from Greenland could be achieved by hydrogen generation through electrolysis. Additionally, ammonia could be used as an energy carrier with water and air combination (Alther et al., 1981).

Figure 2: Distance between Nunavut and Nuuk (Nunatsiaq, 2016).

With distances between countries contributing greatly to the cost of an energy exportation project, there are locations within reach of Greenland which may present opportunities to transfer electric energy to other countries. Studies reveal how energy could be exported to the west, to Nunavut in Canada since Nunavut is only 800 km from Greenland's capital, Nuuk. Currently Nunavut has a population of 23,000 people and requires more electric energy (Nunatsiaq, 2016). Additionally, the western part of Iceland could possibly utilise electric energy from Greenland (Nunatsiaq, 2016).

Methodology

A study from 1981 presents a methodology for harnessing the meltwater of Greenland by utilising electric power transportation stations with reservoirs at different elevations.

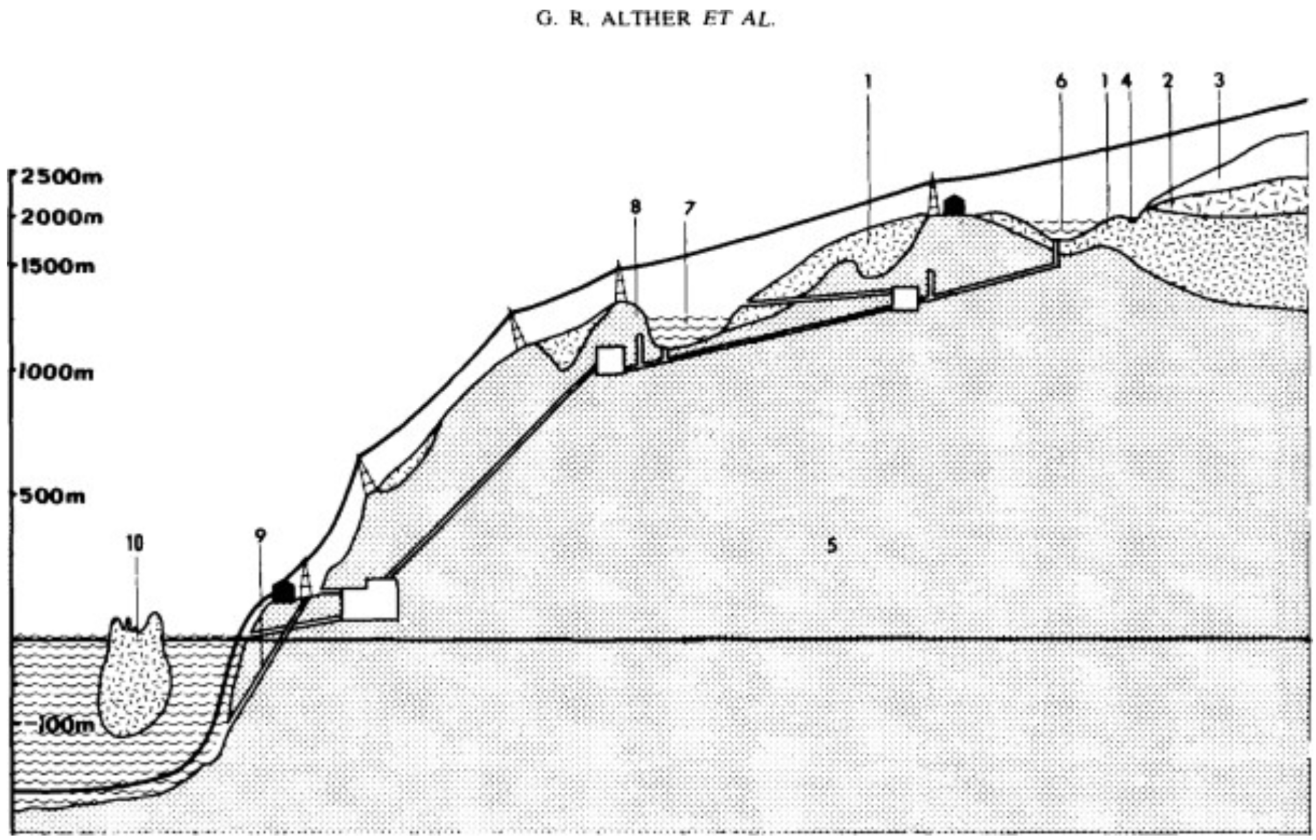

Figure 3: “Schematic illustration of a glacial power station in Greenland. 1 = Inland ice. 2 = Firn. 3 = Snow cover. 4 = Melt water channel. 5 = Bedrock. 6 = Upper reservoir. 7 = Lower reservoir. 8 = Natural dam (Nunataks). 9 = Pipe shaft. 10 = Iceberg.
(After kollbrunner and Stauber, 1972.)” (Alther et al., 1981).

Perpendicular channels which are cut into the bedrock guide the meltwater to the reservoirs with minimal loss. From the reservoir flows water through pipelines to a lower reservoir (7), where the natural dams (Nunataks) serve as a dam wall (8). “These Nunataks provide a natural drop of some 2000 m from the terminus of the ice cap to sea level.” (Alther et al., 1981). Which in turn is guided through pressure pipeline and turbines.

Natural forming reservoirs may be created by distributing coal dust or other heat absorbing material to enable the ice in that area to melt faster than normal during the summer months; this procedure would only serve to initiate the process. This formation could be enlarged and altered as needed and channels made as required by each reservoir at any given time (Alther et al., 1981).

Hydropower Development in Norway

The integration of hydropower in Norway had a large impact on the country’s economic development. The first hydropower plant in Norway, was built in Hamn, Norway in 1882, where the power was used by a nickel production plant (Vasskrafta, 2019a). In the late 19th century and well into the 20th century, the chemical industry developed where hydropower energy was available, mainly because long distance energy transmission was not feasible at that time. An industrial company named Borregaard was established in 1889, to produce biochemical products. Borregaard later developed the hydropower plant Borregaard kraftverk in 1898. This was the beginning of multiple other industrial developments, such as Norsk Hydro, the largest industrial establishment and hydropower developer. Norsk Hydro was the first company to develop synthetic nitrate fertiliser and used hydropower energy and water for this production. In 1907 Norsk Hydro developed a hydropower plant in Notodden named Svelgfoss 1, which was Europe’s largest hydropower plant and the world’s second largest hydropower plant at the time. By 1911, Norsk Hydro had completed Vemork hydropower plan, the world’s largest hydropower plant with an installed capacity of 108MW (“Kraftverk: Vemork”, 2016). Furthermore, the development of Solbergfossen hydropower plant had excessive technological and historical importance for Norway. It was developed during the First World War after the completion of the hydropower laboratory at the Norwegian University of Science and Technology (NTNU). The cooperation among contractors, developers, and NTNU managed to increase the efficiency of the turbine by more than 10% using Norwegian contractors, thus ensuring the country’s competence comparable to an international level. This is historically important as construction started in 1913 and finished in 1924, a time period when political forces wanted to use and develop Norwegian technology (“Kraftverk: Solbergfoss”, 2016) (Vasskrafta, 2004) (NTNU, 2019).

Development of Glomfjorden kraftverk, a hydropower plant using two of what was in 1920 the world's largest turbines, laid the fundamentals of an important industry in Glomfjorden and also bureaucracy in Norway. The project development contributed to the decision to develop NVE, the Norwegian regulators of hydropower ("Kraftverk: Glomfjord", 2016) (Vasskrafta, 2019b).

Hydropower Development in Iceland

Iceland's incentives to create its first large scale hydropower plant came in the 1960's when the company Alusisse showed interest in constructing an aluminium plant in Iceland (Energy, 2019). Afterwards when Iceland had been attracting high energy demanding industries, the national power company of Iceland was established (Landsvirkjun). Its first task was to administrate the construction of Búrfell hydropower plant which came into operation in 1969 with the capacity of 210 megawatts (MW). Iceland has since become a large aluminium and ferrosilicon exporter, with increase in demand through the years, which in turn has increased the energy need and prompted further the construction of more hydropower plants (Energy, 2019). The effects of the construction of hydropower plants to satisfy the industrial energy demand has had a large effect on Iceland's infrastructure, both economic and social, with the construction of the plants and employment from the industry.

Incentives for Greenland

Using Norway and Iceland as an example, there are two proposals for Greenland to proceed with its hydropower development:
Generate interest from high energy demanding industries by proposing access to sustainable clean hydropower electric energy with a comparable geological location as Iceland. Private equity firms and industries could be involved in the construction of a large scale hydropower plant.
Construct a hydropower plant with the aid of Denmark for the future prospects of energy exportation, providing the necessary foundation for large scale industries to operate in Greenland.

Greenland could benefit greatly in terms of economic development and social effect. Greenland could possibly satisfy all of its energy demand and become completely carbon neutral. In the near future a shift in emphasis of the transportation and mobility sector is almost certain. Such development and the ever growing demand for industries to implement sustainability in their manufacturing process, will broaden the market for clean energy and Greenland could be in a position of being able to supply sustainable electric energy for industries willing to offshore their operations to Greenland. It can be said that Greenland certainly has the building blocks to reach similar development as Iceland by harnessing the glacial meltwater and being able to provide sustainable energy for many years to come. Metallurgical processing, used in industries such as copper electrolytic refinement and aluminium, could utilise the meltwater generated electric power (Alther et al., 1981).

International collaboration

For a project of this caliber, international collaboration would be necessary for design and supplying equipment such as excavators to Greenland. With such a collaborative effort the project should be achievable in 15-20 years (Alther et al., 1981). According to The cost estimate for the power scheme would be around \$275 – \$320 per kilowatt (Partl, 1978). With considerations to transportation facilities as gas pipelines or AC/DC rectifiers / inverters, the additional cost could amount to \$220 – \$430 per kilowatt hour. Disruptions to local population would likely be minimal, but would be different between energy harnessing locations since the population is fairly small and dispersed in comparison with Greenland’s geographic size. The effect on the environment should be minimal (Alther et al., 1981). If H2 spillage did occur, such as by the bursting of gas pipelines, the effect on marine life would likely be insignificant.

LCA of Industrial Project

As a requirement to uphold Greenland’s clean reputation and to fulfil environmental require- ments regarding emission standards and pollution, industries that show interest in relocating to Greenland should do a full life cycle analysis (LCA). This would need to be approved by Greenland’s and Denmark’s governments and abide to their requirements.

Social Economics Benefits in Norway

Electricity has increased the welfare of the Norwegian population. The development of effective transmission lines enabled industries to grow and make electricity more available. In the 1920's the majority of people living in Oslo had access to electricity, but in the 1940's, 80% of the entire Norwegian population had gained access to electricity. Since the Second World War and up to the 1990s, there have been large investments in the electrification of Norway and in 1965 nearly every house had access to electricity. This development has been a driver for the continued economic growth and increased welfare in Norway (norske leksikon, 2020).

Social Economics Benefits in Iceland

Since the 1960's Iceland's population has grown from 175,000 to over 340,000 (Worldometer, 2021). Its gross domestic product (GDP) has increased from 1400$ to over 66000$ per capita (Commons, 2019), with a large portion in direct relation to the industrial development that followed the construction of the hydropower plants and the accessibility to electrical energy. The infrastructure of Iceland relies on the energy-demanding industry and seldom has any single industry had such an impact on one country. With employment opportunities and increased quality of life, population is able to grow and other industries can emerge.

Discussions

"Climate change will further exacerbate the unique applied glaciological challenges associated with the proglacial mining described above. Rising atmospheric temperatures are expected to increase the meltwater runoff from the ice sheet by a factor of five by the end of the century" (Colgan et al., 2015). Greenland's glacial meltwater hydropower potential could become more feasible as the global conditions become more severe due to global warming. Emissions from electricity generation using coal and other environmentally polluting methods may be decreased substantially by harnessing Greenland's glacier meltwater. This project might prove to be much more beneficial than anticipated as we witness the growing demand for sustainable electric energy.

Conclusion

As Greenland's glacier melts and opportunities emerge for hydropower, it is these authors' opinion that Greenland should proceed with large-scale projects that keep the best interests of the Indigenous people of Greenland in mind and, at the same time, create an incentive for industries to relocate their operations to Greenland. This may in turn stimulate the economy through employment opportunities and provide Greenland with the incentive to invest in its infrastructure to accommodate this development. With the hydropower developments in Norway and Iceland, and with Greenland sharing similar geological location as Iceland, Greenland should consider this opportunity while it is still a possibility.

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