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FEASIBILITY OF INTERCONNECTIVITY OF GEOTHERMAL ENERGY FROM NEVIS TO OTHER ISLANDS IN THE CARIBBEAN REGION

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ABSTRACT

This research paper examines the feasibility of submarine interconnection for electricity utilisation based on geothermal energy in the Caribbean region. The Caribbean potential for geothermal is extensive as several islands in the region are volcanic with visible high-temperature manifestations. The Eastern Caribbean geothermal potential is estimated at 850 MWe. Several islands in the Lesser Antilles are presently pursuing geothermal energy for electricity generation, such as Nevis, St. Lucia, Dominica, Montserrat and St. Vincent. However, to date Guadeloupe is the only island in the region with an installed capacity of geothermal energy, 15 MW in all. The island of Nevis is actively pursuing geothermal energy with its latest exploration well drilled in March 2018. The geothermal resource on the island is deemed commercially viable with the reservoir capacity estimated at 100-400 MW. The island of Nevis intends to develop a 10 MW geothermal plant, which will cover the island's peak load, thus making the electricity production in Nevis 100% renewable. Additionally, in the future the island has the ability to harness the surplus resource for electricity to be exported to other islands in the region. This study will mainly focus on the possibility for Nevis to interconnect to Puerto Rico as the islands are ideally geographically located. Additionally, there is a great possibility that the electricity market in Puerto Rico will be encouraged to include different renewable energy sources after hurricane Maria destroyed most of the infrastructure on the island. Interconnectivity of geothermal energy has been discussed for several decades in the Caribbean, but is yet to be manifested. There are, however, several regions in the world that have successfully interconnected electricity through submarine cables, such as Great Britain and Norway. The financial model used in this research determines at what cost the island of Nevis must produce geothermal energy to have a financially viable submarine interconnection project.

1. INTRODUCTION

The island of Nevis is volcanic and measures 93 km^2 in area. It is a part of the federation of St. Christopher (St. Kitts) and Nevis located in the Leeward Islands. Nevis Peak is a mountain, located in the centre of the island and stands at 986 m. The main industry on Nevis is tourism followed by the offshore banking sector.

In the last two decades, the island has led the way in the Caribbean with geothermal exploration. In 2007, the Nevis Island Administration (NIA) began the journey towards geothermal energy. A twenty-five year Power Purchase Agreement (PPA) was signed with Windies Indies Power Holdings Ltd (WIPH) to explore and develop the geothermal resource on the island. Three sites were identified for exploration drilling, Spring Hill (N-1), Jessup (N-2) and Hamilton (N-3), all shown in Figure 1. The results of the exploration drilling showed all the sites were within a high-temperature field with temperatures above 232°C, at depths within 899 m (Kelly, 2012). Appropriate temperatures, pressures and flows were found at N-1 and N-3. The geothermal fields were, however, not further developed by WIPH.

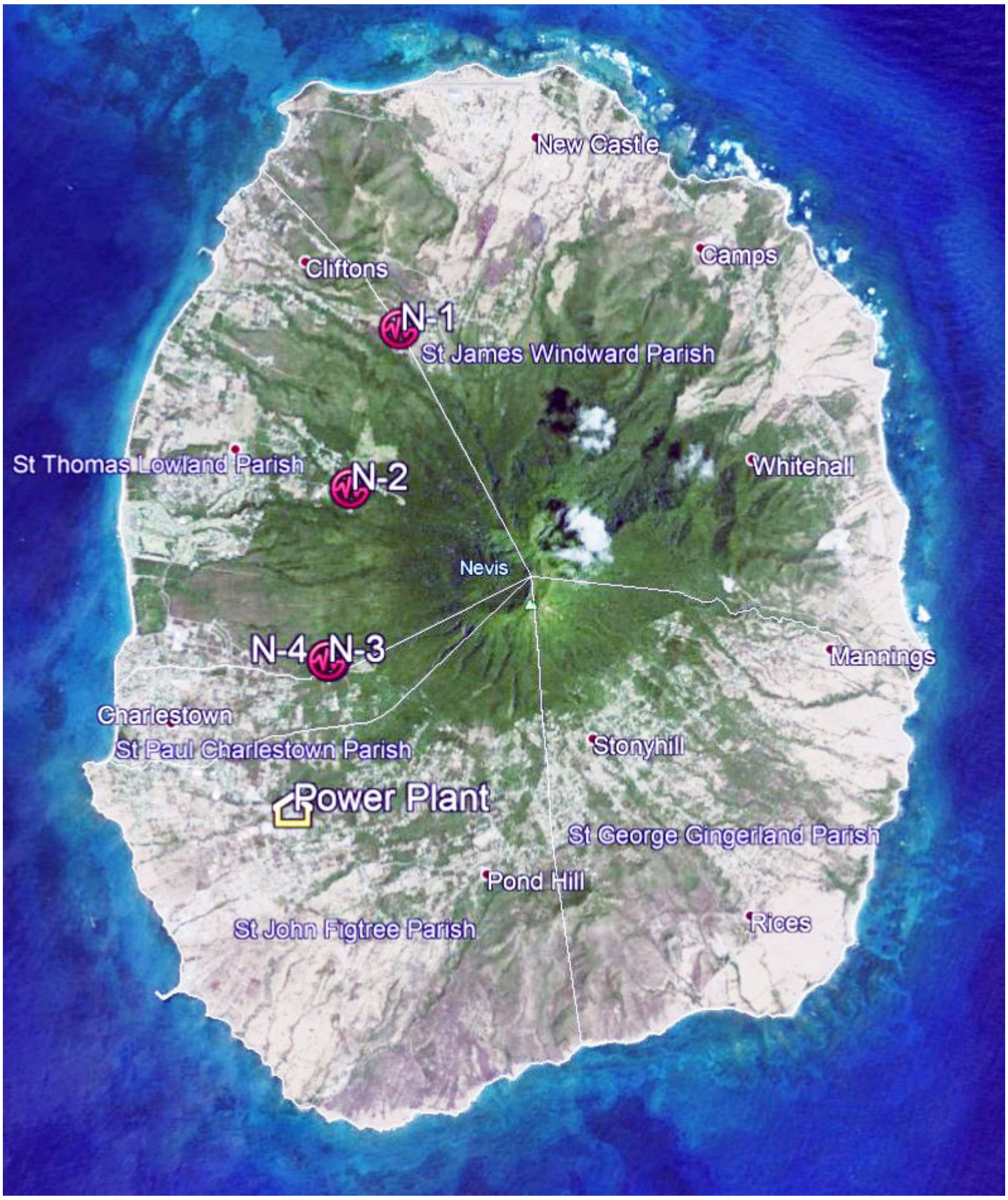

FIGURE 1: Map of Nevis showing locations of geothermal exploration wells drilled on the island

In November 2015, the NIA granted Nevis Renewable Energy International Inc. (NREI), a subsidiary of Thermal Energy Partners, LLC, the rights to develop the geothermal resources on the island. The site identified for further geothermal exploration and development was N-3 Hamilton. NREI is in the process of developing a 10 MW binary geothermal power plant at Hamilton (Point Impact Analysis, 2017). In March 2018 NREL drilled well N-4 at Hamilton to confirm the resource previously identified. The results showed that the geothermal resource is commercially viable with excellent temperatures, pressures and flows at a depth of 1000 m. Summary of data from well N-4 is shown in Table 1.

TABLE 1: Summary of results of exploration well N-4 at Hamilton

Well depth	Water temperature	Steam temperature	Pressure at well head	Flow	Downhole temperature	Downhole pressure
1000 m	123°C	214°C	> 9 Bar	946 L/min.	255°C	> 957 PSI

NREL estimates that one production well can produce 10.5-22 MW of geothermal energy (Nevis Renewable Energy International, 2018). Nevis's reservoir capacity is estimated between 100 and 400 MW based on prior studies conducted on the island (Nevis Renewable Energy International, 2018).

To achieve climate and energy goals, countries and regions in the world need to improve cross border electricity interconnections. Connection of electricity grids, especially smaller ones, will improve the security of electricity supply, improve the utilization of each renewable energy source, and enable the introduction of more and different types of renewables into the energy markets. For islands, such as those in the Caribbean, interconnection means laying an expensive Alternating Current (AC) (for shorter distances) or Direct Current (DC) (for longer distances) power cable on the ocean bed. Some studies have been done for projects of this nature in recent years. The fact that some of the Leeward Islands are believed to have large geothermal potential could make such projects financially more attractive than interconnection of grids without geothermal potential. The reason is that geothermal energy is non-intermittent, i.e. it is not dependant on weather, seasons or hours of the day. In other words, geothermal energy generates baseload electricity that can constantly be fed from one island to another through the interconnector, thus ensuring its revenue base and strengthening its business case.

Thus, interconnectivity of the Nevis geothermal resource to other islands in the region is possible as the Nevis Island peak demand is only 9 MWe. It is forecast that the peak demand of electricity on Nevis by 2028 may reach 29 MWe. Thus, the resource will not be depleted even if a part of the electricity produced was exported (Nexanr, 2010). The island's desire for interconnectivity is reflected in the Nevis Geothermal Resources Development Ordinance of 2009 where concessions are made for submarine cables (Nevis Geothermal Resources Development Ordinance, 2009).

2. LITERATURE REVIEW

Interconnection of electricity produced from geothermal energy through submarine cables has not been examined in its entirety in the Caribbean region and, thus, limited literature is available with regard to such interconnections. The literature found, focused on the lack of interconnection of electricity in the Caribbean as one of the setbacks for the slow development of geothermal energy in region, as to date there are no such examples in the region. There are, however, several nations in the world such as Great Britain, which utilize this technology with interconnection projects dating back to 1986 (Pöyry, 2016). Furthermore, Great Britain intends to expand its interconnection of electricity with nine (9) proposed interconnections from 2019 until 2024 ((Pöyry, 2016).

In the case of Nevis, the literature suggests that an interconnection of geothermal energy for electricity through submarine cables with St. Kitts is feasible (Brederode and Cuba, 2008). The Organisation of American States (OAS) has presented an Puerto Rico – St. Kitts and Nevis electricity interconnection study, however, the full report could not be obtained. Discussions in the past have surrounded the possibility of an interconnection of geothermal energy from Nevis to Puerto Rico. This may be viable as the island of Nevis has an estimated geothermal capacity of up to 400 MW (Nevis Renewable Energy International, 2018) and is located only 441 km away.

3. OVERVIEW OF THE ENERGY SECTOR ON NEVIS

The energy sector on Nevis is a monopoly operated by Nevis Electricity Company Ltd. (NEVLEC). NEVLEC is a subsidiary of the NIA. The island has 100% electricity coverage, however, most of the electrical infrastructure is above ground therefore making it susceptible to natural disasters.

FIGURE 2: The 3.85 MWe Wartsila Engine installed in 2017

NEVLEC operates a 6-diesel generator power plant with an installed capacity of 12.3 MWe at Prospect Estate. The island´s peak load demand is 9 MWe and the base load is 6 MWe. However, in 2017 NEVLEC experienced difficulties at the Prospect Power Station due to the deterioration of some aging diesel engine generators. The older units installed approximately three decades earlier, had to be decommissioned and a new 3.85 MW Wartsila engine, shown in Figure 2, was installed. Additionally, two of the more recently installed diesel engine generators, specifically a 2.78 MWe Wartsila installed in 2000 and a 2.5 MWe MP36 had to be overhauled in the final quarter of 2017 and first quarter of 2018, respectively. After months of electrical instability, the electricity capacity was restored. In the island´s quest towards one hundred percent renewable energy electricity production, a windfarm was installed in 2010, the first of its kind in the Caribbean region.

The windfarm is owned by an Independent Power Provider (IPP) called Windwatt. The windfarm has an installed capacity of 2.2 MW. The farm consists of eight 275 kW wind turbines (Kelly, 2012).

On the island of Nevis, domestic use dominates electricity consumption followed by the commercial sector, which includes hotels, restaurants and other businesses, both profit and non-profit. Government institutions make up the smallest percentage of electricity consumption on the island. The electricity consumption in 2016 by different sectors is shown in Figure 3. It reflects the general trend of consumption on the island since 2012. NEVLEC serves over 7000 customers. These customers pay an average of 0.26 USD/kWh, which includes the cost of fuel surcharge. The average electricity tariff of other islands in the region is 0.33 USD/kWh.

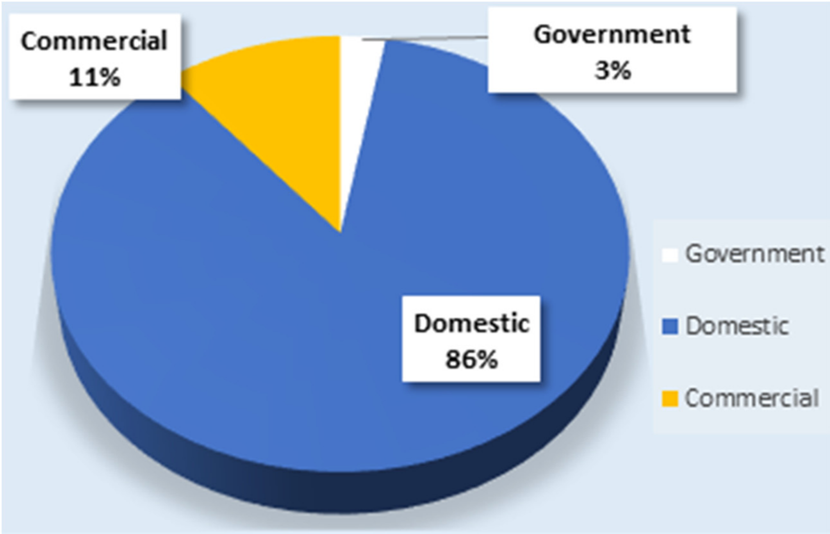

FIGURE 3: Electricity consumption in Nevis by different sector in 2016 (Department of Statistics, 2017)

The average maximum demand of electricity on the island recorded from 2012 to 2016 was 8.9 MW (Department of Statistics, 2017). According to update of geothermal power generation in the world for 2010-2014 (Bertani, 2015), electricity production is forecasted to reach up to 35 MW by 2020, while Nexanr (2010) predicted a growth rate to 29 MWe by 2028, as the island continues to develop. Now is the perfect opportunity for the island to develop and utilize geothermal energy for local consumption and regional interconnection to alleviate the fluctuating cost of fuel prices and ensure energy security. Approximately, 90% of NEVLEC´s annual operational budget is spent on fuel and lubricants cost (Kelly, 2012). Additionally, an average of 20.3% of transmission and distribution losses were recorded on the island due to nontechnical issues (National Renewable Energy Laboratory, 2015b). The losses recorded are greater than those of a larger economy like the United States at 6% (National Renewable Energy Laboratory, 2015b).

4. ELECTRICITY GENERATION IN THE LESSER ANTILLES AND PUERTO RICO

It is estimated that 87% of fossil fuels imported in the Caribbean are for electricity production (Caribbean Hemispheric Affairs, 2017). However, some islands in the Lesser Antilles do have some renewable technologies that contribute to their overall electricity matrix as shown in Table 2. In the case of Nevis, there is an installed renewable capacity of 2.2 MW as a result of the wind farm which contributes to the electricity generation on the island. The neighbouring island of St. Kitts has two solar farms, with a capacity of 0.75 MW and 0.5 MW each. In St. Lucia there is a 3 MW solar farm with 611 kW of consumer site solar energy. The islands of St. Vincent and the Grenadines are one of a few island states in the region with hydropower plants with a total installed capacity of 5.64 MW (National Renewable Energy Laboratory, 2015c). Additionally, the island utilizes solar energy with an installed capacity of 0.3 MW (National Renewable Energy Laboratory, 2015c). The island of Dominica has three hydropower plants with a total installed capacity of 6.5 MW (Emera Caribbean, 2018). The French

TABLE 2: Installed capacity of renewable electricity generation in Lesser Antilles and Puerto Rico

Country	Wind (MW)	Hydropower (MW)	Solar (MW)	Biomass (MW)	Geothermal (MW)
Nevis	2.2				
St. Kitts			1.3		
St. Vincent and Grenadines		5.6	0.3		
Dominica		6.5			
Guadeloupe	24.4	8.7	67.4	57.3	15
St. Lucia			3.6		
Puerto Rico	120	100	22.1		
Total	**146.6**	**120.8**	**94.7**	**57.3**	**15**

island of Guadeloupe however, is the most diverse in the region with regards to renewable technologies. They have an installed capacity of 24.4 MW from wind energy, 8.7 MW from hydropower, 15 MW of geothermal energy, 57.3 MW biomass energy and 67.4 MW of solar energy (National Renewable Energy Laboratory, 2015d). The island of Puerto Rico is bigger than the aforementioned islands and has installed several renewable energy plants, including wind at 120 MW, hydropower at 100 MW and solar energy at 22.1 MW (National Renewable Energy Laboratory, 2015a).

Although several islands in the Caribbean have installed capacity of renewable technologies as a part of their overall electricity generation, the Lesser Antilles and Puerto Rico are still plagued with high consumption of fossil fuels. Puerto Rico has the highest installed capacity of electricity of all the islands shown in Table 3 at 5,840 MW. Of the total installed capacity, 71.82 % of the electricity produced comes from petroleum, 8.47% coal, 17.85% from natural gas while the rest comes from renewable energy technologies (National Renewable Energy Laboratory, 2015a).

TABLE 3: Installed capacity of electricity and peak demand in the Lesser Antilles and Puerto Rico

Country	Installed capacity (MW)	Peak demand (MW)
Nevis	12.3	9
St. Kitts	43	24
Puerto Rico	5,840	3,685
Antigua and Barbuda	118	50
St. Vincent & Grenadines	52	21
Dominica	26.74	17
St. Lucia	88.6	61.7
Grenada	48.59	30.2
Montserrat	6.22	2
Anguilla	26.8	15.5
Guadeloupe	508.5	254

The main consumption of electricity in the Lesser Antilles and Puerto Rico is due to residential use. For most of the islands in the region the main industry is tourism and this sector demands quite a lot of electricity as well. In the hotel industry, electricity is used for air conditioning, lighting, pool pumps, hot water, laundry, kitchen, refrigeration equipment and other general equipment. Thus, the cost of accommodations in the region can be lowered with the implementation of renewable technologies through interconnectivity.

5. POTENTIAL OF GEOTHERMAL ENERGY IN THE REGION

Global Geothermal Energy data indicated that only 0.77 GWh of geothermal energy were utilized in 2014 in the Caribbean region (World Energy Council, 2016). The French Guadeloupe is the only island in the region, which produces electricity with this resource. Guadeloupe's present installed geothermal capacity is 15 MWe (Table 2).

The volcanic islands of the Eastern Caribbean are estimated to have a geothermal energy potential of approximately 850 MW (Jayawardena and Berman, 2013). However, the true geothermal potential on each island still remains uncertain as only a few of the islands have explored their geothermal resources. It is important to outline the potential of geothermal energy for the islands to provide a better picture of the possible capacity of the resource, to be used for production in the future. Table 4 outlines the islands in the region, which have been exploring geothermal energy for electricity production. Here, an important factor is the drive towards renewable energy becoming a priority in the region.

TABLE 4: Lesser Antilles and Puerto Rico: demography, yearly electricity consumption, geothermal potential and planned geothermal development

Country	Population	Annual electrical consumption (GWh)	Geothermal potential (MWe)	Geothermal capacity (MWe)
Nevis	12,000	56	100-400	10 (proposed)
St. Kitts	34,983	196	18-36	-
Puerto Rico	3,337,000	18,800	-	-
Antigua and Barbuda	94,799	320	-	-
St. Vincent & Grenadines	110,000	320	>75	15 (proposed)
Dominica	73,925	110	100	7 (proposed)
St. Lucia	185,000	385	75	-
Grenada	108,339	206	>50	10 (proposed)
Montserrat	5,215	10.89	900	5 (proposed)
Anguilla	16,086	N/A	-	-
Guadeloupe	405,739	733	>40	15

5.1 Dominica

In 2013 the island of Dominica drilled three slim exploration wells in the geothermal area of Wotton Waven. Temperatures of >235°C were recorded. This was followed by the drilling of a production well in 2014 to a depth of 1,500 m with temperatures close to those recorded in the slim wells in 2013 (Huttrer and La Fleur, 2015).

The geothermal project encountered obstacles, one of which was the destruction caused by Hurricane Maria in 2017, which destroyed most of the constructions on the island. A 7 MWe geothermal plant is proposed for Dominica. In the future Dominica hopes to export geothermal energy to the neighbouring islands of Guadeloupe and/or Martinique once the geothermal resource is deemed sufficient (The World Bank, 2017).

5.2 St. Vincent and the Grenadines

The island of St. Vincent is a volcanic island with the potential to harness geothermal energy. St. Vincent's estimated geothermal capacity is more than 75 MW as outlined in Table 4. The government of St. Vincent and the Grenadines, in partnership with Emera Caribbean and Reykjavik Geothermal, is exploring the possibility to develop a 15 MW geothermal plant on the southern slopes of La Soufriere volcano (Environmental Resource Management, 2016). The project is set in two phases. Exploratory drilling and the installation of relevant infrastructure would be completed in phase one while in phase two the geothermal plant would be constructed and the resource would then be connected to the island's grid (Environmental Resource Management., 2016). Exploratory drilling is set to commence in the first quarter of 2019.

5.3 Montserrat

The island of Montserrat is a British territory located in the Leeward Islands. In 1995 the once dormant-Soufriere Hills volcano became active and all residents were evacuated to the United Kingdom and other countries. The eruption destroyed the south side of the island including the capital of Plymouth. The last major eruption was in 2010. Today, though the entire island cannot be inhabited due to the demarcation of exclusion zones, the island has returned to some level of normalcy with its northern side being rebuilt. Montserrat has decided to explore geothermal energy for electricity production. The island is estimated to have a geothermal potential of 900 MW, however, the entire resource cannot be harnessed. Two exploration wells were previously drilled by the Iceland Drilling Company, Ltd., which produce approximately 2.4 MWe (ThinkGeoEnergy, 2016). A third well is scheduled to be drilled for reinjection. If, however, the resource from that well is deemed more viable than that of the two older wells, then it will be used for production (ThinkGeoEnergy, 2016). Montserrat has decided to develop a 5 MWe geothermal plant which will satisfy the island's peak load demand.

5.4 Grenada

The island of Grenada is famous for its active submarine volcano known as Kick´em Jenny, located approximately 8 km from the island. In 2015 and 2016 the island received support from New Zealand and the Japan International Cooperation Agency (JICA) to investigate its geothermal resource potential. The data revealed the island could develop a 15 MW geothermal plant. The project is intended to be executed in five phases. Phase 1 will be the surface exploration and conceptualization, phase 2 an exploration drilling of a slim well, phase 3 appraisal drilling and bankability, phase 4 production drilling and construction, and phase 5 operation of the geothermal plant (JICA, 2018).

5.5 St. Lucia

The island of St. Lucia was one of the first islands in the region to explore geothermal energy. The geothermal exploration was conducted in the Sulphur Springs area, which has several geothermal manifestations such as hot springs, bubbling mud pools, fumaroles and boiling springs. Between 1975 and 1976 seven slim wells were drilled. In 1987 and 1988 two production size wells were drilled (GoSL. Panorama Environmental Inc., 2018). Although the wells produced high temperatures the resource was not deemed commercially viable due to its acidic content (GoSL., Panorama Environmental Inc., 2018).

However, the island has once again decided to explore geothermal energy. In 2018, the Government of St. Lucia released their Environment and Social Impact Assessment (ESIA) for the exploration of geothermal to the public. The areas identified for exploration are Belle Plaine, Mondesir-Saltibus and Fond St. Jacques, which are located outside Sulphur Springs (GoSL., Panorama Environmental Inc., 2018). The Government of St. Lucia is hopeful that the island may be able to accommodate a 30 MW geothermal plant in the future.

5.6 Guadeloupe

Guadeloupe is a French territory located in the Lesser Antilles. Guadeloupe is the only island in the region with an operational geothermal plant, the Bouillante geothermal plant, which has an installed capacity of 15 MW. Ormat now has majority share of Bouillante. The plant may be further expanded to 45 MW by 2021. The island´s estimated geothermal potential is over 40 MW.

6. INTRODUCTION OF SUBSEA INTERCONNECTION OF ELECTRICITY GRIDS

The distribution of electricity from one sea locked country to another is possible through submarine cables. Submarine cable can be laid on the ocean floor as shown in Figure 4, or in some cases buried in it. There are two types of submarine cables used, the high voltage AC cable and the high voltage DC. Normally, for shorter distances of approximately 80 km or less, High voltage AC is used and for longer distances high voltage DC is used (European Subsea Cables, 2013). DC cables require the construction of costly AC/DC and DC/AC conversion stations at the cable landing sites

As the effects of climate change become a reality the need for energy security is a worldwide concern. Thus, countries with natural energy sources have the opportunity to tap into the financial benefits of interconnection. Energy interconnectivity will provide stability in electricity market prices. The idea of electrical interconnection through submarine cables first became a reality in 1954 when Gotland Island received 20 MW of electricity from Sweden, at a distance of 98 km, using a high voltage DC cable (European Subsea Cables, 2013).

FIGURE 4: Typical submarine cable
(Electrical Technology, 2018)

One of the world's leaders for electricity interconnection is Great Britain. In 1986, France exported 2,000 MW of electricity to Great Britain as shown in Table 5 (Pöyry, 2016). Thereafter, Ireland and the Netherlands also supplied Great Britain with electricity through submarine technology. The importance of interconnection for electricity distribution has become a viable option as it gives energy security and provides stability of electricity prices on the market. To date, interconnection of electricity only accounts for 4.4% of the installed capacity in Great Britain (Pöyry, 2016). However, the installed capacity is expected to expand as additional energy providers look to export electricity to Great Britain as shown in Table 6.

TABLE 5: Subsea interconnections for electricity distribution around the world
(Brederode and Cuba, 2008; Pöyry, 2016)

Date	**From**	**To**	**Distance (km)**	**HVAC**	**HVDC**	**Electrical capacity (MWe)**
1986	France	Great Britain	73		x	2,000
1998	Belize	Ambergris Caye Island	19.3	x		
2005	Victoria, Australia	Tasmania, Australia	370		x	500
2008	Norway	Netherlands	508		x	700
2000	Italy	Greece	163		x	500
2002	Ireland	Great Britain	63		x	500
2011	Netherlands	Great Britain	260		x	1,000
2012	Ireland	Great Britain	262		x	500

TABLE 6: Proposed Great Britain interconnectors (modified from Pöyry, 2016)

Connected market	**Capacity (MWe)**	**Suggested commissioning date**	**Status**
Belgium	1,000	2019	Cap and floor granted; preparation for construction
France	1,000	2019	Exemption granted; offering capacity
France	1,000	2020	Cap and floor granted; consultations
Norway	1,400	2021	Cap and floor granted; construction
Irish SEM	500	2021	Cap and floor granted
France	1,400	2020-2022	Cap and floor granted; detailed surveys
Denmark	1,000	2022	Cap and floor granted; survey
Norway	1,400	2022	Development studies
Iceland	800-1,200	2024	Development studies

Iceland is one of the countries identified to interconnect to Great Britain as shown in Table 6. Iceland is one of the world leaders in renewable energy production primarily for geothermal energy and hydropower energy. In 2016, hydropower accounted for 73% of electricity generation on the island, while geothermal energy accounted for 27%. Iceland´s installed electrical capacity was 2.732 MW with the total electricity production of 18.549 GWh. Iceland has a geothermal energy potential of 3,000 to 4,300 MW while installed geothermal projects have a capacity of 1,070 MW (Orkustofnun, 2017).

Iceland's proposed interconnection is expected to be 1000 km long. Therefore, it will be the longest submarine cable connection in the world. Iceland is looking at the possibility to supply Great Britain with 800-1200 MW through high voltage DC cables from 2027. It is expected that the project will provide Great Britain with >5 TWh renewable energy each year at a competitive cost (Landsvirkjun, 2017).

7. POTENTIAL INTERCONNECTION IN THE LESSER ANTILLES AND PUERTO RICO

Although most of the Caribbean islands are close in proximity, especially in the Lesser Antilles, subsea interconnection for electricity distribution has not been utilized. There are countries around the world that have installed and utilized subsea cable technology successfully as shown in Table 5.

Energy security is a priority in the Caribbean, as the effects of climate change dominate the region through powerful hurricanes, not forgetting earthquakes. Additionally, the fluctuations in oil prices have created instability in the price of electricity. Over several decades, most countries in the Lesser Antilles have installed renewable energy technologies while others are exploring. The Caribbean region is plagued with powerful hurricanes and the most powerful hurricanes recorded in recent decades were experienced in 2017, hurricanes Irma and Maria. Several of the Lesser Antilles and Puerto Rico experienced major destruction of infrastructure and loss of lifes. The recovery process on the islands is still ongoing. On Puerto Rico some areas are still without electricity in 2018. Although Puerto Rico has an installed capacity of approximately 242.1 MW of renewable energy on the grid through hydropower, biomass, wind and solar they are susceptible to hurricanes. In the case of St. Thomas and Puerto Rico, entire solar farms were destroyed in the 2017 hurricanes. Although all renewable energy sources are important, geothermal energy is probably more suited for the types of disasters encountered in the Caribbean. Several islands within the Lesser Antilles chain of islands have good potential for developing geothermal energy. Therefore, submarine interconnection might be economically viable for the islands and provide energy security.

Geographically, St. Kitts and Nevis are the closest of the chain of islands shown in Figure 5. Although St. Kitts and Nevis is a Federation, each island has its own electrical structure. Subsea interconnection for the distribution of electricity would be ideal for St. Kitts and Nevis as they are only 3.29 km apart. The geothermal potential of the island of Nevis' can comfortably meet the electrical demands of St. Kitts, as well as several of the Lesser Antilles and Puerto Rico.

The islands of Dominica and Guadeloupe were also identified as possible electricity markets to interconnect to Nevis. Dominica is pursuing geothermal energy for electricity production with a proposed 7 MW geothermal plant, while the island of Guadeloupe has an operational 15 MW geothermal plant. The islands are located 232 and 148 km from Nevis, respectively.

This paper however, focuses on the interconnection of geothermal energy from Nevis to the island of Puerto Rico. The islands are located 441 km apart. The island of Puerto Rico has a population of 3.337 million with an installed electricity capacity of 5,840 MW and a peak demand of 3,685 MW. The island of Puerto Rico has a great need for energy security, which is more evident after the passage of hurricane Maria in 2017. The hurricane destroyed thousands of lives and eroded the island's electricity infrastructure. One year after hurricane Maria, the island still has not achieved complete electricity

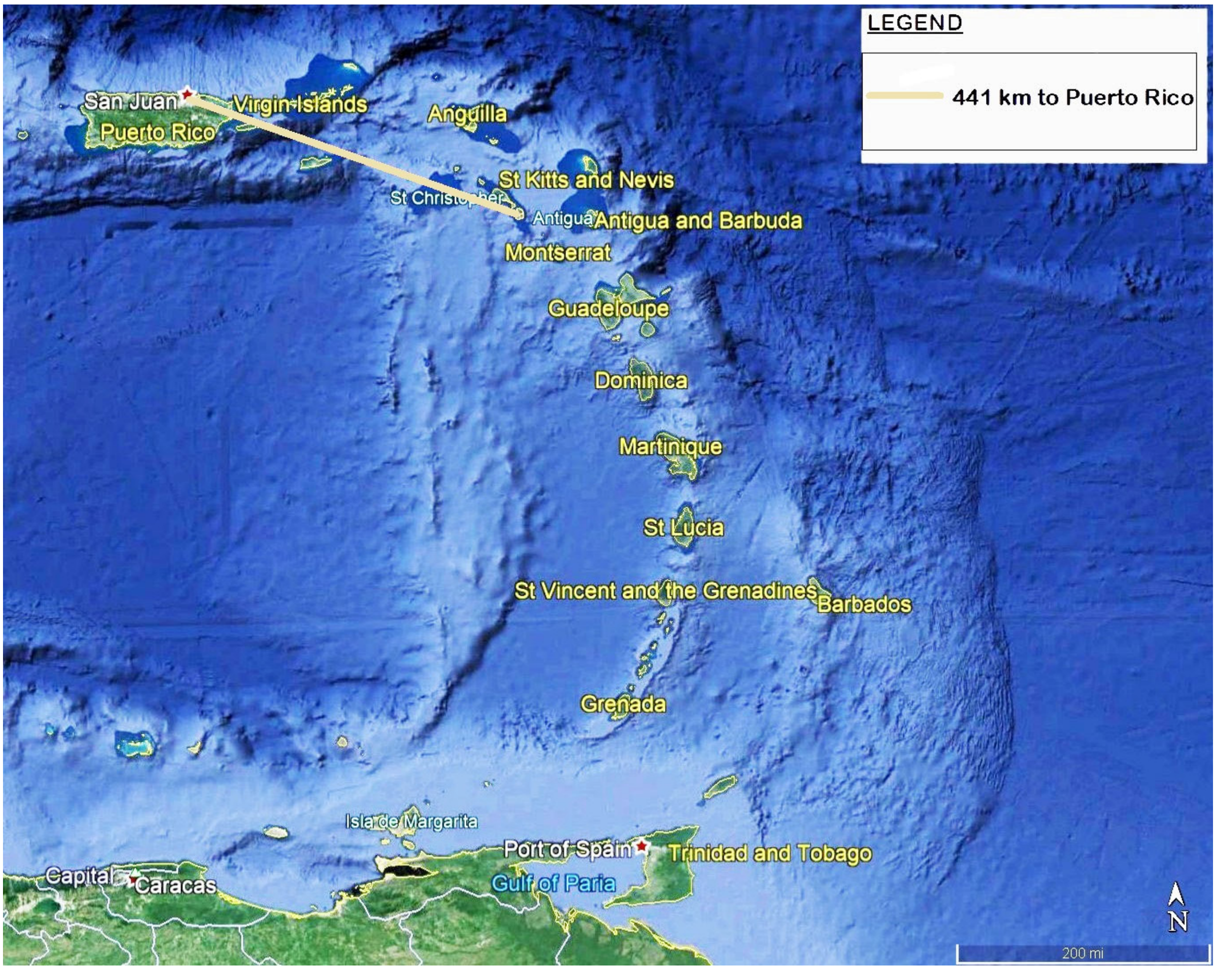

FIGURE 5: The chain of Caribbean Islands showing the proposed submarine interconnector cable from Nevis to Puerto Rico

coverage. The island has installed renewable energy resources for electricity generation with wind, hydropower and solar, however, these renewable sources did not withstand the destructive winds of the hurricane. Additionally, access to fossil fuels becomes extremely difficult after a disaster like this, as the island becomes isolated. Although the island of Nevis' geothermal resource capacity is insufficient to provide complete electricity coverage to Puerto Rico, it is expected that the introduction of geothermal energy on the grid will serve as a more reliable electricity source, which will be able to withstand disasters such as hurricanes and thus, shorten the recovery time after a destructive disaster.

Geographically, Nevis is ideally located to supply Puerto Rico with geothermal energy for electricity through submarine cables. Therefore, a venture of this magnitude is possible, as countries with greater distances between them have interconnected successfully in the past.

However, there are possible impacts that electricity subsea interconnection may encounter. These are outlined in a SWOT (strengths, weaknesses, opportunities and threats) analysis as shown in Table 7. The analysis indicates some possible strengths, weaknesses, opportunities and threats of subsea interconnection for electricity

TABLE 7: Subsea interconnection of the Lesser Antilles and Puerto Rico – SWOT analysis

Strengths	Weaknesses	Opportunities	Threats
Close geographical location between islands	High cost of cable installation	Stable electricity rates	Political will
High cost of imported fuel			
Provides stable renewable baseload to Puerto Rico	Installed cables can be damaged by fishing trawlers and ship anchors	Attract energy intensive industries	Financing
Improves utilization of renewable development in the region			
	Lack of regulatory framework for interconnection	Improved power quality (frequency and voltage control)	Transmission losses Difficulties in laying and maintaining cable at a great depth
	Underwater noise and disturbance from vessels and installation activity	Preservation of the scenery	
	Exclusion of other industries from the area	Lower Carbon footprint in the region	
	Seabed disturbance	Possibility of transmitting large amounts of electrical energy generated by renewable sources	
		Protection against hurricanes	
		Better utilization of installed capacity, enabling faster growth of intermitt. renewables	
		Local infrastructure and jobs	

8. ASSUMPTIONS AND SCENARIOS

The feasibility of interconnection of geothermal energy for electricity generation from Nevis to Puerto Rico is assessed in this report. For this feasibility scenario it is assumed that 200 MWe produced by Nevis's geothermal resources will be exported to Puerto Rico through submarine cables. This feasibility assessment has similar characteristics to the Utsira submarine cable in Norway, shown in Table 8, where up to 300 MW of electricity were transmitted through submarine cables for a distance of 200 km to four offshore platforms. The submarine cable project of Utsira was a theoretical study of procurement strategy for offshore electrification projects. The study sought to provide cost estimates of power from shore solution for Utsira in Norway. Thus, the Nevis interconnection cable project was scaled from the Utsira project shown in Appendix I to suit the island's local context. The island of Puerto Rico has an average electricity rate of 240 USD/MWh (National Renewable Energy Laboratory, 2015a).

TABLE 8: Characteristics of Norway and Nevis interconnectors

	Norway	Nevis
Capacity (MW)	2×150	2×100
Length (km)	200	441

The goal of the feasibility assessment in this report was to see if there is a financial justification for interconnection through subsea cables from Nevis to Puerto Rico. Therefore, it was determined at what cost the island of Nevis can produce electricity from the geothermal resource to compete with the present electricity price in Puerto Rico and still be financially feasible for Nevis. The resources required to execute the project were broken down with a cost assigned to each. The main resources and activities required for the project are submarine cables, engineering, management, laying, type testing, trenching, transport, mobilizing, demobilizing, extension onshore substation and onshore converter VSC 2 × 100 MW. The lifetime of the project is slated for 40 years with an investment time schedule for five years as shown in Appendix II. If the island of Nevis exported 200 MW via submarine cable to Puerto Rico the project would become financially viable once Nevis can produce their geothermal resource at a maximum cost of 184 USD/MWh.

The interconnection of submarine cables for electricity utilization from Nevis to Puerto Rico can be executed as shown in Figure 6. From the Nevis grid 200 MW of geothermal energy will be transmitted to the converter station where the high voltage AC will be converted to high voltage DC. After DC conversion the geothermal resource is transmitted 441 km to Puerto Rico to a converter station. There the geothermal energy will be converted from DC to high voltage AC. Then the electricity will be transmitted to Puerto Rico's grid.

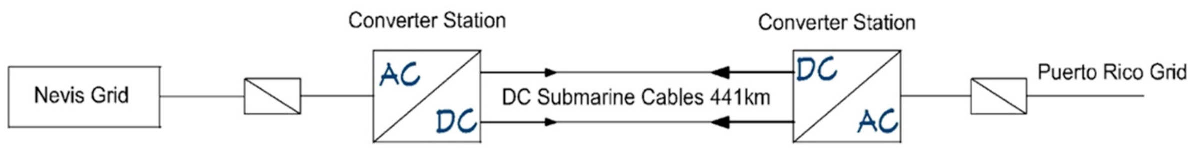

FIGURE 6: Interconnector of submarine cables from Nevis and Puerto Rico

8.1 Feasibility indication

The Capital Recovery model, shown in Table 9, was used to determine the maximum price at which the island of Nevis must produce its geothermal resource to be financially viable. It was scaled from the earlier mentioned reference project in Norway. In the context of Nevis, the project estimated cost of 613 million USD includes the construction and operation of the submarine cable. The weighted average cost of capital is 8% with an average of 1,226,400 MWh of energy transmitted annually. Although 200 MW would be exported, it is estimated that 5% of the power will be lost through the transmission phase. It is estimated that 70% of the cable transmission capacity will be utilized while 30% is calculated as downtimes due to repair or low demand of power at any particular time. There must be consistent operation and maintenance of the submarine cables during the lifetime of the project. Thus, cost operation and maintenance will account for 1.75% of the total cost of the investment annually. The annualized cost of investment and operation was calculated at 69 million USD with the cost of transmission per unit energy at 56.3 USD/MWh.

TABLE 9: Capital recovery model for 200 MW interconncector

Capacity	200 MW
Utilization rate	70%
Investment	613 m USD
Construction time	5 years
WACC	8.0%
Lifetime	40 years
O & M	1.75
Transmission losses	5%
Calculation	
Interest during construction	82 mUSD
Total project cost	695 mUSD
Capital recovery factor	8.4%
Annualized cost	
Capital recovery & cost	58.3 mUSD/year
O&M	10.7 mUSD/year
Total	69.0 mUSD/year
Cost per energy	
Transmitted energy	1,226,400 MWh/year
Cost of transmission per unit el. energy	56.3 USD/MWh

9. RECOMMENDATIONS AND CONCLUSIONS

It is possible for the island of Nevis to interconnect through submarine cables to Puerto Rico in the future as both islands are located in ideal geographical locations to each other. However, the capital cost of interconnection through submarine cable is high as there are limited suppliers and experts in this field. However, if interconnection between Nevis and Puerto Rico is materialized it would foster the steady development of other geothermal plants in the Caribbean region, thus opening a new market where islands can export their excess geothermal energy. This will also lead to decreased dependence on fossil fuels imported in the region, thus reducing CO_2 emissions in the region. It would also contribute to the stability of electricity rates and the increase of energy security and independence in the Caribbean. Additionally, in the context of Puerto Rico interconnectivity of geothermal energy will allow for faster build-up of other, intermittent renewable energy technologies. Despite hindrances to submarine interconnections in the region such as financial, human resources and political will, it is clear that a more dependable renewable energy source is now needed in the region, with the region now encountering more destructive natural disasters such as hurricanes

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APPENDIX I: Cost estimate of Nevis interconnector project scaled from the DC link Norway project

			DC link Norway interconnection		Nevis interconnector		
			Karstö-Utsira		Nevis-Puerto Rico		
	Unit	**Unit cost [USD]**	**Qty**	**Cost [USD]**	**Scaling factor**	**Qty**	**Cost [USD]**
Cable							
Submarine cable	km	300,481	400	120,192,308	0.72	882	191,607,392
Engineering	pcs	1,201,923	1	1,201,923	1.36	1	1,635,801
Management	pcs	6,009,615	1	6,009,615	1.88	1	11,312,890
Type testing	pcs	6,009,615	1	6,009,615	1.36	1	8,179,006
Sum cable				**133,413,462**			**212,735,090**
Installation cost							
Laying	km	120,192	400	48,076,923	1.36	882	144,277,672
Trenching	km	120,192	400	48,076,923	1.36	882	144,277,672
Mob./de. mol	pcs	600,962	2	1,201,923	1.36	2	1,635,801
Transport	days	144,231	30	4,326,923	1.36	30	5,888,885
Sum installation				**101,682,692**			**296,080,030**
Converter							
Extens. onshore subst.	pcs	18,028,846	1	18,028,846	0.72	2	26,069,033
Pull in J tube	pcs	2,403,846	2	4,807,692			0
Onshore converter VSC 2×150 MW	pcs	54,086,538	1	54,086,538	0.72	2	78,207,099
Offshore converter VSC 2×150 MW	pcs	99,158,654	1	99,158,654			0
Sum converter				**176,081,731**			**104,276,132**
Total				**411,177,885**			**613,091,252**

Scaling factors	
Scaling factor capacity (MW)	0.72
Scaling factor length (km)	1.88

APPENDIX II: Time schedule of investment for submarine interconnector cable

	Year 1	Year 2	Year 3	Year 4	Year 5
Cable					
Submarine cable	20%	20%	20%	20%	20%
Engineering	20%	20%	20%	20%	20%
Management	20%	20%	20%	20%	20%
Type testing	20%	20%	20%	20%	20%
Sum cable	**42,547,018**	**42,547,018**	**42,547,018**	**42,547,018**	**42,547,018**
Installation cost					
Laying	20%	20%	20%	20%	20%
Trenching	20%	20%	20%	20%	20%
Mob.del.mol	20%	20%	20%	20%	20%
Transport	20%	20%	20%	20%	20%
Sum installation	**59,216,006**	**59,216,006**	**59,216,006**	**59,216,006**	**59,216,006**
Converter					
Extension Onshore substation	20%	20%	20%	20%	20%
Pull in J tube					
Onshore converter VSC 2×150MW	20%	20%	20%	20%	20%
Offshore converter VSC 2×150MW					
Sum converter	**20,855,226**	**20,855,226**	**20,855,226**	**20,855,226**	**20,855,226**
Total	**122,618,250**	**122,618,250**	**122,618,250**	**122,618,250**	**122,618,250**