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AN ESTIMATION OF THE HYDROELECTRIC POTENTIAL OF PUMPED HYDRO STORAGE SYSTEMS USING SEAWATER FOR RENEWABLE ENERGY PRODUCTION IN A SMALL ISLAND DEVELOPING STATE

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ABSTRACT

Most of the Small Island Developing State (SIDS) nations are now focusing on variable renewable energy sources. However, these variable renewable energy sources such as wind and solar are unpredictable and bring instabilities in the electric power system if not buffered by a reliable storage system. The proposed system will be a low head pumped hydro storage system using seawater as the medium. Given the fact that most SIDS are isolated and surrounded by large bodies of water, this paper will examine the potential use of the sea as a lower reservoir to generate sufficient energy from a relatively low head. This research will focus on detecting potential locations for the pumped hydro storage system sites on the island of Trinidad and Tobago (one of the SIDS nations) using the ArcGIS.Pro program. These sites were classified based on several criteria and the average potential power that can be generated was established. A total of 2001 potential sites were found that can sufficiently generate substantial energy for the island. Of these 2001 potential sites, 1127 were within the “Fair” classification, 725 were within the “Good” classification, 108 were within the “Very Good” classification and 41 were within the “Excellent” classification. The estimated total energy that can be generated from the seawater pumped hydro storage system with the SIDS of Trinidad was found to be approximately 70.43 x 1014 J with a total estimated cumulative storage capacity of 4.81 x 109 m^3.

Keywords: Hydroelectric, Pumped Hydro Storage, Seawater, ArcGIS Pro, SIDS.

INTRODUCTION

The increasing global economy is one of the reasons for rising energy demand (Boubou-Bouziani, 2015). Due to high energy demand, energy-related CO_2 emissions have risen by 1.7% (Stolten and Scherer, 2013). At the moment the energy industry is facing challenges in that they need to fulfil the increasing demand for energy and on the other hand, there is a restriction on greenhouse emissions (Kelman and Harrison, 2019). Every country is aware of climate change, and decarbonisation has become, except for a few exceptions, a common goal (Haouchine et al., 2015; Assemian et al., 2021; Nakou et al., 2023). SIDS have also aimed for low-carbon production as these countries are highly dependent on fossil fuels (Kelman and Harrison, 2019). The majority of energy in most of SIDS is produced from non-renewable sources. Under the objective of reducing carbon footprint, SIDS are trying to minimize the import of fossil fuel and focus more on renewable sources (Gielen et al., 2019).

According to Gielen et al., (2019) and the United Nations, Trinidad and Tobago is considered one of the larger Small Island Developing States (SIDS) and is highly dependent of fossil fuel for energy production. Additionally, Trinidad and Tobago per capita electric energy usage is 6,467 kwh which is sustainably higher than the world's average of per capita electric energy usage 3,105 kwh (Francis, et al., 2007). Therefore, given Trinidad and Tobago has a population density of 299 per square kilometre while the world's average population density is 59.7 per square kilometre, Trinidad and Tobago is considered to have a high carbon emission (MOPD, 2023). One of the solutions to reduce those emissions is to increase the usage of renewable sources of energy, for the production of electrical energy (Gielen et al., 2019).

However, electrical demand varies throughout the day (Long et al., 2023). Typically, the electrical demand is higher at night, therefore a flexible power system should be created whereby energy can either be stored and or released when the demand for the energy fluctuates (European Commission, 2013). Therefore, a pump storage scheme could be a good choice for a renewable energy storage system in terms of cost, CO_2 emission, energy rating, response time and efficiency (Krüger et al., 2018).

A typical pumped hydro storage facility consists of at least two large water reservoirs located at different height elevations. The reservoirs are connected via pipelines to move water between them (Hariri-Asli and Nazari, 2021; Berrezel et al., 2023; Hooda et al., 2024; Mehta et al., 2024). Potential energy is stored via pumping water from the lower to the upper reservoir (Moussi and Saadi, 2002; Baxter, 2006; Hountondji et al., 2020). Kinetic energy is utilized by releasing water from the upper to the lower reservoir through a turbine which is connected to a generator. The total energy efficiency of typical pumped hydro storage usually varies around 70–80% for various sites (Koohi-Fayegh and Rosen, 2020).

Within this research the pumped hydro storage system will utilize the sea as the lower reservoir. The main difference for seawater pumped storage is that instead of having a lake, river, or some other source of fresh water serve as the lower reservoir, this system pumps saltwater uphill from the sea to a land reservoir above (Zella and Smadhi, 2010;

Kenning, 2017). This lowers the system's freshwater footprint and greatly expands the potential for pumped hydro storage worldwide because seawater pumped storage is much less site-specific than traditional systems (Ming et al., 2013). For pumping salt water and treating it, it is imperative to choose both the appropriate desalination process and the location of the water intake (Remini and Amitouche, 2023a; 2023b).

The only pumped hydro storage system, which utilized seawater was the 30 MW Yanbaru pumped hydro plant located on Okinawa Island in Japan (Foley et al., 2015). No details on Yanbaru's performance are readily available, but the plant operated for 17 years between 1999 and 2016 and it went into commercial operation around 2003. The fact that it operated for so long suggests that seawater pumped hydro storage technology can be regarded as at least partially proven (Pradhan et al., 2021).

The historical development of pumped hydro storage has primarily focused on site locations where there is a large difference in height elevations between the reservoirs. The main reason for this is due to the available power and storage capacity being a function of head and flow rate (Ruiz et al., 2022). Thus, with a higher head, a lower flow rate is required, which also leads to a smaller size of the reservoirs (Amara et al., 2013). On the other hand, high head pumped hydro storage is not possible to construct in areas with flat topography (Kitsikoudis et al., 2020). Therefore, in low lying islands such as the SIDS, the traditional supply of electrical energy would prove to be quite difficult. However, with the development of recent research such as new pump turbine technology, low head hydro storage can be potentially converted into sufficient renewable energy (Ekweoba, 2022).

With respect to these low-lying SIDS, the possible location of the pumped hydro storage system must be identified by analysing the topography and hydrology. Several GIS-based studies have been carried out to discover promising sites for developing pump storage hydro but very few research have investigated seawater pump storage hydro scheme. Gimeno-Gutierrez and Lacal-Arantegui (2015) evaluated that for two existing reservoirs under consideration the maximum potential pumped hydropower is twice that of the existing being generated.

Connolly et al., (2010) develop a model that identifies the possible pump hydro scheme sites by analysing the respective terrain and minimizing the required earthworks. Fitzgerald et al., (2012) developed a GIS-based model to discover a new reservoir site for a pumped hydro project near an existing reservoir while Lu and Wang, (2017) used a GIS application to identify the potential pump hydro storage sites in Tibet. Kucukali (2014) assessed the existing hydropower sites for the development of pumped storage project using multiple criteria. Lu et al., (2018) differentiated and evaluated two different site models; "dry gully" and "turkey's nest", to detect promising sites for the new reservoirs.

Moreover, Pandey et al., (2016) described seawater pumped storage as a type of artificial pumped storage scheme which harnesses coastal mountainous topography and abundant seawater. This seawater pumped hydro storage system provides a simple solution for storing electrical energy minus the problems associated with the conventional hydro plants of obstructing natural freshwater flow, high cost of building dams, water availability etc. (Pandey et al., 2016). Such types of plants are especially useful in an island type condition and off grid areas. These pumped storage schemes can be a cost-effective renewable energy source offering high efficiency and operational flexibility (Rehman et al., 2015).

Furthermore, Pradhan et al., (2021) proved that the dependency of reliable power supply in Curacao on fossil fuel could be reduced, by concentrating on seawater pump storage hydropower systems. However, this study only utilized GIS as a proof of the concept to show the potential that Curacao has in reducing the dependency on fossil fuels.

Meanwhile, Italian research conducted by Frigerio et al., (2012) helped to identify the most suitable sites for the seawater pumped hydro storage implementation, particularly in the South Italy and the islands where the electricity grid presents the most critical problems. Among this seawater pumped hydro storage potential sites, Foxi Murdegu in Sardinia was selected to be further developed. However, this study was also a proof of concept. Another study conducted by Alterach et al., (2014) estimated the benefits that the presence of the seawater pumped hydro storage plant of Foxi Murdegu bring to the Italian electricity system and regional level.

More importantly, the creation of new dams and reservoirs for hydropower implies serious interference with nature in the form of flooding terrestrial areas, land use change, modification of natural stream flow regimes, disruption of the river continuum, and change of terrestrial and aquatic ecosystems (Stolten and Scherer, 2013). Currently the construction of pumped hydro storage facilities requires drilling, blasting, and excavation. These activities affect the terrestrial ecosystem and biodiversity by area use and landscape fragmentation (Stolten and Scherer, 2013).

The main aim of this research is to determine the locations of potential sites for the seawater pumped hydro storage system. In so doing, a methodology was developed and used within ArcGIS.Pro to identify the potential sites. An assessment was done to classify these sites based on several criteria and the potential energy supply for each classification was determined.

METHODOLOGY

Study Area

Trinidad and Tobago is a member of the SIDS, located off the coast of Venezuela (Refer to Figure 1). It has a population of approximately 1,365,800 citizens living in an area of 5,128 square kilometres (MOPD, 2023). In 2010, Trinidad and Tobago generated 8.5 TWh of electricity with CO_2 emissions of 700 g per kWh generated. Trinidad and Tobago's electricity generation is almost 100% based on natural gas (Marzolf et al., 2015). When compared to international benchmarks for 2010, these figures demonstrate a high electricity consumption and CO_2 emissions per capita from energy-related activities at nearly 2.5 times the world average (IEA, 2020).

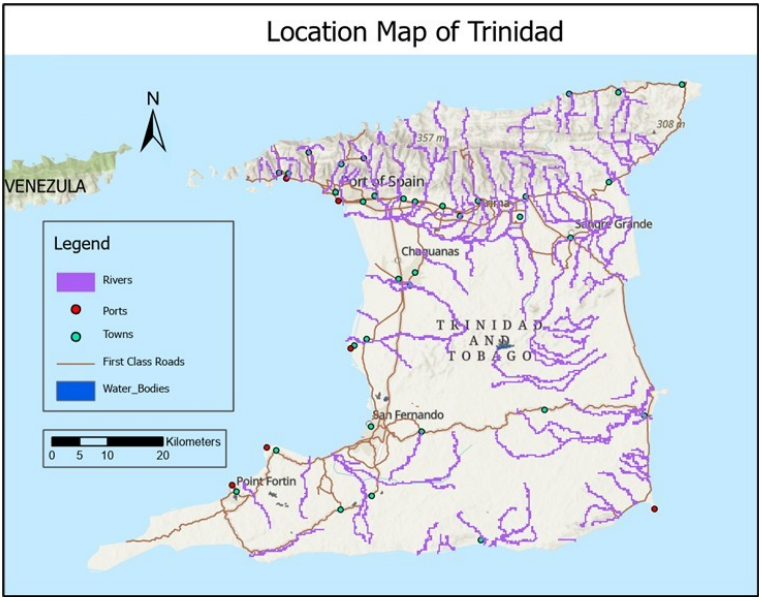

Figure 1: Location Map of Trinidad and Tobago

Datasets

Among renewables, hydropower provides a significant amount of energy throughout the world and is present in more than 100 countries. Given that the small island of Trinidad and Tobago is surrounded by water, there is an unexploited hydroelectric potential resource that can be utilized. In order to develop a sustainable hydropower system, baseline spatial data is essential to provide the starting point for discussion.

There were several environmental datasets that were modified and used within the site selection analysis. Table 1 below defines the numerical value of model's parameters and constraints while Table 2 below summaries the datasets used and the general tools that were applied to each before a weighted analysis was done.

Table 1: Model Parameters and Constraints

Parameter / Constraint	Value
Maximum Distance from Sea	10 km
Minimum Head	100 m
Minimum Area of Upper Reservoir	125,000 m^2
Minimum Volume of Upper Reservoir	1,000,000 m^3

Table 2: Datasets Used for Analysis and their Limitations.

Dataset	Geoprocessing Tools	Limitations
Digital Elevation Model	Feature to Raster, Slope, Reclassify	N/A
Coastal Outline	Buffer, Feature to Raster, Reclassify	N/A
Named Roads	Feature to Raster, Reclassify, Merge, Mask	Rural roads are not part of the dataset
Rivers	Feature to Raster, Reclassify, Merge, Mask	Minor tributaries are not represented
Water Bodies	Reclassify, Merge, Mask	N/A
Protected Parks and Forest Reserves	Feature to Raster, Reclassify, Merge, Mask	N/A
Geology	Feature to Raster, Reclassify	N/A
All Buildings	Feature to Raster, Reclassify	Complied in 2007

The Digital Elevation Model (DEM) is required to ascertain a reasonable operating head between the proposed upper reservoir and the lower reservoir (the sea). Generally, with a small head, either the rated power will be small or the investment will be high because of the larger turbines and basins. Ideally higher heads are preferred as they will decrease the construction and equipment costs. However, SIDS are generally low-lying islands and therefore a reasonable head must be found to result in a feasible outcome. In this respect, higher heads represent preferable site conditions and they will have higher scores.

In addition to the operating head, the other key parameter is the length of the waterway from the upper reservoir to the sea. Ideally the shorter the waterway length, the lower the cost and the lower the hydraulic losses. Hence the buffer tool was used for the coastal outline of the island. Therefore, the shorter the distance from the coastline, the higher the score.

Furthermore, the physical structure of the pumped hydro storage system will have impacts on the natural environment through habitat destruction and biodiversity loss Therefore, the protected parks, forest reserves and water bodies such as dams were excluded from the area of analysis. Similarly, the location of the rivers was also excluded from the area of analysis.

The soil characteristics of the geological location are also used to factor in the most suitable soil type of the construction of the upper reservoirs. Ideally, the soil type should be study and impermeable such as impermeable rock so that the foundation of the upper reservoir will be sturdy and there would be minimal possibility of leaks into the surrounding environment. Given the fact that seawater is being introduced within a closed loop that is surrounded by freshwater catchment areas, special care must be given to ensure that no seawater enters the freshwater streams and aquifers. Therefore, the more impermeable and the sturdier the soil, the higher the rating.

With respect to the social environment, the buildings dataset was used. Therefore, in order to have minimal impact on the social environment, the areas with highly populated houses were given the lowest rating while those with no buildings were given the highest rating. This will therefore reduce both the social impact due to resettlement and the cost associated with the resettlement.

Model Development

The methodology consists of taking the existing surrounding sea as a lower reservoir and analyzing the surrounding topography and environmental to determine if there is sufficient potential for the pumped hydro storage systems. The ModelBuilder application within ArcGIS.Pro was used to build the model within the restraints of the available datasets to identify potential seawater pumped storage sites within the island of Trinidad and Tobago. This modular design was selected as it allows for easy application of the model to different regions, and for substitution of data layers if new data becomes available.

Initially, the datasets were imported into the ArcGIS.Pro software and georeferenced. As shown in Table 2, each dataset underwent particular geoprocessing tools based on the constraints required for the sites. Most datasets had to be changed into a "Raster" file so that geoprocessing tools would be able to work within the domain. Then based on the constraint of the environment, particular geoprocessing tools were used to filter the potential locations for the seawater pumped hydro storage sites.

The surrounding sea will be used as the lower reservoir for each potential site. Since the site location of the lower reservoir is already established, the potential locations of the upper reservoirs must be established. As the length of the waterway is directly proportional to head loss and cost, a buffer zone from the coastline of a maximum range of 10 kilometres was used. Hence the buffer distance parameter 10 kilometres was used to define the search radius from the sea to potential upper reservoir sites, based on knowledge of existing terrain and the waterway range used in past research studies.

Moreover, it is appropriate to identify reasonable sites where it would be possible to construct a reservoir at high elevations on moderate slopes. Elevations lower than 100 meters were eliminated from the site selection as they were deemed to be too low for reasonable power generation. Additionally, the minimum reservoir capacity to be examined was limited to 1,000,000m^3. Being conservative by making the assumption that the average depth of the reservoir is 8 m, due to the rugged terrain in most of the higher elevations within the island, the minimum area of the upper reservoir would need to be 125,000m^2.

The remaining datasets such as major rivers, roads, geological fault lines, forest reserves and water bodies were used to "Mask" the sites to eliminate potential sites that overlay any rivers, roads, major fault lines, forest reserves and or water bodies. Then a weighted overlay analysis was performed with the site elevations being given the highest priority, the length of the waterway being given the second highest priority and the buildings being given the lowest priority (Table 3).

Within the scale for elevations, as aforementioned, only elevations greater than 100 meters were considered up to 900 meters within the island and graduated in equal increments for the 1 to 4 scale. With respect to the waterway length in equal increments from 0 meters to 10000 meters from the coastline was considered on the 1 to 4 scale. This was also similarly done for the building density with the island on the same scale. The scale was then renamed “Fair”, “Good”, “Very Good” and “Excellent” for the values 1 to 4 respectively.

Table 3: Selected weights for the Criteria used for the Weighted Analysis

Criteria	Weight, %	Scale
Elevations	60	1 to 4
Waterway Length	30	1 to 4
Building Density	10	1 to 4
	∑ 100	

Finally given the outcome of the weighted analysis map, there were several potential sites for upper reservoirs within each graduation of the established Likert Scale. Therefore, as a means of further evaluating these potential site classifications, the energy storage capacity for each site classification will be cumulatively calculated within ArcGIS.Pro. The total potential hydraulic energy available in within a body of water is defined in the equation below:

$$E = n\, p\, g\, h\, V \qquad (1)$$

Where, E is the energy available (Joules), n is the efficiency (assume 80%), p is the density of seawater (1020 kgm^{-3}), g is the acceleration due to gravity (9.81 ms^{-2}), h is the available head (m) and V is the estimated volume of reservoir (m^3).

RESULTS AND DISCUSSION

Applicable Sites

The output file from ArcGIS.Pro illustrated that there were several sites that could be potentially used for the upper reservoir of the seawater pumped hydro storage system (Refer to Figure 2). As shown, the majority of the sites were located on the northern part of the island. This is mainly due to the most mountainous part of the island being within the northern range. In addition, the island is relatively small and surrounded by the sea, therefore the coastline of the island is a relatively short distance away from any point on the island. Therefore, given the large buffer that was used, there were several sites that fit the criteria for the pumped hydro storage system.

It should also be noted that there were a few scattered locations for the potential sites within the central and south-eastern parts of the island. These sites may not result in much hydro power generation as they were classified as “Fair” but they can still be vital to supply power to a small community nearby or act as a backup in the event of a nearby power failure.

Overall, the sites were classified into four categories, given that they passed the minimum requirements and constraints listed in Table 1. Table 4 illustrates the number of sites found for each classification. Many of these sites that are neighbors can be grouped together and formed into a larger reservoir to generate a greater amount of energy within one system. However, with several of these sites, it would require extensive excavation and earth retaining structures. Therefore, for simplicity each site within each classification will be considered collectively and the summated energy from each site classification would be found.

With respect to Fig. 2, there is a defined classification for each site based on the environmental and social parameters implemented for the island. The “Fair” classification contained areas with elevations between 100 meters to 200 meters within a fair distance to the sea and moderate building density while the “Good” classification considers areas with elevations between 200 meters and 400 meters at a moderate distance to the sea with a moderate building density. The “Very Good” classification contained elevations between the range of 400 meters to 600 meters, a close distance to the sea and a low building density. The “Excellent” classification possessed the range of highest elevations within the island over 600 meters, relatively close distance to the sea and very low building density within the area.

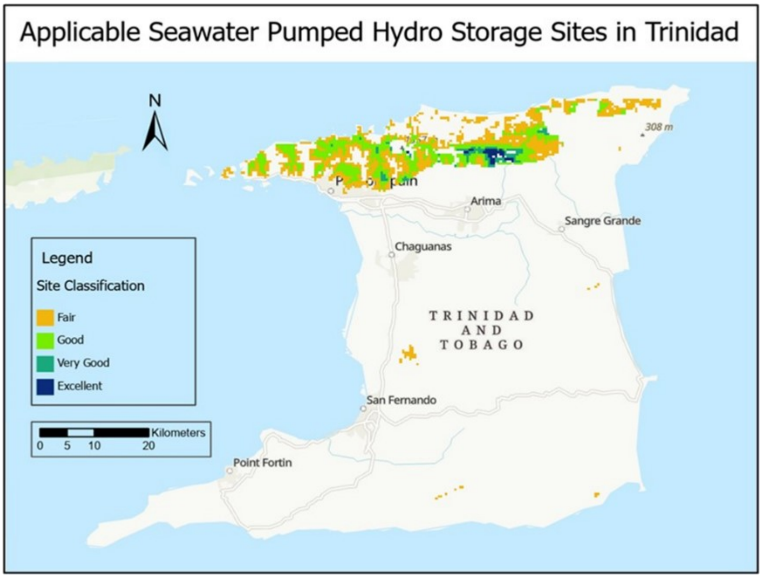

Figure 2: Map of Trinidad that Classifies the Applicable Sites for the Seawater Pumped Hydro Storage Systems

Estimated Power Generation

With reference to Fig. 2 and Table 4, for each site classification there is an estimated amount of energy that can be generated. The "Fair" site classification produced the greatest number of sites at 1127 with the largest estimated cumulative volume at 1.62 x 10^9 m^3. However, it was the second highest generator of energy at 25.98 x10^{14} J, with the highest generator of energy being the "Good" site classification. This was due to the combination of the increased average head within the "Good" site classification compared to the lower average head within the "Fair" site classification. It should also be noted that due to the scattered sites within the "Fair" selection, it would have the greatest cost to implement.

Additionally, there were a total of 108 sites that fell within the "Very Good" site classification and produced a total estimated volume quite close to the "Fair" classification of 1.56 x 10^9 m^3. However, given that the number of sites were less than 1/10th of the number of sites within the "Fair" classification, the total estimated energy was found to be 7.47 x^{14} J. There were only 41 sites that were classified as "Excellent" with the lowest storage capacity of 0.59 x 10^9 m^3 and the lowest estimated energy of 3.55 x 10^{14} J.

Moreover, irrespective of the total amount of sites, the total estimated storage volume, and the total estimated energy, one common trend was observed and that is that the estimated energy production per site within each site classification increased with the increase in the rating of the site classification. Therefore, the lowest estimated energy per site was within the "Fair" classification and the highest estimated energy per site was within the "Excellent" site classification.

Table 4: Total Estimated Energy that can be developed from the Seawater Pumped Hydro Storage Systems

Site Classification	No. of Sites	Total Estimated Volume, V_T, (m^3 x 10^9)	Total Estimated Energy, E_T, (J x 10^{14})	Estimated Energy per site, E_T, (J x 10^{12})
Fair	1127	1.62	25.98	2.31
Good	725	1.04	33.43	4.61
Very Good	108	1.56	7.47	6.92
Excellent	41	0.59	3.55	8.65
TOTAL	2001	4.81	70.43	3.52

CONCLUSION

This study has taken several environmental and social considerations, as aforementioned, in the selection of the potential seawater pumped hydro storage sites. In so doing a total of 2001 potential sites were found that can sufficiently generate substantial energy for the island. Of these 2001 potential sites, 1127 were within the "Fair" classification, 725 were within the "Good" classification, 108 were within the "Very Good" classification and 41 were within the "Excellent" classification. Moreover, given the factors that were taken into consideration, the "Excellent" site classification seems to produce the most efficient amount of energy at 8.65×10^{12} J per site.

The overall analysis of the estimated total energy that can be generated from the seawater pumped hydro storage system with the SIDS of Trinidad was found to be approximately 70.43×10^{14} J with a total estimated cumulative storage capacity of 4.81×10^{9} m^3. For this SIDS, this is more than sufficient energy to power the island. However, the cost to undertake all of these projects may not be feasible. Therefore, if this energy production option were to be constructed, it would be recommended to start with the collective "Excellent" site classification sites due to these sites being the most energy efficient.

Finally, with some refinements and the impact of newer and additional datasets for any respective SIDS, the methodology within this research can be used as a template for identifying potential seawater pumped hydro storage sites for energy production within the respective SIDS.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability statement

The data is owned by the Geomatics Engineering and Land Management Department of the University of the West Indies – St. Augustine Campus. The data can be made available, upon request.

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