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A Review of Caribbean Geothermal Energy Resource Potential

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Abstract: *The Caribbean Community (CARICOM) is comprised of fifteen-member states each exhibiting geographic, cultural and economic diversity. Six of these CARICOM member states along the Eastern Caribbean chain of islands display high-enthalpy systems for geothermal energy exploitation. This paper aims to provide a review into the geothermal energy resource potential across the Caribbean and presents quantitative findings as to the potential power production, economic and environmental savings through which geothermal energy development can bring to each respective nation. Notable findings for a 2027 scenario project an estimated 184.49 MW of geothermal capacity that can be absorbed into the national energy mix, displacing 855,600 barrels of oil (bbls) importation, resulting in approximately 1.1 million tonnes of carbon dioxide (tCO_2) emissions being avoided per year. An inter-island grid connection approach is presented to tackle large-scale energy projects to attract financial investors in an effort to combat the upfront challenges associated with geothermal energy development.*

Keywords: *Geothermal energy; Eastern Caribbean islands; Inter-island grid connection; Caribbean geothermal landscape, renewable energy*

1. Introduction

1.1 The Caribbean Energy Situation

The Eastern Caribbean islands within the Caribbean Community exhibit many geopolitical and socio-economic diversities. The fifteen-member island states encompassing CARICOM have all experienced the extent of the fluctuations of the cost of fossil fuel-based products. The existing dependence on the importation of petroleum products affects all CARICOM nations and as such there is a growing need for the transition to renewable forms of energy. The pursuit of enhanced energy security regionally can be obtained through higher penetration rates of renewables. Furthermore, a reduction in the price of electricity is expected through this foreseeable outcome. The averaged domestic retail cost of electricity within the Caribbean stands at around USD $0.35/kWh (Energy Chamber, 2017).

However, the region has progressed over the years in tackling this shared problem, and as such has yielded a regional Energy-policy in 2013 (Ochs et al., 2015). Policy frameworks complement and provide enhanced opportunities and energy diversifications for the continued transition towards greater penetration rates of renewables.

1.2 Building Climate Resilience

The Caribbean has recently been a strong advocate on the world stage for greater reductions in greenhouse gas emissions globally. Recent research, published in the Intergovernmental Panel on Climate Change (IPCC) Special Report on warming of 1.5℃ above pre-industrial levels, saw over 90 Caribbean and Latin American authors contributing to a body of data for increasing climate security for the vulnerable regional small island developing states (SIDS) (IPCC, 2018). The word "resilience" has been hotly debated within the Caribbean, as many scientists call for strengthening energy resources as a means to mitigate climate change impacts in the region (Gay et al., 2019; Chen and Stephens, 2018; Angeles et al., 2018; Shirley and Kammen, 2015). The Caribbean's energy infrastructure is aging and severely limited in its distribution across larger islands. Many islands rely on centralised forms of energy distribution which are further limited by crippling fossil fuel imports (Surroop et al., 2018). Climate resilience is thus built through modernising and restructuring the region's energy and transportation sectors to not only mitigate but adapt to already changing climate regimes.

The hurricane season of 2017 was a clear indication of work to be done. Eastern Caribbean islands such as Dominica and Antigua and Barbuda were devastated after the passage of Hurricanes María and Irma respectively. An increased intensity of hurricanes is expected through near- and long-term simulations for deep-convective tropical regions (Bhatia et al., 2019), and many Caribbean SIDS are waking up to energy resilience to combat climate change. Popke and Harrison (2018) provide a critique of Dominica's energy systems, both through a historical and current perspective, proposing that recent (and successful) ventures in geothermal power will bring much greater energy security to the island.

1.3 Geothermal Energy Impact

Geothermal Energy is also of interest due to its relatively minuscule carbon emissions whilst being able to supply massive amounts of energy due to high capacity factors (in excess of 90%). This allows for the plants to run non-stop, hence being a good producer of a more governable and consistent supply of baseload energy and heat as opposed to other renewable sources such as solar and wind (Dickson and Fanelli, 2005). Geothermal energy exploitation among Caribbean nations can play a key role in realising targets in energy security, economic development and mitigating the effects of climate change.

Through harnessing the stored thermal energy trapped within rocks, this resource can be utilised in generating electricity and direct applications. The paper aims to provide an update on geothermal energy within the Caribbean, especially within the Eastern Caribbean islands as these nations possess the indigenous resource. Furthermore, reanalysed data are presented for national energy targets, avoided costs associated with fossil fuel importation, beneficial contributions toward national energy grids, climate sensitivity and existing ideas on inter-island grid connections.

2. Caribbean Geothermal Landscape

2.1 Geothermal Energy - Hydrothermal Systems

Geothermal energy is a clean and renewable form of energy naturally occurring within the Earth as well as the primordial heat of planetary formation (Turcotte and Schubert, 2014). This form of energy can be thought of as heat mining. It is a result of the heat flow from the unhurried decay of naturally occurring radioisotopes, namely: Uranium 235, Potassium 40, Uranium 238 and Thorium 232 having half-lives of 0.7, 1.25, 4.5 and 14 billion years respectively (Adams et al., 2015; Kale, 2015), thus making this heat source almost inexhaustible and sustainable - at least on a human scale.

A naturally occurring geothermal resource (hydrothermal resource) has three major facets, a heat source (hot rock system, magmatic intrusion), fluid (fluid-filled reservoirs, subsurface interconnections to fluid pockets – the resulting fluid is generally the result of contributions from different sources such as surface/meteoric water, seawater, and magmatic volatiles) (Nicholson, 1993), and a permeability network (the reservoir must be conducive to allow fluid flow). The increase of temperature per unit depth within the Earth (crustal region specific for geothermal energy exploration purposes) is defined as the geothermal gradient. This gradient can vary from one location to the other; however, it averages 25-30 ºC/km in most regions (Haraksingh and Koon Koon, 2011).

The Eastern Caribbean comprises of a chain of geologically young volcanic islands where the thermal gradient is even higher than average. Some notable volcanic systems across the islands are, Mt. Liamuigua in St. Kitts, Nevis Peak in Nevis, Soufrière Hills in Montserrat, La Soufrière in Guadeloupe, Soufrière Volcanic Centre in St. Lucia, The Soufrière in St. Vincent, and Kick 'em Jenny (submarine), Ronde/Caille and Mt. St. Catherine all of Grenada (Stewart I 2000).

Coupled with a complex tectonically active region (exhibited by the Caribbean plate as seen in Figure 1) this presents many naturally occurring hydrothermal systems within the Caribbean, as such making certain islands prime for geothermal energy exploitation. Thermal manifestations such as fumaroles, hot springs, dormant and active volcanoes across the Caribbean islands are predominantly associated with the subduction of the North Atlantic crustal plate beneath the Caribbean plate and also being a seismically active region (Huttrer and LaFleur, 2015). A tectonically active regime creates a more advantageous subsurface profile, enhancing permeability at depth, allowing a greater extent of fluid transfer, and can also aid in magma intrusion.

Figure 1: The tectonic plates seen across the Caribbean islands. Source: Google Earth (2018)

Amongst the fifteen CARICOM member states, the six islands of Dominica, Grenada, Montserrat, St. Lucia, St. Kitts and Nevis, and St. Vincent and the Grenadines all exhibit immense untapped geothermal energy potential. With an except for the 15 MW geothermal electricity production power plant in Guadeloupe, there is no other established power plant among the CARICOM member states. The geothermal potential for these six islands of interest can be seen in Figure 2, all along the Eastern Caribbean chain of islands (Ochs et al., 2015). Further details into these six islands of interest as to the resource potential, location, depth of exploratory wells and temperatures are tabulated in Table 1.

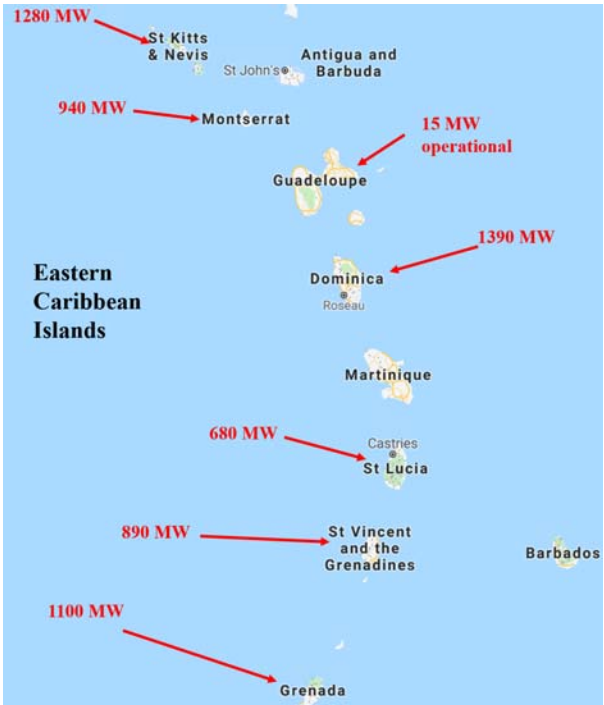

Figure 2: Exploitable potential geothermal energy for ECIs of interest

2.2 Energy Security Through Geothermal Exploits

Through carefully controlled conditions an extraction well is positioned into the reservoir to obtain high-enthalpy fluid trapped within the crustal region. The stored energy within the hot geofluid (naturally occurring fluid found in rock formations) in a pressurised form is extracted through steam turbines, rotating a mechanical shaft connected to a generator which produces electricity. It must be noted that the fluid obtained from condensation (energy extracted from the steam, hence a phase shift to the liquid form) is reinjected back into the reservoir at a calculated depths and radial distances from the extraction well. Hence, injection wells supply fluid back into the reservoir to maintain a sustainable balance, and as a result, this avoids depletion of the resource.

Geothermal sources are classified by their temperature into two main categories: High-enthalpy (exceeding 150 ºC) or low-enthalpy (less than 85 ºC) (Nicholson, 1993). Regions of high tectonic activity are usually analogous to high-enthalpy sources which can be used for the generation of power and heat, whereas the production of heat is the main use of low-enthalpy sources; all these are in more tectonically indolent regions (Matek, 2014). All six ECIs of interest possess high-enthalpy geothermal resources with temperatures exceeding 150 ºC as seen in Table 1. The ECIs have an opportunity to truly become energy independent from conventional fossil fuel importations.

Through the Caribbean Sustainable Energy Roadmap and Strategy (C-SERMS) data are obtained in regard to these six islands national renewable energy targets as a percentage share of the total generation to meet CARICOM's target of 47 % by 2027, and the respective annual fossil fuel importation costs (for 2015). Apart from St. Vincent, all others can have a 100 % transition to achieve their national target. Furthermore, approximately US$529 million accounts for fossil fuel importation collectively among the six ECIs as seen in Table 1. The implementation of geothermal power plants can provide reliable baseload power into the energy mix and satisfy energy demands. Section 3.3 of the paper further explores the extent of energy demand and production and the reduction of power required to be transmitted along the grid.

3. Geothermal Resource and Potential

This section delves into matters that will address the issue of possible cases of geothermal energy installations solely across the six ECIs. Therefore, it examines

Table 1. National energy targets, fossil fuel importation and resource potential for the six ECIs

Country	National Target (%)[a]	Annual Fossil Fuel Import Costs [a]	Comments on resource potential [b,c,d,e]
Dominica	100	5 % GDP ~ USD 27 million	Wotten Waven area, temperatures above 235 ºC were recorded around 1500 m in depth[b]
Grenada	100	18 % GDP ~ USD 159 million	A small solfatara has been revealed through pre-feasibility studies on Mt. St Katherine[b]
Montserrat	100	29 % GDP ~ USD 12 million	The highest recorded temperatures were in well MON-2. This was 265 °C at 2870 m[c]
St. Lucia	100	16 % GDP ~ USD 225 million	Hot resource of 230 ºC at moderate depths; hot dry rock up to depths of ~ 2 km[b]
St. Kitts and Nevis	100	4 % GDP ~ USD 33 million	At Nevis, 3 exploratory wells were drilled to depths of 782 m - 1,134 m. All 3 wells encountered temperatures in excess of 225 ºC. Reservoir temperature is projected at least 260 ºC[e]
St. Vincent and the Grenadines	81	10 % GDP ~ USD 73 million	Exploratory drilling reached depths of 1 km - 3 km, within the presence of temperatures up to 230 ºC within the geothermal reservoir[d]

Sources: Compiled from, [a] Ochs et al. (2015), [b] Huttrer and LaFleur (2015), [c] Ryan et al. (2019), [d] Environmental Resource Management (2016), and [e] LaFleur and Hoag (2010)

Table 2. Reconstructed data for geothermal energy installation, generation, avoided fuel imports and greenhouse gas emissions for the six ECIs

Eastern Caribbean Island	Estimated geothermal installed capacity, 2027 (MW)[a]	Estimated annual geothermal electricity generation (GWh/year)[b]	Estimated savings from avoided fuel imports (US$million/year)[c]	Estimated annual avoided greenhouse gas emissions (million tCO_2e/year)[d]
Dominica	19.32	152.32	4.48-8.96	0.12
Grenada	40.48	319.14	9.39-18.77	0.24
Montserrat	2.68	21.13	0.62-1.24	0.02
St. Lucia	50.00	394.20	11.59-23.19	0.30
St. Kitts and Nevis	49.87	393.18	11.56-17.35	0.30
St. Vincent and the Grenadines	22.14*	174.60	5.13-10.27	0.13

b - A 90 % capacity factor is assumed for the geothermal power plants.
c - A conversion factor of 1700 kWh = 1 barrel of oil equivalent (boe) was utilised (SPE 2019), after which an oil price range of US$ (50 - 100)/bbl was investigated as a minimum and maximum range.
d - An emission factor of 760 gCO_2e/kWh is utilised (Honorio et al., 2003).
*50 % of the oil imports are assumed to be displaced through geothermal energy as a benchmark.
Sources: Compiled from, [a] Ochs et al. (2015), [c] SPE (2019), and [d] Honorio et al. (2003)

future installations in 2027, this is consistent with data obtained from the C-SERMS report. Table 2 is reconstructed data that immediately provides a keen insight into the immense untapped power geothermal energy possesses. The aforementioned of fossil fuel importation collectively among the six ECIs accounted for US$529 million. This daunting financial burden is shared by all members; however, this can be alleviated through higher penetration rates of renewables. Collectively, there exists an estimated geothermal energy potential of 6280 MW (Ochs et al., 2015).

The manner in which this huge resource is exploited and managed can chart a new financially, climatic and societal course for each nation. Further, details to note in the reconstruction of Table 2 are the reanalysed conversion factors to obtain the number of barrels of oil (bbl) from the calculated MWh/year (SPE, 2019). In addition, the ECIs mainly employ the use of low-speed diesel engines to generate electricity. This results in emissions factors of some 760 gCO_2e/kWh (Honorio et al., 2003).

Realising the potential for geothermal energy integration through distributed generations into the utility across each respective nation presents a major opportunity to increase energy security, whilst improving the balance of trade by reducing oil importation. Furthermore, three crucial advantages are addressed through a higher penetration rate of renewable and geothermal in particular. These three areas are:

1. The economic aspect, in terms of avoided costs, implies saving as a result of the reduction and dependence on fossil fuel-based products.
2. The environmental and climatic aspects in terms of the reduction in the number of barrels of oil imported per year resulting in a beneficial decline in the number of tonnes of carbon dioxide emission avoided.
3. The utility and more so the enhanced grid flexibility of having geothermal energy integration into the national grid.

3.1 Economic Analysis

The possibility of the CARICOM to attain the renewable energy target of 47% by 2027 is ambitious, however, highly probable given the intervention to aggressively pursue geothermal energy implementation. It can be noted from Table 2 that an estimated 184.49 MW of geothermal capacity can be absorbed into the energy mix across invaluable base-load power. A major economic alleviation is certainly realised if the national energy targets are attained as stated in Table 1. The findings clearly show that the reliance on the importation of fossil fuel products for electricity generation can be drastically reduced. It is calculated that an estimated 855,600 bbls through importation can be displaced collectively across all ECIs. A breakdown into the estimated number of bbls per island displaced is illustrated through the label callouts as seen in Figure 3.

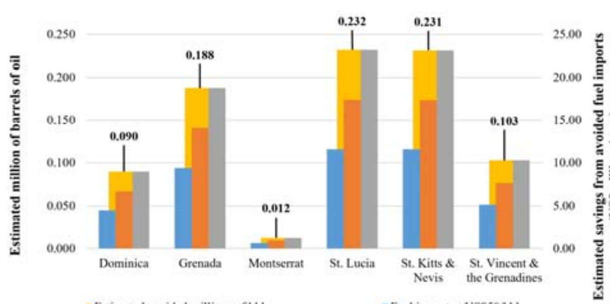

Figure 3: Estimated avoided importation of bbl and perturbed cases of the price per bbl

Three cases are used to further display the idea of the variation of the price per bbl at US$50.00, US$75.00 and US$100.00 accounting for roughly, US$42.78 M/year, US$64.17 M/year and US$85.56 M/year, respectively. It can be noted that Dominica possesses that largest exploitable potential geothermal resource of 1390 MW, followed by St. Kitts and Nevis (1280 MW) and Grenada (1100 MW), however, this does not necessarily translate to the same order of potential implementation.

3.2 Towards a More Climate-Sensitive Region

The Caribbean islands are geographically positioned at lower latitudes and in direct relation to the vast Atlantic Ocean. The lessons of the 2017 hurricane season and a changing climate regime have clearly illustrated to Caribbean island governments the impacts of extreme events, particularly on energy resilience and security (Klotzbach *et al*., 2018; Popke and Harrison, 2018). The enhanced drive for higher penetration rates of distributed generations are key to aid in the reduction of greenhouse gases (carbon dioxide in particular) being released into the atmosphere.

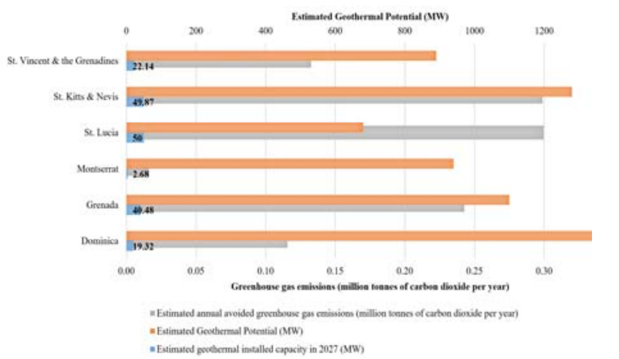

Figure 4: Estimated geothermal potential and installation capacity to displace avoided CO_2 emissions

Potential geothermal generation is estimated at 1.1 million tCO_2e/year collectively across all six ECIs, with a further breakdown per island as seen in Figure 4. Both St. Lucia and St. Kitts and Nevis each exhibits the largest quantities of avoided carbon emission, roughly 0.3 million tCO_2e/year, resulting primarily from each also leading in estimated 2027 installed capacities of 50 MW and 49.87 MW respectively. In addition, geothermal power plants neither releases nitrogen oxide nor particulate matter thus promotes a cleaner environmental impact positively on sustainable tourism as a key driver in many nations.

3.3 Promoting a More Resilient Grid Network

In addition to the installation of geothermal energy among the nations of interest other forms of renewables are being pursued. Solar and wind energy industries are leading the charge in terms of installation and power provided to the national grid. However, the intermittent nature of solar and wind energy adds complexity and variability to the grid. Hence with an increase in the penetration rate of renewables, the national grid must enhance its flexibility. Grid flexibility is required to incorporate fluctuations in demand throughout the day. Unexpected situations such as malfunctions or climatic conditions can affect the power supply (as with the cases of wind and solar energy). However, geothermal energy provides base-load power, a more reliable form of power. It has a high capacity factor of up to 90 % and is not affected by climatic conditions. Hence a constant power supply can be provided to the grid, without additional costs to enhance its flexibility.

More importantly, the reconstructed data from Table 2, indicates at a capacity factor of 90 %, having a full installation of geothermal power plants by all nations will account for 184.49 MW (1454.52 GWh/year) in 2027, of an averaged peak demand of 335 MW. The dearth and dependence on hydrocarbon resources for most ECIs have resulted in a high importation of fossil fuel to meet their energy demands and thus high rates of electricity. This realisation is clearly illustrated in Figure 5 with nations such as Grenada, Dominica, and St. Lucia having higher than average prices of electricity of US\$0.43/kWh, US\$0.38/kWh and US\$0.34/kWh respectively. However, Grenada, Dominica and St. Lucia are projected to have roughly 60%, 70%, and 45%, respectively of their power to be supplied by geothermal energy in 2027. This will hugely impact their economies providing a much cheaper form of indigenous readily available power.

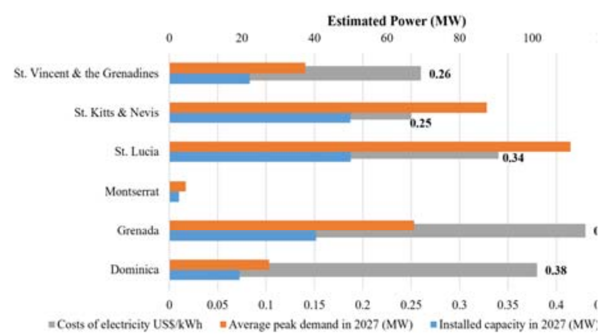

Figure 5: Estimated average peak demand, installed capacity and cost of electricity per island

4. Inter-Island Grid Connections

There have been two inter-island grid connection ideas previously published by Maynard-Date (2015). These two possibilities are the *Dominica-Guadeloupe-Martinique* and *St. Kitts and Nevis* inter-island connection plans. The approximate distance to cover via submarine cables for electrical transmission of high-voltage is about (45-50) km both ways between Guadeloupe - Dominica, and Dominica - Martinique. Clearly, these islands are relatively within proximity to each other to make this plan quite viable. Guadeloupe's 15 MW geothermal electricity production power plant in

Bouillante is the only such plant currently in the Caribbean. Dominica stands out among the Caribbean islands in terms of geothermal potential. Even the 2027 forecast has Dominica at roughly 1.4 % installed capacity out of its total resource. Such a small percentage of 1.4 % is enough to satisfy approximately 70 % of its power demand in 2027.

Hence Dominica can become a leader within the inter-island grid connection scheme and also across the Caribbean. The other proposed inter-island grid connection scheme is that of *St. Kitts- Nevis*. The distance between these two islands is about 3.5 km (from coast to coast) making the installation of submarine cables even more attractive. Once more roughly 3.9 % of the total resource potential is utilised in the proposed plans at 2027, clearly reiterating the immense potential for power production inherent with geothermal energy exploits.

The realisation of the potential for these inter-island grid connections and for geothermal installation throughout the islands have been hindered by shared challenges. A lack of energy diversification, uncertainty in energy prices (as most energy schemes are based on oil and gas industry prices) are among a few hindrances encountered throughout the Caribbean for the transition to renewables. Geothermal energy inherently possesses a much larger upfront, initial costs when compared to other renewables.

In addition, geothermal energy exploitation and implementation are categorised as a large-scale renewable energy project, and as such many of these ECIs lack the size to self-sufficiently challenge such projects in an attempt to attract volume-oriented international financial markets (Ochs et al., 2015). Therefore, a collaborative stance by groups of nations such as the inter-island plans can prove beneficial to attract and establish financial opportunities on a regional scale and as such is an alternative approach in tackling geothermal energy projects.

5. Conclusion

The Eastern Caribbean islands possess a profound opportunity through the integration of geothermal energy into their national energy mix to ensure a greater sense of energy security, economic diversification, and growth. These high-enthalpy hydrothermal systems collectively provide an estimated energy potential of 6280 MW, as such provides these islands to distinguishably carve massive socioeconomic, and environmental benefits. Extensive documentation through feasibility studies and reports on exploratory wells have confirmed and localised sites of geothermal reservoirs for all six ECIs.

In 2015, importation of fossil fuels accounted for US$529 million, with Dominica, St. Lucia and Grenada having the highest price of electricity. As such, the findings indicate an estimated 184.49 MW of geothermal capacity can be absorbed into the national energy mix, displacing 855,600 bbls imports, resulting in approximately 1.1 million tonnes of carbon dioxide emissions being avoided per year. Geothermal integration leads to reliable base-load power to the grid, ensuring cleaner and cheaper power readily available, resulting in an eventual reduction in the price of electricity well below the Caribbean average of US$0.35/kWh. Finally, the upfront challenges associated to implement large-scale energy project can be tackled through an inter-island grid connection approach to allure financial investors.

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Randy Koon Koon *is currently a lecturer in renewable energy at the Department of Physics, The University of the West Indies (UWI), Mona campus. His desire for enhanced renewable energy integration throughout the Caribbean coupled with active research in renewable technologies and energy efficiency methods positions him as an avid renewable energy advocate.*

Sheldon Marshall *is a postgraduate student pursuing an MSc Renewable Energy Management with special interest in renewable energy technologies and solutions. He is a certified Photovoltaic Associate through the North America Board of Certified Energy Practitioners, thus solidifying his keen interest in renewables.*

Dawin Morna *is a postgraduate research student in the Department of Physics, UWI, Mona, who is currently pursuing a full-time MPhil degree in Physics. He has a particular interest in Fire Dynamics, Material Science, Optics as well as modelling and simulations of aspects of Raman spectroscopic systems using COMSOL Multiphysics.*

Randy McCallum *is currently a Secondary School Teacher in Physics who attained a BSc. in Medical Physics at UWI Mona. He has interests in Material Science such as red mud as pozzolan for Portland cement, skid resistance testing using glass and most importantly renewable energy applications particularly because of his time spent at the University.*

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