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ABSTRACT

This paper presents an alternative to the current use of gasoline and diesel for transportation in Barbados. By relying on experimental evidence, it shows that biomethane emanating from the combination of Sargassum seaweed that is found on the seashores of the country with wastewater from rum distillery production can be used to produce an alternative transportation fuel. If implemented successfully, this alternative combustion method can avoid as much as 1 million metric tons of CO_2 emissions every year in the country. These findings have important implications for policymakers. First, they can contribute to the national objective of becoming fossil fuel free by 2030 and diversifying the energy matrix. Second, this alternative fuel can improve resilience to natural catastrophes, complementing the transition to renewables and diversification of the sector. Third, the impact on the tourism industry is expected to be high and positive, as the Sargassum seaweed has been declared a national emergency due to its prevalence on beach tourism spots.

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1. Introduction

Barbados has recently seen a surge in households' use of appliances, which has led to an increase in their use of electricity, despite a general decrease in overall total energy usage (Howard 2020). Similarly to other small island developing states (henceforth SIDS), Barbados depends considerably on imported fossil fuels for energy consumption. For instance, between 1998 and 2009, oil importation climbed from 7 percent to 20 percent due to increased energy consumption, surpassing food and beverages, and continues to do so (Moore 2011). Currently, total energy consumption per capita is equivalent to 5.03 barrels of oil equivalent (bbl) per person per year in Barbados (U.E.S 2017) and the country imports 35,000 bbl to 40,000 bbl of ultra-low sulfur diesel and unleaded gasoline up to twice a month, depending on local demand (Cox 2019). The total daily diesel consumption ranges from 1,125 to 1,300 tons, with a total daily gasoline consumption ranging from 1,900 tons to 2,500 tons (Moore et al. 2016).

This dependency on imported fossil fuel is problematic for two reasons. On the one hand, Barbados' high reliance on imported oil suggests vulnerability to world commodity prices and to their shocks. As a result, the government of Barbados recently published a National Energy Policy (Ministry of Energy and Water Resources 2019) that highlights its commitment to becoming fossil fuel free by the year 2030, calling for the diversification of its energy sources. On the other hand, prevalent fossil fuel deployment in Barbados is aligned to the worldwide energy consumption practices that have led to climate change, to which Barbados is particularly vulnerable (York et al. 2019; Johnson et al. 2019; Tang et al. 2020; Jamshidi et al. 2020; Baes et al. 1977). Indeed, over the past four years, climate change has led to the most catastrophic and destructive Atlantic hurricane seasons in the Caribbean region (Robinson et al. 2019; Moulton et al. 2019; Keelings et al. 2019; Zegarra et al. 2020; Shultz et al. 2020; Carroll et al., 2019).

One of the major contributors to the carbon footprint in Barbados and in the Caribbean is the widespread regional use of fossil fuels, not only for electricity generation, but also for transportation (Sheinbaum-Pardo et al. 2012; Gay et al. 2018; Cox 2019).

In 2015, roughly a fifth of total Caribbean regional CO_2 emissions came from transportation in the Caribbean. In Barbados alone, more than half of CO_2 emissions came from that sector (LAC-OLADE 2020). In fact, based on present usage, without the changes in current local habits expected from the new national energy policy, Barbados traverses a path that can produce over 2 million tons of CO_2 emissions from fuel combustion by 2040 (Moore et al. 2016). In Barbados, the national fleet consists of approximately 136,400 registered vehicles (Ministry of Transport, Works and Maintenance 2020), with most of the cars being run on petroleum via internal combustion engines. In recent years, there has been a small private-sector-driven penetration of electric vehicles into the country's transportation sector, where there are now upwards of 50 charging ports and 300 licensed electric vehicles (Edgehill et al. 2014), and one of the largest fleets of electric buses per capita in the world. However, with most charging points connected to the mainly fossil fuel powered national grid, these vehicles and electric buses have not yet begun to significantly reduce the emissions from transport.

One potential alternative to the issue just mentioned would be to have electric vehicles powered by renewable energy sources, which would reduce transport related CO_2 emissions. Nonetheless, at this stage, the purchase of electric vehicles alongside solar home-charging ports still poses a financial challenge to most persons anywhere in the world (Tsioloaridou et al. 2004; Edgehill et al. 2014).

Considering all these challenges and the 2030 objective of a fossil fuel-free and carbon neutral Barbados, the present work investigates the use of biofuels as a complementary alternative for transportation. More specifically, biomethane, which is a transportation fuel, can be produced by the anaerobic digestion of organic wastes or dedicated energy crops, producing biogas which contains biomethane (Uusitalo et al. 2014). The required biomass can be obtained from agricultural and forestry waste, grasses (Holder et al. 2020; Holder et al. 2019), sugar cane (Kennedy 2001), landfill gas, municipal solid waste, and other crops planted specifically for energy production (Sims et al. 2003). The disposal of some agricultural and forestry residue such as bagasse, rice husks, bark and saw dust, usually comes at a CO_2 emissions cost, meaning that their disposal requires the use of energy. For their disposal to become carbon neutral, sustainable re-purposing of these materials to produce energy is necessary (Sims et al. 2003).

In parallel to the increased interest in using biofuel as an alternative fuel for transportation, a recent phenomenon that has been taking place on the coastal shores of Barbados, as well as neighboring countries, is the increased prevalence of Sargassum seaweed. The latter is a marine macroalgae that has inconveniently inundated beach tourism spots at alarming rates and was recently declared a national emergency in Barbados. This increase in Sargassum seaweed is expected to worsen (Wang 2019). Due to the novel nature of the recent escalation in Sargassum seaweed influx, the Barbados Ministry of Maritime Affairs and the Blue Economy is now in the process of developing their Sargassum Adaptive Management Strategy. Studies such as the present work can help to shape the regulatory framework around Sargassum seaweed for Barbados and the wider Caribbean. Thus far, Sargassum seaweed is easily accessible and free. It can be used as a biofuel feedstock. Exploiting Sargassum seaweed also supports the idea of the circular economy (Saldarriaga-Hernandez 2020).

Therefore, the present work is centered around three research questions. First, how can the 2030 fossil fuel-free and carbon neutral objective be reached in the transportation sector of Barbados? Second, how useful is biomethane as an alternative fuel for transportation to meet this objective? Third, what are the potential economic and environmental implications of using biomethane from Sargassum seaweed for transportation purposes?

To answer these, an experiment was carried out that combined and processed Sargassum seaweed samples collected on the Barbados coast with wastewater from local rum distilleries to produce biomethane. The latter can then be used in Compressed Natural Gas (henceforth CNG) vehicles as a transportation fuel. The reasons why CNG vehicles are relevant in this specific case are manifold. First, they can be driven completely on biomethane (Alamia et al. 2016; Miltner et al. 2009). Second, seventeen demonstration CNG vehicles operated by staff at select government and university offices, are already operational in Barbados (Cox 2019) and there are larger numbers in the wider Caribbean region, particularly Trinidad and Tobago where the CNG business is successful (Green et al. 2017). Third, there is currently a high penetration of CNG vehicle maintenance and repair expertise in the Caribbean region (ibid.). Finally, there exist CNG conversion kits to enable conventional gasoline-powered internal combustion engine vehicles to run on CNG (ibid.). These, along with the refueling cylinder, cost approximately $500 USD (Nathaniel 2012). For all these reasons, it can be argued that biomethane is a potential alternative transportation fuel, and that its use can contribute to Barbados's 2030 fossil fuel free target.

The rest of this paper is organized as follows. The next section details the motivation behind the transition from fossil fuel to biofuel, citing economic, environmental and climate viewpoints. References to successful international case studies are also made. The third section provides an estimate of the benefits that a full transition to biomethane could have in terms of CO_2 emissions. The fourth section describes our anaerobic digestion experimental set-up and presents the results of the anaerobic digestion experiment. We then conclude in the fifth section by summarizing the findings and outlining limitations.

2. The call for a transition from fossil fuel to biofuel

Several factors motivate the transition from fossil fuel to biofuel (particularly biomethane) for the transportation sector in Barbados. One of them is the economic need to diversify the energy matrix, as 91 percent of energy consumption in Barbados is supported by fossil fuels, most of which are imported. This large share renders the country's economy fully dependent on imported fossil fuels. Thus, new policies and decisions made by OPEC, unpredictable pressures from changing international markets, as well as global crises (Sharif et al. 2020; Barsky 2004) have subjected oil-dependent SIDS to economic shocks and have forced these vulnerable economies to obtain loans for basic needs on several occasions (Niles et al. 2013).

Another factor is linked to the widespread worldwide transport-related practices which result in heightened CO_2 emissions of transportation globally. Approximately 15% of total global CO_2 emissions, resulting in a climate crisis, are due to the use of gasoline and diesel in road transport. Thus, the transport sector is seen as one of the largest emitters of greenhouse gases in the world (Uusitalo et al. 2014). Barbados, though small, can have tangible impacts on the global climate crisis by shifting its entire transportation sector from being principally fossil fuel-powered to being fully renewable energy-powered.

Given its geographic location, Barbados is particularly susceptible to natural disasters like hurricanes, flooding and landslides that are worsened by climate change. This necessitates heightened resiliency in its energy generation infrastructure. Liquid fuel energy sources such as biofuel provide an added layer of resilience, compared with other sources of renewable energy such as solar PV systems which cannot always withstand today's hurricane speeds.

Biofuel is particularly beneficial for converting Barbados's transportation sector since it offers the possibility of re-purposing existing fossil-fuel infrastructure (pipelines, refueling stations, internal combustion engines) rather than stranding all fuel-related assets, infrastructure, and expertise (Green et al. 2017) in the coming fossil fuel-free context. This is relevant in the case of Barbados, as internal combustion engine vehicles driven on fossil fuels dominate the transportation sector: 116,508 gasoline vehicles, 19348 diesel vehicles, and 352 electric vehicles make up near 100% of the national fleet (Barbados Ministry of Transport, Works and Maintenance 2020).Transitioning from this form of transportation to one which is fossil fuel-free would require a strategy that converts all registered vehicles to fossil fuel-free drive trains (Gay et al. 2018).

One type of locally produced biofuel in Barbados that has the potential to drastically reduce the dependency on imported fossil fuels for energy consumption is compressed biomethane. Biomethane is an indigenous, gaseous, and sustainable transport fuel that requires the anaerobic digestion of an organic feedstock to be produced. In some countries, biomethane is also used to displace natural gas for electricity generation and then the digestate from the anaerobic digestion process is used to displace synthetic fertilizer (Pourbafrani et al. 2013). Through biofuels, CO_2 emissions can be greatly reduced (Browne et al. 2011), although this calls for strategic planning, as the overall emissions reduction of the process is not automatic.

The production of biogas and biomethane in the Caribbean has gained increasing coverage in recent years, though it has been present in the region for decades (Silva-Martinez and Pereira-Sanchez 2018). The literature reports different biomass resources, depending on the country. For instance, in Belize, the biomass resources come from municipal (i.e., sewer and solid) waste, banana agricultural waste, shrimp waste, chicken manure, and citrus waste (Schmit et al 2016). In Haiti, it mostly comes from agricultural wastes, domestic wastewaters, and animal manure (Silva-Martinez and Pereira-Sanchez 2018). Other countries like the Dominican Republic or Cuba have their biomass coming from the sugar cane industry, among others (ibid.). In the case of Barbados, the production of biogas and biomethane are projected to also come from the sugar cane industry for two reasons. First, sugarcane has a high potential for energy production, as it is a C4 plant (Kocar et al. 2013). Second, it has proven to be successful as a biomass resource in countries such as Brazil. However, further research is being executed in Barbados to evaluate the possibility of using other grass sources (Holder et al.

2019). In the present work, and in other recent publications, Barbados' naturally occurring abundant Sargassum seaweed inundation is being actively tested for its biofuel potential (McKenzie et al. 2019).

On a large scale, the resulting biomethane can be distributed using existing natural gas pipelines (as Figure 14 below shows), as well as via trucks as liquefied biomethane and compressed biomethane (Dada et al. 2017).

The remaining part of this section takes a closer look at three of the motivating factors behind the transitioning from fossil fuel to biofuel, which are specific to Barbados and therefore worth detailing. First, we zoom in on the natural disaster exposure and the resilience of renewables' infrastructure at the geographical location of this small, oil-dependent island to provide a better understanding of the climate change-related challenges it faces, along with its neighbors. Then, the study takes a closer look at the sugar cane industry in the country to explain why it might not be as sustainable a source of biomethane as expected. This section concludes by exploring the advantages of converting internal combustion engine vehicles to CNG vehicles based on international successes.

2.1 Exposure to natural disasters and infrastructure resilience in the Caribbean

As previously stated, a shift of the transportation sector from fossil fuel to biofuel would considerably reduce the imported fossil fuel dependency, lower CO_2 emissions, and prove to be beneficial towards mitigating global climate change. SIDS bear the brunt of global climate change effects, are more affected by rising sea levels, and face more frequent and stronger extreme weather, including hurricane devastation, landslides, flooding, beach erosion and land erosion (Schubert et al. 2017). A natural hazard is defined as any natural process that poses a threat to human life or property, or any interaction between humans and a natural process, which results in significant property damage, injuries, or loss of life (Keller et al. 2016).

The Caribbean region is naturally disaster-prone because of its geographical location, putting the islands at risk of damage by atmospheric processes, such as hurricanes and tropical storms, floods, with rock types, faults and terrain that make it susceptible to damage from landslides and other geological processes (Ahmad 2007).

The most common, and often the most devastating of the natural hazards affecting the Caribbean region, are hurricanes, which have left lasting effects in islands such as Dominica, Grenada, and the British Virgin Islands, and most recently in The Bahamas, to cite a few. Hurricanes affecting the Caribbean, also known as tropical cyclones, form over the warm water in the Atlantic Ocean, and are fueled by the warmth (Keller et al. 2016).

Tropical cyclones are classified based on their wind speed, from the lowest wind speeds of a tropical depression (33 kt or less) to a tropical storm (34 kt to 63kt) to a hurricane (64 kt and greater). Due to global warming, hurricanes have become significantly more severe, as well as more common. For example, there were two category 5 hurricanes that ravaged the Caribbean region in 2017 alone. In 2020, a record number of hurricanes have also traversed the region, due to climate change.

Undoubtedly, over the years, the region has been impacted by hurricanes. Figure 1 tracks hurricanes in the Atlantic Ocean from 1851 to 2016. Blue lines signify tropical depressions, green lines signify tropical storms, yellow lines signify category 1 hurricanes, orange lines signify category 2 hurricanes, red lines signify category 3 hurricanes, pink lines signify category 4 hurricanes and purple lines signify category 5 hurricanes.

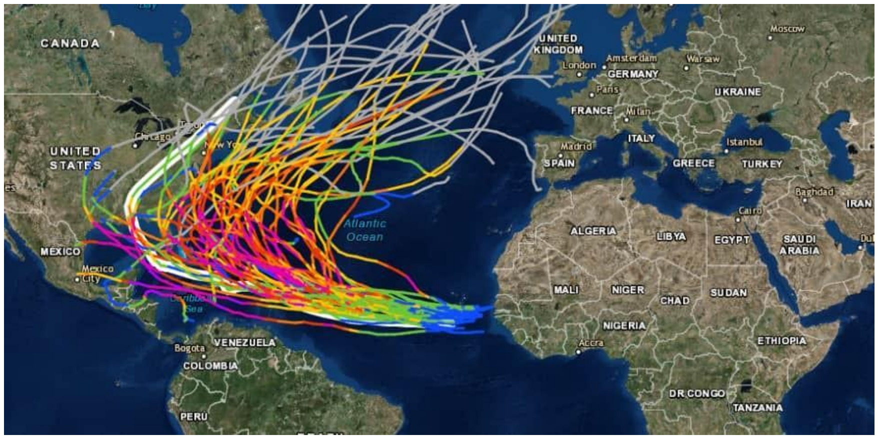

Figure 1: Figure showing Hurricane Tracks in the Caribbean (Kosin et al. 2010)

Barbados is, like many of the SIDS surrounding it, vulnerable to natural disasters, because of its geographical location. It is mostly exposed to hurricanes, floods, and landslides. When determining sources of renewable energy for SIDS, resilience to hurricane and other natural disasters is a major factor to consider. Wind and solar energy have been applied and tested in several of the islands of the Caribbean. However, with the increasing number of intense hurricanes, these sources cannot be considered on their own due to their vulnerability. For instance, evidence of damage to wind farms caused by hurricanes was recently found in SIDS in the Caribbean region (Kwasinski & Alexis 2018). In most instances, the damages were caused when turbines were stuck in one position (due to power outages), unable to rotate and adjust to the wind direction to reduce wind damage to the blades, hull, and tower.

Another example of the challenge that hurricanes can pose is that while solar panels may still be able to generate electricity in cloudy conditions, the damage from airborne debris during a hurricane can allegedly pose problems to electricity generation. In terms of floods and landslides, recent anecdotal evidence points to the possibility of landslides being caused by poorly planned wind farms (McCarthaig 2019), indicating the greater need for careful consideration of locations for wind resource exploration in Caribbean islands that are susceptible to landslides.

In other words, the Caribbean regional solar PV panels and wind turbines which are more vulnerable to Caribbean natural disasters than their petroleum counterpart must be implemented with extreme care. This calls for the exploitation of other renewable energy resources that could complement the renewables already in use in the country. One of these complementary renewable energy resources could be biogas, for example.

Biomethane is a particularly attractive additional source of renewable energy for two reasons. First, it can be implemented by re-purposing existing natural gas and petroleum infrastructure instead of requiring newly built infrastructure (Karatzos et al. 2014). This means that already built pipelines can be used without further exploitation or siting needed. Second, natural disasters have not been widely noted to affect oil and gas infrastructure in the Caribbean islands (as pipelines are mostly underground and generators indoor). In the case of hurricanes, for example, evidence reveals that damage to (usually ductile) petroleum infrastructure associated with these neither results in disaster nor poses challenges that cannot be overcome (Corrales et al. 2017).

There is little evidence of significant damage to onshore oil and natural gas pipelines resulting from natural disasters. Along with this, the recent push to upgrade and fix existing pipelines in Barbados (Cox 2019) makes the use of biomethane as a renewable energy source feasible and desirable. Furthermore, these upgrades that increase the resilience of the biomethane technology to floods and other disasters would allow this source to become more stable and predictable than energy sources that are easily susceptible to damages by natural disasters.

Now that we have made the case for the use of biofuel for transportation as a complement to other renewable energy sources, we discuss a novel source of biomethane, produced via the anaerobic digestion of Sargassum seaweed alongside rum distillery wastewater in the next section.

2.2 Sargassum seaweed as an alternative to sugar cane

In powering the projected biofuel-dominated transportation sector, the choice of feedstock matters. Caribbean SIDS have limited land space that is to be divided between commercial use, domestic settlements, and seminatural habitats, such as beaches, arable fields, pastures, managed forests, and woodlands (Mincey et al. 2013). Still, carbohydrate-rich feedstocks like sugar cane are especially featured in biofuel discussions, as they can be processed and distilled to produce bioethanol (Karmee et al. 2014). One example of a country with nationwide use of sugar cane as a biofuel is Brazil, which has near-tropical weather comparable to Caribbean islands like Barbados.

For the past three decades, Brazil has successfully implemented sugar-cane-derived bioethanol for at least two-thirds of the country's transportation needs (La Rovere et al. 2011), making it the world leader in the sugar industry, arguably to the limits of sustainability (Brinkman et al. 2018; Martinelli et al. 2008). Production of bioethanol in Brazil involves the use of large amounts of agricultural land (ibid.). However, land availability and suitability on a small island like Barbados is constrained. The example of Jamaica, another SIDS, reflects the limitations of being land constrained for the further exploitation of the sugar industry for fuel purposes. Whereas Jamaica began producing bioethanol from sugar cane in 1985, producing ethanol from 1 ton of sugar cane annually, the system did not survive past the mid-nineties (Mohee et al. 2015), leading national efforts towards ethanol gasoline blends in the early 2000's to no avail (Johnson et al. 2020).

Additionally, the successful production of Brazilian ethanol and biodiesel depends on a wider agricultural sector, including the production of corn (Kim et al. 2004) and a variety of oils, such as sunflower oil, palm oil, soybean oil and others (La Rovere et al. 2011). The Brazilian ecosystem that led to its success story is quite complex and importing this solution to a small island like Barbados may not be feasible. On top of these obstacles, sugar cane, which was once the most promising biofuel feedstock for tropical territories (Karmee et al. 2014) has been on a severe decline in Barbados for over seven decades (Anderson et al. 1995; Cox 2019). Figures 2, 3 and 4 below show the fall off over a period of 12 years, from 2006 to 2017.

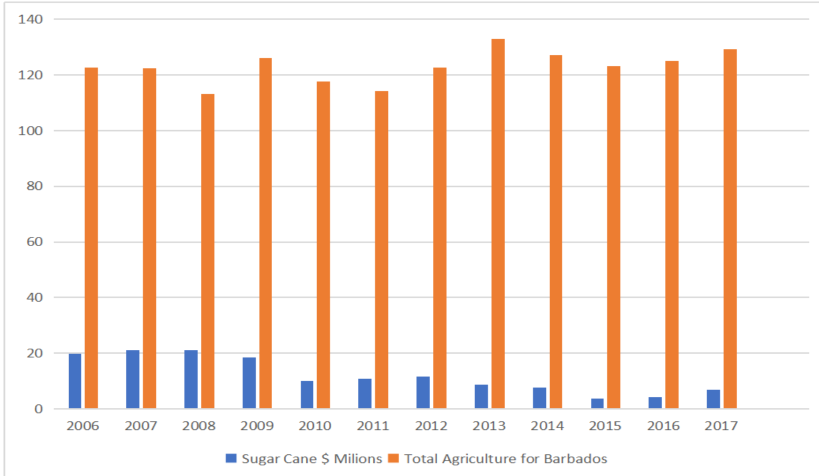

Figure 2: Total agriculture earnings Vs Sugar Cane Earnings in Millions from 2006-2017 (Barbados Statistical Service 2006)

Figure 2 compares the total number of earnings from sugar cane with the total number of earnings for the whole agricultural sector, thereby indirectly representing how big the share of sugar cane revenues industry is compared to other agricultural sectors. Whereas the total amount of earnings from agriculture has fluctuated over the years since 2015 it has been going up, while earnings from sugar cane have been going down. Independently from total earnings of agriculture, earnings from sugar are much lower after 2009 than their average during 2006-2009. These findings suggest a slump in earnings from the sugar cane industry, on its own and relative to total earnings from agriculture.

Figure 3 offers a somewhat similar picture as Figure 2, in as much as it shows declining sugar cane manufacturing over time between 2006 and 2017, as well as a diminishing share of manufacturing from sugar cane over total agricultural manufacturing. While total manufacturing is also lower in 2017 than it was during 2006-2009, it is slightly higher in 2017 than in 2010, but with a lower manufacturing from sugar cane relative to the total for the manufacturing sector.

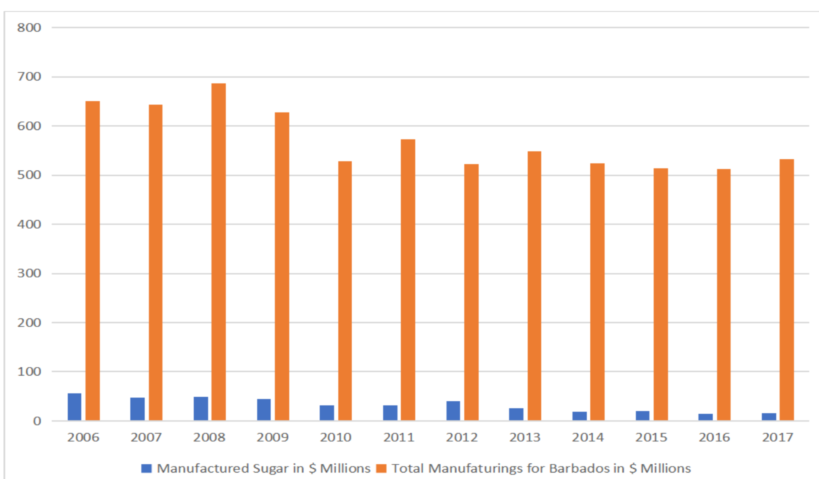

Figure 3: Total agriculture manufacturing Vs Sugar Cane manufacturing in Millions from 2006-2017 (Barbados Statistical Service 2006)

Finally, in line with the two previous figures, Figure 4 confirms the fall of the sugar cane industry in terms of production and earnings. Despite a growing GDP per capita post-2009, the general trend has been a dwindling of sugar cane, with the value in 2017 almost a quarter of what it was a decade earlier. One of the reasons for the sugar yield's slump is the change in the soil's chemical properties under long-term sugar cane monoculture (Bramley et al. 1996). Another reason why the sugar cane industry's production has been falling since 2006 has to do with plunging sugar prices in Europe (Menard 2006; Richardson-Ngwenya 2012).

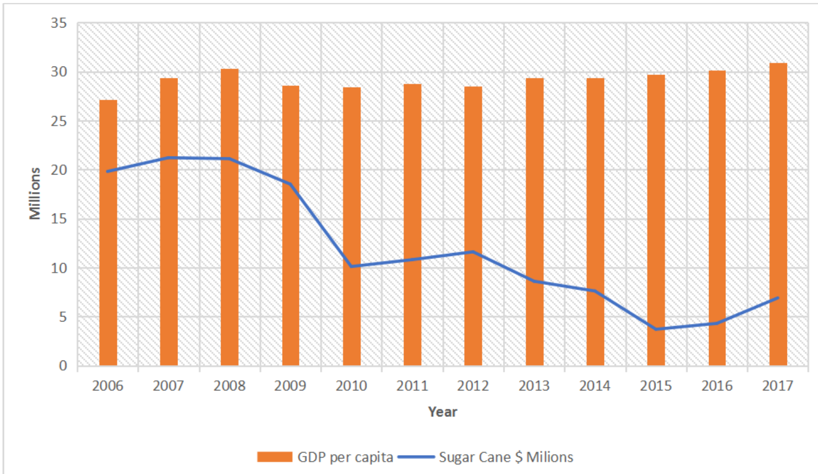

Figure 4: Barbados GDP per capita compared with sugar revenue from 2006-2017 (Barbados Statistical Service 2006)

Sugar cane is not a sustainable source of biofuel for the transportation sector in Barbados, given its falling production. If all the sugar cane produced in 2017 were to be used as a biofuel via a transformation to bioethanol, following the Brazilian example, a mere 6% of the transportation fuel that would be needed in 2018 could be produced (Box 1), equivalent to a revenue of approximately $4.3 million USD (Ministry of Energy and Water Resources 2019). It should be noted that only very small volumes of locally produced rum depend on locally produced sugarcane molasses, and that most of the volume of rum produced on the island is made from imported molasses (Seale, Richard 2019; Hassell, Andrew 2019).

As such, the diminishing sugar cane industry, and the volatility of sugar prices motivates the need to look for an alternative source of biofuel that is sustainable, less affected by global prices, and more abundant without the need for potentially limited agricultural land. Sargassum seaweed seems to satisfy all these requirements.

Sargassum seaweed, a naturally occurring seaweed species that floats freely in the ocean (Gower et al. 2019; Guiry 2020), was first identified in the Atlantic Ocean by Christopher Columbus in the fifteenth century. Currently, the world's largest Sargassum seaweed belt extends from the coast of West African to the Caribbean Sea and the Gulf of Mexico (Wang et al. 2019).

Sargassum seaweed is an alien invasive species within the Caribbean and its proliferation is hard to control. When it washes up onshore in large volumes and begins to disintegrate, it releases toxic gases to the extent that doctors in Guadeloupe and Martinique reported more than 10,000 cases of dangerous human toxic exposures associated with Sargassum seaweed between January and August 2018 (Wang et al. 2019). Beyond this, its inundation on Caribbean beaches is associated with disruptions in beach tourism (Casas-Beltran et al. 2020; Cashman et al. 2012), fisheries (Ramlogan et al. 2017) and eco-tourism (Casas-Beltran et al. 2020; Maurer et al.

2015). Thus, in 2018, the government of Barbados declared Sargassum seaweed a national emergency (Rawlins-Bentham 2018; Mendez-Tejeda et al. 2019).

Sugar cane production in Barbados totaled 102,181 tons in 2017 (Barbados Statistical Service, 2006; Simoes et al.,2011). It is known that one ton of sugar cane can be estimated to produce roughly 19.5 gallons of bioethanol (Gallagher et al., 2005).

If Barbados re-purposed its entire sugar industry to energy production the in the year 2017, Barbados could have produced:

$$102{,}181 \times 19.5 \approx 7{,}542{,}542 \text{ liters of bioethanol} \quad (1)$$

Nearly 2 million gallons of bioethanol would have been produced. In 2020 there were 136,400 registered vehicles in Barbados (Barbados Ministry of Transport, Works and Maintenance 2020). Assuming a vehicle travels 30 km for 5 days per week, for a total of:

$$5 \times 30 \times 136{,}400 \times 52 = 1,063,920,000 \text{ km}, \quad (2)$$

driven per year in Barbados.

It takes approximately 0.125 L of ethanol to drive one kilometer (Bai et al., 2010). This would indicate the potential of Barbados' entire 2017 sugar cane product to produce only:

$$7{,}542{,}542/0.125 = 60{,}340{,}336 \text{ km}, \quad (3)$$

accounting for only 5.7 % of the required transport fuel needed in 2018.

Box 1. Simulation exercise for the use of sugar cane ethanol applied to transportation in Barbados

To the extent that its presence on the coasts of Barbados is not desirable, and that it is freely available and accessible, harvesting the Sargassum seaweed in the open sea before it gets to the beach and using it as a biofuel feedstock is an attractive alternative to sugar cane as a biofuel. This is particularly true given several facts. First, the literature argues that the Atlantic Sargassum seaweed belt is a large source of biomass, which is here to stay and will continue to increase (Wang et al. 2019). Second, under the use of Sargassum seaweed there is no competition for agricultural land use, as Sargassum is harvested from the ocean in Barbados's large exclusive economic zone. Lastly, harvesting the Sargassum can positively impact beach tourism, fisheries, eco-tourism, and employment. For instance, at the global level, the biogas sector was responsible for creating 334,000 direct and indirect jobs in 2018 (IRENA 2019).

Whereas the use of Sargassum seaweed as an alternative to sugar cane has so far shown promise, its anaerobic digestion towards biomethane for a combustible transportation fuel requires an additional element, which is water. Anaerobic digestion requires up to 7% solid feedstocks, while the remaining 93% of the digestate is basically water (Parkin et al. 1986). Even if Sargassum seaweed were to provide all the needed solid matter to produce biofuel for Barbados, a source of water would still be needed. We propose that this need can be met by industrial wastewater, such as what is daily produced at local rum distilleries.

As is well-known, many Caribbean SIDS, including Barbados, have fully developed rum industries due to their colonial history (Ostrander & Gilman 1956, Quinn 1975). Wastewater from the rum distillation systems, currently being discarded in the ocean (West Indies Rum Distillery) or primarily left in troughs to evaporate (Distillery 2 Rum Distillery) can be redirected towards producing energy in the form of biogas and biofuel via the process of anaerobic digestion. While rum distillery waste is very dilute, it is still effectively high in chemical oxygen demand (COD) (Tauseef et al. 2013), which enhances the process of anaerobic digestion. In Barbados, where there are three major rum distilleries and a handful of much smaller operations, the present work looks specifically at the three largest rum distilleries, namely Distillery 1Rum Distillery, West Indies Rum Distillery and Distillery 2 Rum Distillery, as each produce thousands of liters of COD-rich wastewater every day (Seale 2019; Hassell 2019).

The argument of using the wastewater from rum distilleries combined with the Sargassum seaweed is attractive from the viewpoint of the circular economy, as it involves recycling wastewater and obliterating a harmful, invasive species from Barbados's marine environment. One might argue that if the sugar cane industry is declining, as was previously mentioned, then this might affect the rum production that depends on it, and hence the availability of the wastewater. However, this would not hold mainly because most of the rum volume produced in Barbados is produced using imported molasses as opposed to products of the local sugar industry which would be used for very small volumes of specialized premium rums (Seale & Richard, 2019; Hassell & Andrew, 2019). In total, approximately 3 million liters of industrial and municipal wastewater are treated daily in Barbados (Anjos & Nelson 1998).

Now that the necessary sources to produce biomethane have been covered, in the next sub-section we examine compressed natural gas (CNG) vehicles, which can be driven on compressed biomethane.

2.3 The success of CNG vehicles through an international lens

If Barbados is to successfully implement the transition from fossil fuel using biofuel as an alternative fuel for transportation— by relying on Sargassum seaweed and rum distillery wastewater, one necessary step is to convert gasoline-consuming internal combustion engine (ICE) vehicles to CNG vehicles. As argued earlier, this transformation of the transportation sector in Barbados is feasible for several reasons. First, CNG vehicles can be driven completely on biomethane (Alamia et al. 2016; Miltner et al. 2009; Chandra et al. 2011). Second, seventeen CNG vehicles are currently operational in Barbados (Cox 2019) and there are thousands in the wider Caribbean region (Dolcy et al. 2020). Third, there is currently a high penetration of CNG vehicle maintenance and repair expertise in the Caribbean region (ibid.). Finally, there are inexpensive CNG conversion kits to enable ICE vehicles to run on CNG (ibid.).

Looking at international case studies, countries like Armenia, Bangladesh, Iran, and Pakistan have already adopted the widespread use of CNG-converted vehicles (Khan et al. 2015). In Thailand (Dussadee et al. 2014) and Europe (Alamia et al. 2016), there is increasing evidence of the successful implementation of biomethane to fuel CNG-converted vehicles. CNG vehicles use compressed natural gas as engine fuel for driving. This gas can be replaced with locally produced compressed biomethane, which will reduce harmful CO_2 emissions and reduce fossil fuel importation and consumption.

Large international corporations such as Volvo, Bosch and Ford have already tested and used CNG technology in vehicles like the Volvo FH LNG. There are several registered CNG vehicles in Pakistan, Argentina, and Brazil, where their CNG vehicle numbers are as high as 2 million, 1.7 million and 1.6 million, respectively, with about 2600, 1800 and 1700 refueling stations, respectively, at a ratio of 1000 cars per fueling station (Engerer et al. 2010).

In Pakistan, the compressed natural gas vehicle program began in 1998 with about 150 refueling stations and 10000 vehicles. Currently, out of a nationwide total of 6.167 million vehicles, approximately 3 million are CNG vehicles (Khan et al. 2014). Pakistan has a total energy consumption of 40.03 million tons of oil equivalent, of which 43 percent is natural gas. By 2016, it was predicted that Pakistan would consume 5980 million standard cubic feet of oil equivalent per day. Under this case scenario, Pakistan was expected to import natural gas from Iran, as local production could not keep up with such numbers.

CNG prospered in Pakistan mainly because natural gas is cheaper than gasoline and diesel, but also because provisional incentives for investors in the CNG sector were in place. These included committed government support for CNG vehicles, gas connection priorities to CNG stations, deregulated market price for CNG, setup loans for refueling stations and exemption from import duty and general sales tax for CNG stations and vehicle conversion equipment for a limited time. All these contributed to attracting 89 billion dollars of investment in Pakistan and created approximately 121,000 jobs.

In Pakistan, over 90 percent of local companies, ranging from engineering design, development, testing, and hi-tech manufacturing setup, have shares in the CNG market. They all possess a common goal of continuous production and advancement of CNG Kits. As a result, Pakistan regularly exports CNG kits to China, Brazil, the Far East, and European countries, thereby increasing the country's GDP (Khan et al. 2014).

Converting from gasoline to CNG vehicles requires a CNG Kit and refueling cylinder, which roughly costs the equivalent of $500 USD, using Trinidad and Tobago as a reference point. The CNG Kit, as shown in Figure 5, consists of (1) the high-pressure regulators which reduce and regulate the pressure of the fuel exiting the tank from about 200 bars to the 10 bars required by the engine's fuel injection system, (2) the gas filter, (3) the natural gas sensors, which monitor the pressure of the gas. Additionally, a CNG compressor and dispenser are needed for CNG refueling stations (Nathaniel 2012).

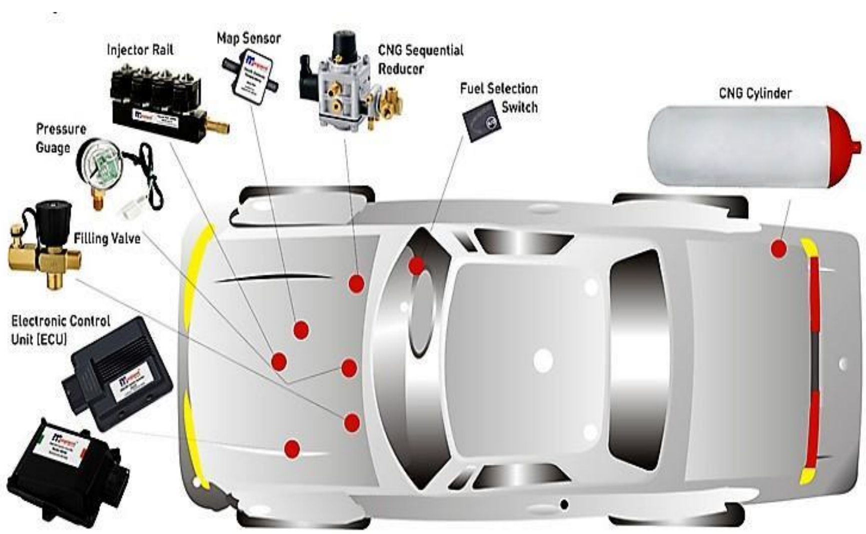

Figure 5: Components of a CNG Kit (Hussain et al. 2015)

Despite the abundant advantages CNG vehicles bring, it is worth noting that its biggest disadvantage is that CNG-related road accidents are more likely to be life-threatening to passengers (Khan et al. 2014) than gasoline or diesel vehicles. Nonetheless, there is constant progress in technological innovation that can promote greater safety (Al Eissaei et al. 2020). Alternatively, supplementary road safety measures could be implemented to counter this issue and minimize risks.

One might also argue that electric vehicles (EV) could be the carbon neutral solution for Barbados, as they have successfully begun to penetrate Barbados's transportation sector (Edgehill et al. 2014). However, they are not enough on their own to ensure an emissions-free transition for two reasons. First, the manufacture and import of large numbers of electric vehicles to Barbados can be more inefficient and expensive than biofuel conversions (Engerer et al. 2010). This is because the price of each individual car being converted would cost approximately $5000 Barbados dollars per car, (as opposed to the $1500 Barbados dollars it would take to convert a regular internal combustion engine (running on gasoline or diesel) to CNG drive train (Muteri et al. 2020). Second, unless Barbados finds alternative methods of powering the upgraded national grid, such as solar, wind or biofuel, fossil fuel imports will need to increase tremendously to support the entire national fleet via the electric grid.

Thus far the motivation behind the present research has been detailed and the case for the use of Sargassum seaweed, rum distillery wastewater and CNG-vehicles towards the 2030 fossil fuel free Barbados has been made. Next, a preliminary estimation of the possible reduction in CO_2 emissions and a description our experimental set-up is provided.

3. Preliminary emissions estimation and experimental set-up

In this section we start by presenting an empirical analysis that illustrates the CO_2 emission reduction when using biofuel instead of gasoline or diesel. This estimation is key because it makes a strong statement to policymakers. In the second part of this section, we present the physical set-up for our investigative anaerobic digestion experiment. This details the complexity of the process and shows potential implications.

3.1 The potential effect of biomethane in reducing CO_2 emissions.

We argue that biofuels do not introduce new carbon dioxide into the biosphere, and hence that their emissions are carbon neutral. However, in the process of producing biofuel, it is necessary to consider the carbon emissions that are involved in the logistical details of the process, to avoid introducing large amounts of fossil-fuel-derived-carbon in the processes around anaerobic digestion. As an illustration, comparing three types of fuels; neat gasoline (E0) and gasoline-ethanol blends (E5 and E85), the difference in CO_2 emissions between the process of producing E0 and producing E5 is 0.5% and between E5 and E85 the difference is 18% (Winther et al. 2012).

Biomethane is already being utilized as a fuel worldwide. Its use as a gaseous biofuel in European transport (and the electric grid) could reach 18–20 billion normal cubic meters (Nm^3) in 2030, while in Latin America, the installed biogas electricity capacity increased to as much as 450 MW in 2016 (Scarlat et al. 2018). Any car modified to run on natural gas can be driven as a biomethane car shown to reduce CO_2 emissions, compared with gasoline and diesel cars, possibly by up to 200 % (Papacz & Wladyslaw 2011).

When compared to gasoline and diesel vehicles, CNG vehicles fueled by compressed biomethane produced from anaerobic digestion of waste can lower the levels of CO_2 emissions by 81% over the course of the vehicle's lifetime, from its manufacture to the end of its road use (Bordelanne et al. 2011). The levels of CO_2 emissions can be managed, as seen in a field test in Germany where CO_2 is reduced up to 32 gCO_2eq/kWh and emissions are cut by 72 % compared with natural gas (Repele et al. 2014).

While being a renewable source of energy, the biomethane production from energy crops can emit considerable amounts of CO_2 during the processes of cultivation, harvesting, storage, anaerobic digestion, bio-methane scrubbing, and bio-methane storage. During the bio-methane storage stage of the listed process, there can be high emissions if the storing is done incorrectly (Buratti et al. 2013). For leakage of methane equivalent to 4% or higher, the process results are no longer sustainable (Ravina et al. 2015). Digesters with sealed tops have the potential to output the most biomethane, under the condition that the sealed digesters capture more methane, therefore increasing production and avoiding unnecessary emissions (Liebetrau et al. 2010).

When the greenhouse emissions from biomethane are considerably less than greenhouse emissions from natural gas production (Repele et al. 2014). With the improvements of gas-tight plants and digesters, as well as the efficient use of fermentation residue as fertilizers, the emissions in the production of biomethane can be reduced by up to 82%. To avoid the use of electricity produced from fossil fuels as another cause of additional emissions, the electricity used to run the machinery must also come from renewable sources (Buratti et al. 2013).

The emission factor is a representative value which acts as a ratio between the quantity of a pollutant released to the atmosphere and the activity associated with the release of the pollutant, and we can observe the emission factor values for different fuels (Junker & Liousse 2008). Emission factor values can vary based on the technology and the source used, although the emission factor is most significantly determined by the type of the fuel.

For biomethane to be used as a biofuel for transportation, the biogas must be refined to natural gas grade. Compared to other fuels, including the first-generation biofuels, biomethane has the largest negative emissions factor in the well-to-tank (refinement) component, which counteracts the positive emission factor in the tank-to-wheels component (Tilche et al. 2008).

In fact, for every gigajoule (GJ) of heat released during the combustion of fuel, there is a fixed quantity of kilograms of carbon released. The coefficients of kilograms of CO_2 can be used to calculate the Carbon Emission Signature (CES), along with the conversion efficiency η, which is usually a value around $\eta \approx 0.34$. The CES can be written such that:

$$\text{CES} = \eta \times (112 \times \%C) + (49 \times \%NG) + (66 \times \%P), \tag{1}$$

where **C** is coal, **NG** is natural gas and **P** is petroleum. This equation is utilized to calculate the Carbon Emitted (CE) by a system that uses electrical energy from a power grid as follows:

$$\text{CE} = EC(GJ) \times CES\ (kg\text{CO}_2/GJ) \tag{2}$$

where **EC** is the energy consumed, and **CES** is the carbon emissions signature (Jeswiet & Nava 2009).

During the process of biomethane production, CO_2 emissions can amount to as little as 44.6 g CO_2eq/kWh. This corresponds to an overall CO_2 emission reduction of 82% when compared with natural gas. By comparison with other fossil fuels, the evaluation of biomethane is based on two important indicators: CO_2 emissions in g_{eq}/MJ or gCO_2eq/kWh and cumulative energy demand (CED) in MJ/MJ or kWh/kWh.

CO_2 emissions are expressed as GWP100 (global warming potential) in accordance with International Panel for Climate Change (IPCC) guidelines and describe the contribution of emissions to the greenhouse effect over 100 years. In the case of biofuels, 'CO_2 equivalents' refers to all the emissions of the greenhouse gases CO_2, CH_4 and N_2O, which are converted using appropriate factors (Bernstein et al. 2008).

The calculation done for the CO_2 emissions (Merritt 2019) of different fuels initially for 1 liter of fuel and then for a vehicle with a 60-litre gas tank are shown. The CO_2 emissions for a fleet of 136,400 registered vehicles in Barbados (Barbados Ministry of Transport, Works and Maintenance 2020) is estimated with gasoline being used as an example. Along with gasoline (C_8H_{18}) the other fuels used were Diesel ($C_{12}H_{23}$), Ethanol (C_2H_5OH), Methanol (CH_3OH), Liquid Methane (CH_4) and Biodiesel/Rapeseed Oil ($C_{19}H_{36}O_2$).

We can precisely deduce the CO_2 emissions per liter of fuel, such as in the case of Gasoline:

Gasoline Density = 0.703 kg/L (Jansen & Michael 2000)

Gasoline Chemical formula: C_8H_{18}

Gasoline Molecular mass $C = 12 \times 8 = 96$

$$H = 1 \times 18 = 18 \quad (3)$$

$$\text{Carbon in one liter of gasoline} = 0.703 \times [96 \div 114] = 0.592 kg/L \quad (4)$$

$$CO_2 \text{ emitted from one liter of gasoline} = 0.592 \times [44 \div 12] = 2.17 kg/L \quad (5)$$

where CO_2 has a molecular mass of 44 (C = 12, O_2 = 32). For a 60L gas tank:

$$2.17 kg/L \times 60L \approx 130 kg \quad (6)$$

Of the 136,400 cars in Barbados, approximately 116,508 cars run on gasoline, and 19,348 on diesel. For 116,508 gas cars, we estimate the CO_2 emissions as follows:

$$130.147 kg \times 116{,}508 \approx 15{,}146{,}040\ kg \quad (7)$$

Fuel Type	CO_2 **Emissions kg/L of 1L**	CO_2 **Emissions kg of 60L**	CO_2 **Emissions kg of 136,400 cars**
Gasoline [76]	2.17	130	787,594,080
Diesel [77]	2.65	159	159,969,264
Total Emissions			947,563,344

Table 1: CO_2 Emissions per liter of gasoline and diesel for 136,400 registered cars in Barbados

As seen in Tables 1, the CO_2 emissions of 136,400 cars were calculated for both primary fuels. Barbados imports approximately 66,433,000 liters of fuel per year (Cox 2019), with an approximate total yearly consumption of 43,200,000 liters of gasoline and 23,600,000 liters of diesel. Beyond the emissions of the well-to-tank process, the burning of fuel in tanks also produces emissions, which we estimate. Using the density values from previous calculations, the CO_2 emissions of each fuel was calculated. Four hypothetical scenarios are now proposed for alternative fuels.

Fuel Type	CO_2 **Emissions kg/L of 1L**	CO_2 **Emissions kg of 60L**	CO_2 **Emissions kg of 136,400 cars**
Ethanol [78]	1.51	90.7	643,316,960
Methanol [79]	1.1	66	468,124,800
Liquid Methane [80]	1.26	75.7	536,924,960
Biodiesel	0.703	42.2	299,316,160

Table 2: CO_2 Emissions per liter of fuel for 136,400 cars in Barbados

In this scenario, if Barbados consumes the listed volume of gasoline, we can compute:

$$\text{Volume of consumed gasoline} = 43{,}200{,}000L$$

1L of gasoline produces 2.17 kg of CO_2.

Thus, the total imported gasoline volume produces:
2.17 kg/L $\times$ 43,200,000 L $\approx$ 93,700,000 kg of harmful emissions CO_2 emissions

Category	Fuel Type	Volume (L)	CO_2 **Emissions in a year (kg)**
Fossil Fuel	Gasoline	43200000	93700000
	Diesel	23600000	62600000
Biofuel (Renewable Energy)	Ethanol	66800000	100900000
	Methanol	66800000	73500000
	Liquid Methane	66800000	84300000
	Biodiesel	66800000	156000000

Table 3: Annual Projected CO_2 Emissions of hypothetical alternative fuels (Ethanol, Methanol, Liquid Methane, Biodiesel) compared to the emissions of imported fuels (Gasoline, Diesel)

The same exercise was repeated for all other fuel types and results shown in the third column in Table 3. The table shows the emissions of fuel imported and consumed yearly compared with the hypothetical equivalent use of alternative biofuels. As can be seen, using biofuels to power the transport sector, even in a small island like Barbados can stop CO_2 emissions every year.

3.2 Experimental set-up for the anaerobic digestion

In the experimental set-up illustrated in Figure 7, a small amount of rum distillery waste (25 ml) is placed into the sealed jar alongside 25 ml of inoculum (a mixture of Barbados sour grass and fish offal) and 3.5 g of fresh Sargassum seaweed undergoing various pre-treatments as described in Table 4. The different components of each treatment are presented on the left-hand side, while the right-hand side shows which components are applied to the controls and to the samples, respectively. The numbers on the first line of the right-hand side help refer to a specific control or sample. For instance, control 1 included Sargassum, saltwater pre-treatment and a bacteria source (inoculum).

Component	Controls			Samples					
	1	9	10	2	3	5	12	6	13
Sargassum	yes					yes	yes	yes	yes
Saltwater pre-treatment	yes					yes		yes	
Fresh water pre-treatment							yes		yes
Low COD (Mount Gay) wastewater		yes		yes		yes	yes		
High COD (Foursquare)wastewater		yes	yes		yes			yes	yes
Bacteria source (Inoculum)	yes			yes	yes	yes	yes	yes	yes

Table 4: Comparison of biomethane potential test components

Fresh Sargassum seaweed is collected on the southern-most tip of Barbados (at Silver Sands Beach), washed with freshwater, and stored at 25^{o}C. The weights of forty empty jars are first measured (see jar in Figure 6), and the fresh Sargassum samples are then added to the jars and the jars weighed again to verify a mass of 3.5g of fresh matter being used in each jar.

Figure 6: Sargassum seaweed sample in 50 ml jar

The sample is then dried for 24 hours at 100^{o}C and then weighed again in the jar to record the dry matter weight of the sample. The Sargassum is then mechanically ground to 10mm size particles and added to the jar, to which a small amount of effluent and 25ml of distillery wastewater are also added. The experimental set-up for the biomethane potential test is performed in the micro-digester set-up illustrated in Figure 7, as described in (Holder et al.2019). All samples and controls mentioned in Table 4 went through this process before results could be observed, as we present next.

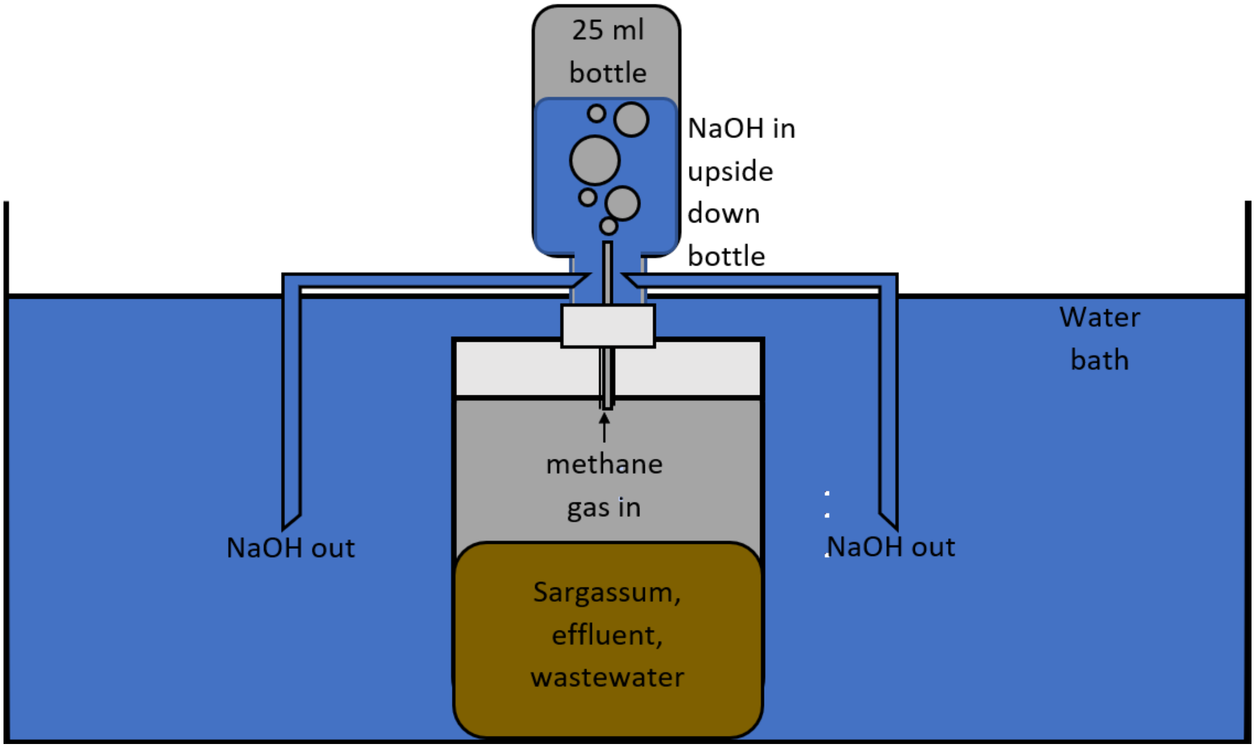

Figure 7: Experimental set-up for biomethane potential test. Micro-digester set-up taken from Holder et al.2019.

4. Results

Experimental methane production outcomes for each sample are described in Figures 8-11. These results are then applied to the numbers in Barbados.

4.1 Results from samples

This section shows the outcomes of the experiments executed for the different samples. The letters A, B, C and D are used to refer to the replicates of each sample. For instance, Figure 8 shows the results of four replicates, A, B, C and D, of a biomethane potential test of Distillery 1low chemical oxygen demand (COD) wastewater, and our bacteria-rich inoculum, which corresponds to sample 2 in Table 4. The x-axis represents the number of days and the y-axis the production of methane.

What we observe is a fifteen-day rise that reaches a methane production of 45 Nml/gFM by day 15. These results can be compared to replicates A, B, C and D of Sample 3 in Figure 9, which contained Distillery 2 high COD wastewater, which led to an immediately production of 45 Nml of methane as early as day 1.

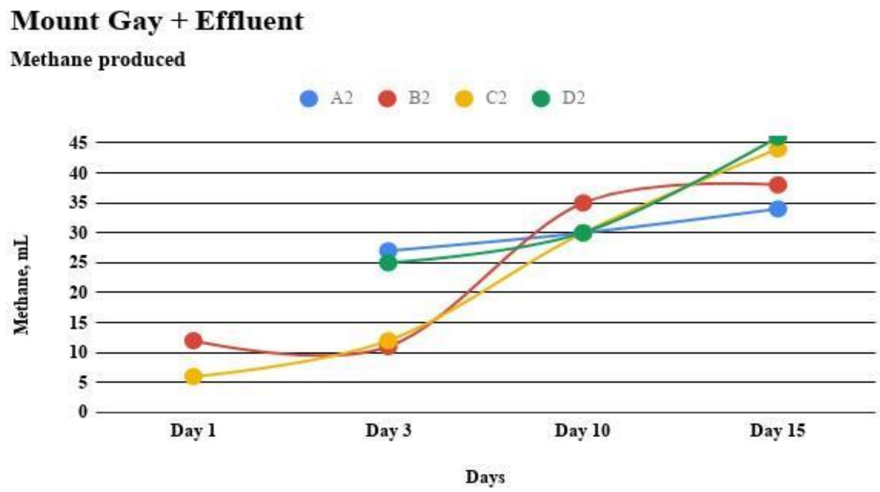

Figure 8: Volume of methane (Nml/gFM) produced from sample 2 that was the low COD wastewater and effluent mixture with no Sargassum seaweed (Source: own elaboration)

Comparing results from Figures 8 and 9, it can be observed that the level of COD in wastewater is demonstrated to influence the rate of methane production in the first 15 days of the process. Longer time scales need to be observed in future tests, to observe the stabilized long-term behavior of this biomethane production system. In the absence of Sargassum seaweed, it can be observed that the methane product of rum distillery waste is less predictable and more varied, as data lines across experimental replicates show greater spread in these images when compared with Figures 10 and 11.

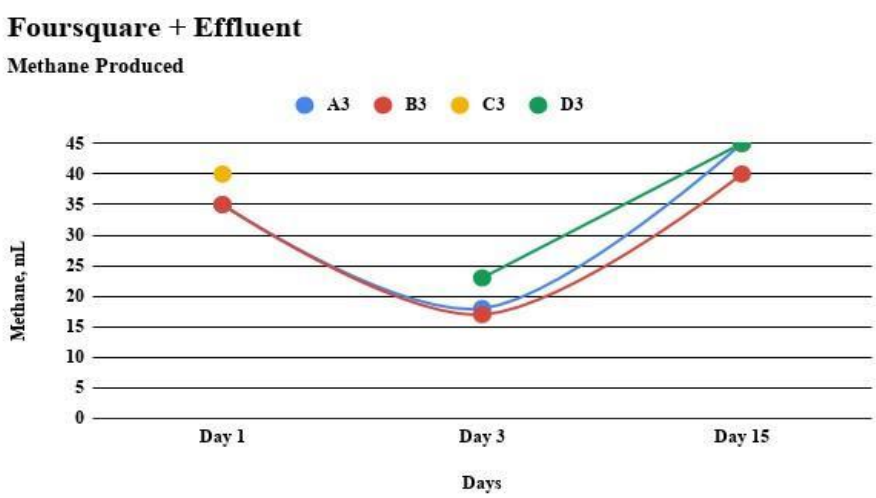

Figure 9: Volume of methane (Nml) produced from sample 3 high COD wastewater and effluent mixture with no Sargassum seaweed (Source: own elaboration)

Outcomes from samples 5 and 12 are shown in Figure 10. One can observe that a low COD wastewater and effluent mixture with saltwater and fresh water pre-treated Sargassum seaweed produce methane in lower amounts than results from samples 6 and 13 in Figure 11, which show methane output of systems with high COD wastewater and effluent mixture with salt-water and fresh water pre-treated Sargassum seaweed.

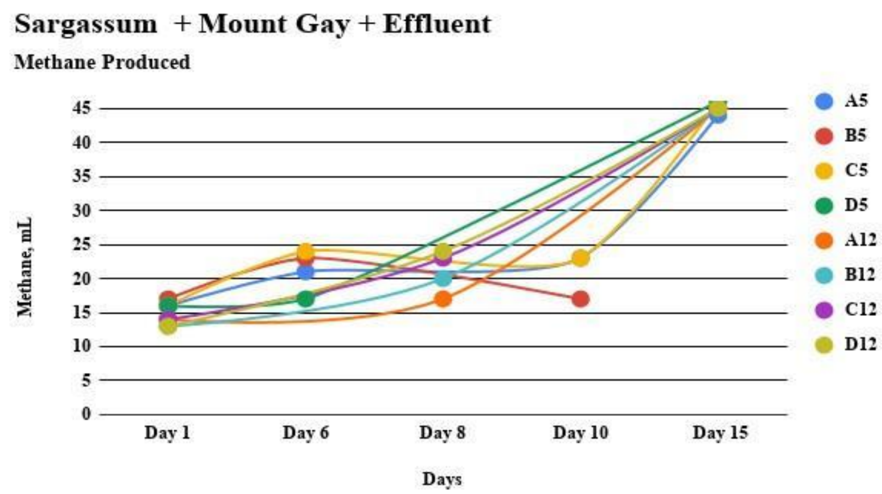

Figure 10: Volume of methane (Nml) produced from samples 5 and 12 that were both in the low COD wastewater and effluent mixture with salt-water and fresh water pre-treated Sargassum seaweed respectively (Source: own elaboration)

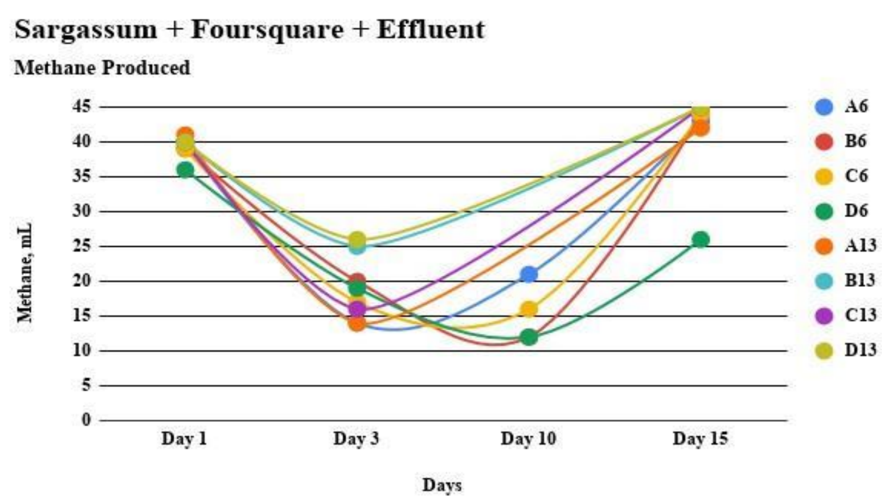

Figure 11: Volume of methane (Nml) produced from samples 6 and 13 that were both in the high COD wastewater and effluent mixture with salt-water and fresh water pre-treated Sargassum seaweed respectively (Source: own elaboration)

What can be seen from Figures 10 and 11 is that behaviors are converging across replicates and even across different conditions, showing that Sargassum combined with rum distillery waste makes for predictable biomethane output.

When combining all results from the different samples into a single figure, as in Figure 12, the best methane output comes from sample 13, with its high COD rum distillery waste combined with Sargassum seaweed that was pre-treated with freshwater as seen in Table 4. Overall, low COD levels in rum distillery wastewater coincide with less output biomethane with and without Sargassum.

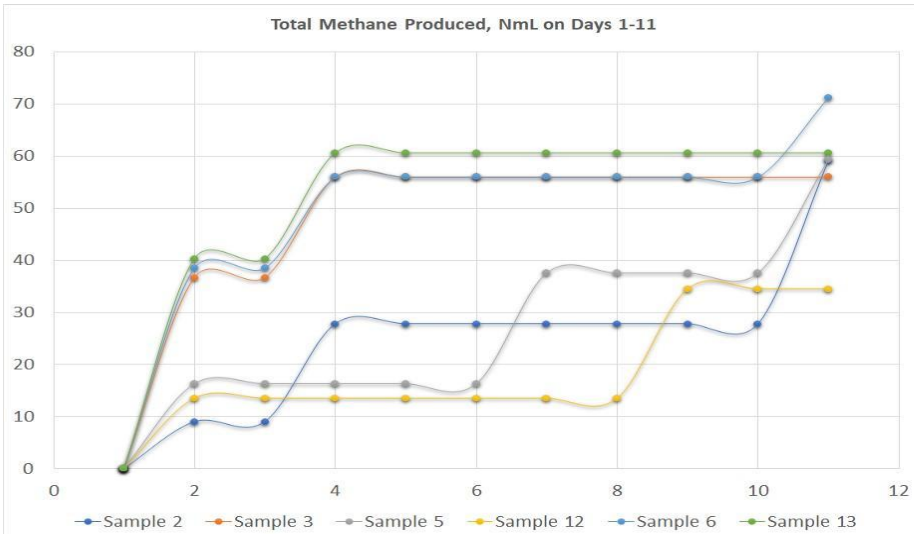

Figure 12: Cumulative methane produced (Nml/gFM) versus time (days) from all tests (Source: own elaboration)

Based on results displayed in Figure 12, an approximate regression relationship between methane product, *M*, and time, *t* could be generated, as follows:

$$M = (3.08 + 0.09t)^3 \quad (8)$$

The results from the anaerobic digestion of Sargassum seaweed with rum distillery waste (McKenzie et al.2019) just presented above are promising, as they reveal the potential of the Sargassum seaweed for Barbados and other rum-producing Caribbean nations.

4.2 Application of the results to the case of Barbados

Biogas is produced by anaerobic digestion where micro-organisms breakdown organic matter (Dada et al. 2017). Once extracted, biogas is then scrubbed to remove carbon dioxide and any trace gases, such as hydrogen sulfide and small amounts of other elements. The biogas is then upgraded, and the resulting product is biomethane, a gas consisting of 95% to 97% methane and 1% to 3% carbon dioxide (Ryckebosch et al. 2011). Anaerobic digestion for methane production can be performed using biofuel crops, sewage treatment waste, landfill gas, and even plant waste, such as grass cuttings (Moreira 2010).

Four square Rum Distillery produces 60m^3 of wastewater daily, for 260 days every year (Seale 2019), whereas the West Indies Rum Distillery produces 600m3 of wastewater for 330 days every year (Hassell 2019). Between these two distilleries, this is a total of 213,600,000 liters of high COD rum distillery wastewater from two local distilleries in a year.

Using our results, we estimate the production of methane after 15 days of anaerobic digestion of high-COD rum distillery wastewater and inoculum (a mixture of Barbados sour grass and fish offal). The outcome is an average of 43.75 Nml/gFm = 4.375×10^{-5} Nm^3 of methane gas produced by 25 ml of wastewater in a micro-digester. From Equation 8, we can roughly estimate that approximately 185 Nml of biomethane can be produced in 30 days from this system. Using the ideal gas law, this amounts to 0.00815 moles of biomethane gas.

It takes a total of 50 liters of methane gas compressed at 200 bars pressure to power a regular CNG vehicle for a week (Nathaniel 2012; Murray 2020). Using the ideal gas law, this totals to 396 moles of gas. With approximately 52 weeks in a year, it therefore would take 396 moles× 52 weeks × 136,400 cars = 2, 808, 748, 800 moles of methane gas to sustain the transportation sector of Barbados on CNG for a year. This would require 8, 615, 793, 865 liters of rum distillery waste and 1.21 * 10^6 tons of fresh Sargassum in a year. Nearly 800,000,000 liters of wastewater, including all rum distilleries' wastewater, other industrial wastewater, and sewage, are treated every day in Barbados (Anjos & Nelson 1998) so one tenth of the required fluid volume can already be found locally, although this would require further lab investigation and research.

In 2017, twenty million tons of Sargassum seaweed were estimated to inundate the Caribbean Sea and the central Atlantic Ocean (Wang et al. 2019), presenting evidence that more than sufficient volumes of fresh Sargassum are available in Barbados' very large EEZ depicted in Figure 13. Thus, while the needed volume of Sargassum is readily available, one would have to go beyond just wastewater from local rum distilleries to power large segments of the transportation sector with biomethane produced via Sargassum seaweed and industrial wastewater.

Processing large amounts of fresh Sargassum seaweed and storing large volumes of biomethane gas are not simple tasks, and the process is largely simplified if distilleries and other industrial sources of high COD wastewater install anaerobic digesters, and transfer impure, untreated biogas to gas companies for purification and compression (Seale 2019). Once the biomethane is produced and purified, it can be pumped directly into gas pipes. As previously stated, one of the key advantages of biomethane is that it can be implemented by re-purposing existing natural gas infrastructure instead of requiring newly built infrastructure (Karatzos et al. 2014), meaning that already built pipelines and infrastructure can be used without further siting needed.

To give an idea of the connections that would need to be established to ensure a functioning system, Figure 14 illustrates Barbados' already existing natural gas pipeline network and its proximity to the larger rum distilleries (National Petroleum Corporation 2021).

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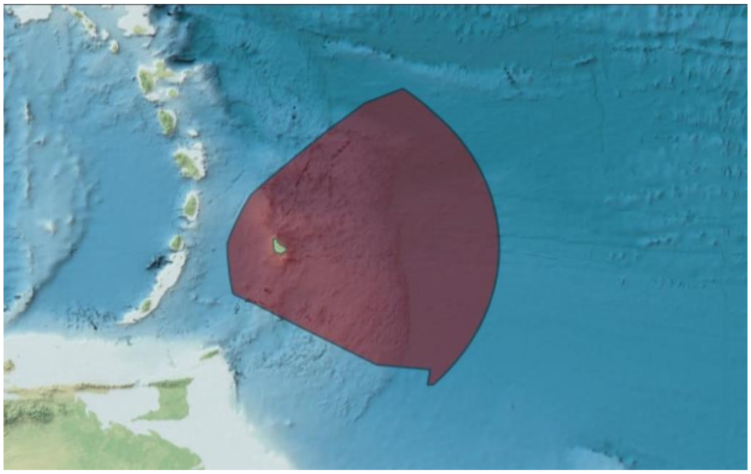

Figure 13: The EEZ of Barbados is 433 times its land space (Marine Regions 2020).

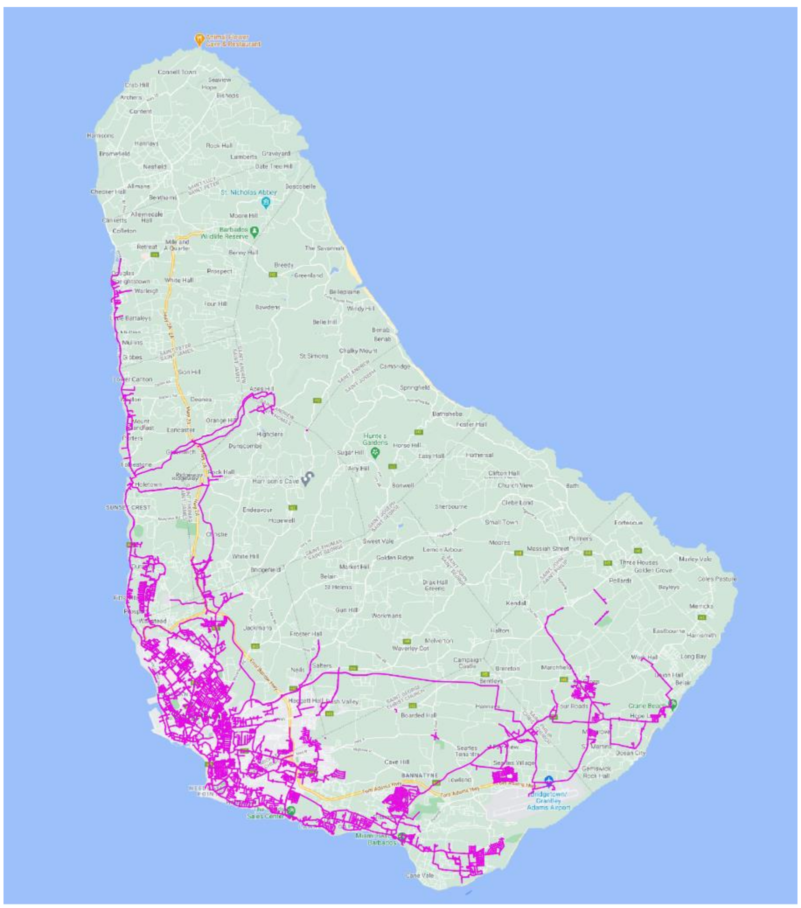

Figure 14: Map of Barbados's natural gas pipelines (National Petroleum Corporation 2021)

5. Conclusions

The present work explores the potential of exploiting the Sargassum seaweed that inundates the coasts of Barbados, along with locally produced wastewater from rum distilleries, to produce biomethane gas as an alternative transportation fuel, via CNG conversions of local gasoline vehicles.

As discussed, Barbados faces several economic and environmental challenges. First, it is overly reliant on oil imports for its transportation sector and hence vulnerable to worldwide shocks. Second, it has considerable levels of CO_2 emissions that translate into worsening global warming leading to an increase in natural catastrophes to which Barbados is particularly vulnerable. Third, its beaches are being inundated by Sargassum seaweed which affects the tourism industry, and releases toxic gases to the detriment of human health. Finally, its sugar cane industry cannot be exploited as a major biofuel feedstock source due to its decline. All these factors combined pave the way for a transition from fossil fuel to Sargassum-seaweed-derived biofuel for Barbados to reach its 2030 target of being fossil fuel free.

One key advantage of transitioning to biomethane from Sargassum seaweed and local rum distillery wastewater is that it will require smoother changes to the already existing infrastructure that fundamentally consists of the soon to be upgraded (Cox 2019) nationwide natural gas grid. Minimizing required changes to existing infrastructure is beneficial since it reduces cost and places Barbados on a faster track to achieving its energy policy goal of becoming 100 % fossil fuel-free and carbon neutral by 2030.

As mentioned previously, focusing exclusively on other renewables such as solar and wind might be problematic due to its level of exposure to natural disasters and therefore, resilience issues associated with these technologies. The same applies to EVs when they are charged with electricity generated from solar panels, as these are meant to be located above ground, often on rooftops, which makes them vulnerable to damage with hurricane wind speeds above 100 miles per hour (mph). As indicated in Section 2.1, during the hurricane season, wind speeds can easily surpass 150 mph, which makes it unwise to exclusively invest in solar panels, as the ubiquitous nationwide solution to a fossil fuel free transportation sector in Barbados (Moore 2011; Gay et al. 2018; U.E.S 2017).

While the use of Sargassum seaweed is a suitable alternative, thanks to the fact that it is free, sustainable, accessible, and that its transformation to biomethane is resilient to natural catastrophes, it does not come without shortcomings. One of the biggest issues for biomethane operations (gaseous, liquid, or compressed) would be safety, as stated above, and storage, as Barbados currently does not store natural gas (Cox 2019). Another potential limitation could allegedly be the emissions associated with the process of anaerobic digestion at a larger scale.

Also, sargassum seaweed, which is currently abundant on the coasts of many Caribbean countries, is not expected to be an intermittent resource, but stable (Wang et al. 2019 and expected to get worse over the years.

From another long-term perspective, it would be also interesting to carry out some estimates of the impact of the declining sugar cane industry on the release of wastewater from rum distillery in order to see whether this could have an impact on the amount of wastewater that will be produced, which is needed in the anaerobic digestion process that leads to biomethane production. This is particularly relevant in a country like Barbados that is one of the most water scarce countries in the world.

Finally, the transition from fossil fuel to biofuel as an alternative fuel would also require the widespread conversion of conventional vehicles to CNG vehicles and needed additional road safety measures once these are in place, considering the higher risk of driving these vehicles compared to conventional vehicles.

However, international experience has demonstrated that the widespread conversion to CNG vehicles is possible and particularly feasible in the case of Barbados. The textbook example of Pakistan's CNG success suggests that industrialized bio-methane production via large-scale anaerobic digestion can create jobs. Removing the Sargassum seaweed from the coasts also leads to job creation, directly by hiring people to collect the Sargassum seaweed, and indirectly by boosting the tourism industry that has been affected by the presence of the Sargassum seaweed on popular beaches. Therefore, the transition from fossil fuel to biomethane as an alternative via the use of Sargassum seaweed and wastewater leads to a 'quadruple win': it tackles climate change and contributes to the 2030 agenda of becoming fossil fuel free by reducing CO_2 emissions; it can bring economic benefits by making Barbados less reliant on fossil fuel price shocks and boosting the tourism industry; it allows the industrialization of wastewater which is otherwise poorly utilized at present, feeding into the idea of the circular economy; and it can create employment and promote new skills via the process of Sargassum seaweed collection, CNG vehicle conversion, the production of bio-methane and an upturn in beach tourism.

While the Sargassum seaweed collection and use seem to be a viable solution to the economic and environmental threats currently faced by Barbados, future research would need to be carried out to analyze the potential costs of seaweed collection and anaerobic digestion, its overall financial suitability when compared to other alternatives and its complementarity, and most importantly, security of supply throughout the year. Evaluation of the regulation of the seaweed would be necessary for when it is considered a public good, in the context of the circular economy optimizing the use of all related resources in this process.

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6. Appendices

Prevalence of natural disasters in the Caribbean region

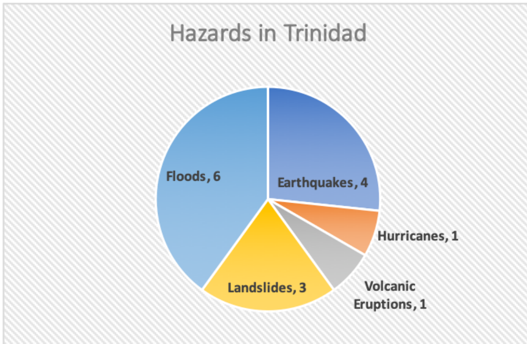
We examine datasets on Haiti, Trinidad and Tobago, Barbados, Dominica, St. Vincent, Grenada, the Bahamas and Jamaica to present the prevalence of various forms of natural disasters occurring in each country in the period 1950 to present (Smith, Martin & John 1999, Emanuel & Kerry 2005, Braun et al. 2010, Lawrence, Miles & Joseph 1982, Beven et al. 2003, McFarquhar et al.2005, , Serwan & Kamal 2005, Kahandwa et al. 2018, Allison 1972, Hawkins, Harry & Stephen 1976, NASA Earth Observatory 2008, Christian, Stewart & Stacy 2017, Robinson, Danielle & Ken 2006, Beven & John 2004, Bensen et al. 2001, Morrow, Betty & Kathleen 1996, Perkins & Paul 1968, Forrest & Thomas 1979, McFarquhar et al.2006, Beven 2000, Atallah, Eyad & Lance 1999, Alsiemer & Frank 2004, Lawrence & Cobb 2005, Rappaport 1993, Jaregui 2003 and Blanco & Maria 2018). We generate figures representing the distribution of these natural hazards in eight Caribbean nations, which are represented in Tables A.1 and A.2.

Country	Earthquakes	Hurricanes	Volcanic Eruptions	Landslides	Floods
Haiti	4	0	0	30,823	25
Trinidad and Tobago	4	1	1	3	6
Barbados	0	4	0	8	34
Dominica	5	4	1	294	12
St. Vincent	1	2	2	64	128
Grenada	0	6	12	13	15
Bahamas	0	24	0	NI	NI
Jamaica	2	8	1	NI	21

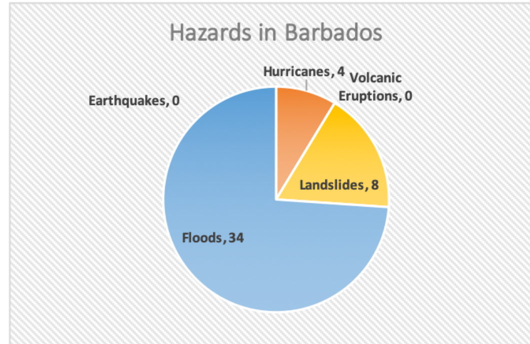
Table A.1: Tabulation of Caribbean natural hazards by the number of occurrences of each natural disaster in each of the study countries

Country	Storm Carib	NOAA
Haiti	9	4
Trinidad	1	0
Barbados	4	0
Dominica	5	3
St. Vincent	2	2
Grenada	5	2
The Bahamas	23	15
Jamaica	8	3

Table A.2: Number of hurricanes recorded in the study countries using two sources, Storm Carib, and NOAA (Allison 1972).

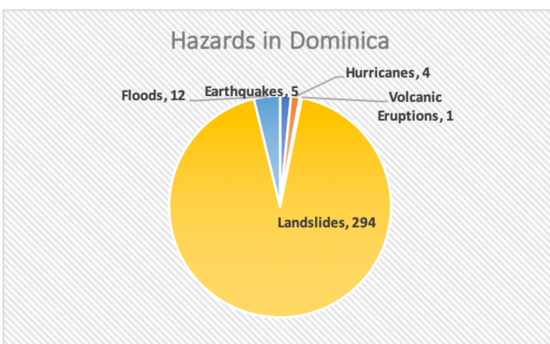


(a) Occurrences of natural disasters in Trinidad

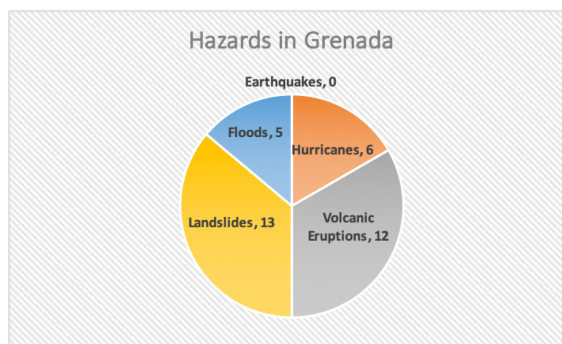


(b) Occurrences of natural disasters in Barbados

Figure A.1: Occurrences of natural disasters in Trinidad (left) compared to Barbados (right). The location of some of the islands, such as Barbados and Trinidad, often allows them to be spared from the direct impact of hurricanes. However, they both experience some impacts of the passing hurricanes, particularly flooding, with added risks of storm surges, heavy rainfall, and destructive high winds.

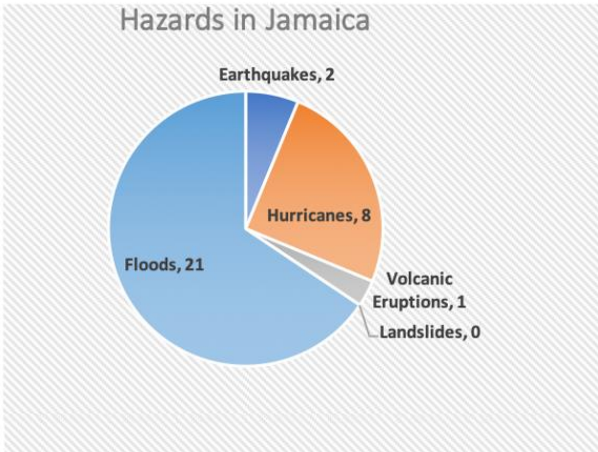


(a) Occurrences of natural disasters in Dominica

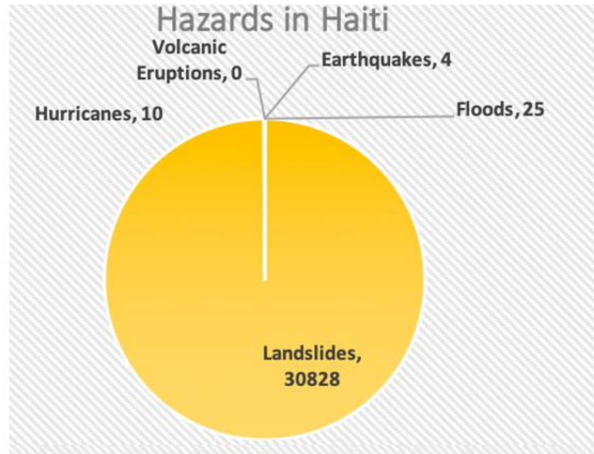


(b) Occurrences of natural disasters in Grenada

Figure A.2: Occurrences of natural disasters in Dominica (left) compared to Grenada (right). Many islands experience landslides after hurricanes because of the over-saturation of the soils, especially in mountainous islands such as Dominica. In this study, the volcanic islands of Dominica, St. Vincent and Grenada were identified to have experienced volcanic eruptions within the period of 1950 to present. The islands of Trinidad and Jamaica have also experienced some volcanic activity from a mud volcano and a submarine volcano, respectively (Wadge 1982). Kick Em Jenny, a submarine volcano off the coast of Grenada has recently been the most active volcano in the region.

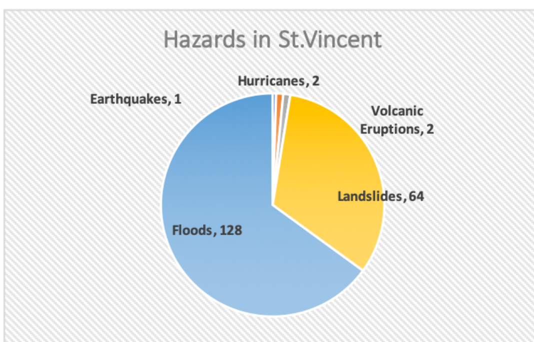


(a) Occurrences of natural disasters in Jamaica

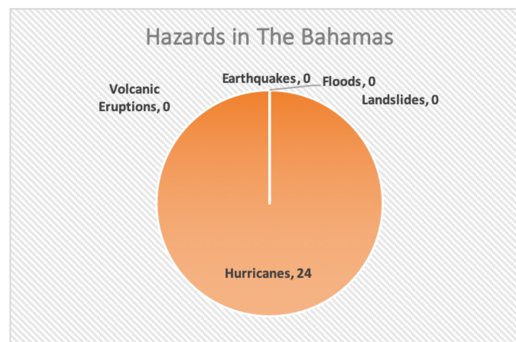


(b) Occurrences of natural disasters in Haiti

Figure A.3: Occurrences of natural disasters in Jamaica (left) compared to Haiti (right). Haiti also experienced numerous landslides, because of the immense amount of deforestation that has taken place there. Without tree roots to bind the soil and to provide shelter from the direct impact of raindrops, the soil is then vulnerable and susceptible to landslides.



(a) Occurrences of natural disasters in St. Vincent



(b) Occurrences of natural disasters in the Bahamas

Figure A.4: Occurrences of natural disasters in St. Vincent (left) compared to the Bahamas (right).