CASTALIA

Montego Bay Bus Fleet Electrification Business Case

IDB

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Definitions

BEB	Battery-electric bus
BEB (RE)	Battery-electric bus charged using renewable energy
BEB (grid)	Battery-electric bus charged from the grid
HFCEB	Hydrogen fuel cell electric bus
FSPV	Floating solar PV
LBSPV	Land-based solar PV
LCOE	Levelized Cost of Electricity
MBM	Montego Bay Metro
NWC	National Water Commission
PPP	Public-private partnership
PV	Photovoltaics
SCC	Social cost of carbon
TCO	Total cost of ownership

Executive summary

This report assesses the feasibility of a scalable and replicable project to replace Montego Bay Metro's (MBM) aging fleet of diesel buses with electric buses powered by 100 percent renewable energy. This report:

- Identifies battery electric buses charged with electricity from floating solar PV as the best option for achieving that goal
- Shows that, when the social cost of carbon is included, this is least cost option compared with the cost of replacing MBM's fleet with new diesel buses and with electric buses powered by Jamaica's electricity grid
- Provides advice on what support is required to make this trailblazing project a reality.

Battery electric buses powered by floating solar PV is the best option for electric buses powered by renewable energy

Determining which type of electric bus, battery electric buses (BEB) or hydrogen fuel cell electric buses (HFCEB), powered by which type of renewable energy is the best option requires comparing the bus cost and energy cost of each option. Table 0.1 compares the cost of technically viable combinations of renewable energy options with BEB and HFCEB:

Table 0.1: Comparison of Electric Bus and Renewable Energy Source Options

Energy source	Battery-electric bus	Hydrogen fuel cell electric bus
Floating Solar	Bus Cost (US$): 465,307 Energy Cost: (US$/km): 0.43 **Physical Configuration:** Least cost option is smaller-battery pack buses that charge at depot overnight and opportunistically during the day using a fast-charger	Bus Cost (US$): 814,688 Energy Cost: (US$/km): 2.17 **Physical Configuration:** Buses Refuel with hydrogen produced within the MBM depot
Rooftop Solar	Bus Cost (US$): 465,307 Energy Cost: (US$/km): 0.44 (does not include the cost of constructing a roof) **Physical Configuration:** Least cost option is smaller-battery pack buses that charge at depot overnight and opportunistically during the day using a fast-charger	Not technically viable due to insufficient area of the MBM bus depot****
Land-Based Solar PV	Not Technically viable due to lack of a suitably large piece of land near the MBM bus depot***	Bus Cost (US$): 814,688 Energy Cost: (US$/km): 1.43

		Physical Configuration: buses travel to refuel with hydrogen produced at the land-based PV installation

**Capital cost of the bus is an average of observed prices for each type of bus*
***Cost of energy on bus includes the full cost of energy—for solar PV options this includes the full cost the PV installation as well as required energy storage—required to power the bus*
****Even BEB with a larger battery pack and larger possible range (for example, the Proterra ZX5 40-Foot Bus model with a battery capacity of 675kWh battery and a significantly higher price of US$1,400,000 per bus) have a maximum effective driving range of 371km which would only just be enough to cover the average daily km for MBM's buses of 370km. There would be no remaining battery charge for driving to and from a land-based solar PV installation for overnight charging.*
*****HFCEB requires 35,126.18m3 of area to generate enough electricity to create the required amount of hydrogen and the MBM bus depot has only 10,000m3 of potential roof space.*

Table 0.1 shows that the best option for powering electric buses with 100 percent renewable energy is to combine floating solar PV with BEB. Both viable HFCEB options have significantly higher bus costs and energy costs than both BEB options. Further, the cost of energy for BEB from floating solar PV is cheaper than the cost of rooftop solar without considering the additional cost of roof construction that would be required. As a result, the best option must be BEB powered by floating solar PV.

Waste-to-Energy technologies were considered, but are not included in Table 0.1 because:

- Waste to Energy fueled by wastewater treatment in the Bogue oxidation ponds is not technically viable because the ponds need to be exposed to the sun and cannot be covered to collect methane
- Waste to Energy fueled by wastewater from cruise ships is not technically viable because the supply of wastewater from cruise ships is not consistent enough
- Waste to Energy fueled by municipal solid waste is not viable in the near term due to uncertainty around the location of a proposed municipal solid waste facility, when the facility will become operational, and the facility's ability to sell electricity directly to MBM. Further, the LCOE of generating electricity from biomethanation is US$0.418 per kWh, which is significantly higher that the LCOE of using floating solar PV of US$0.362 per kWh.
- Plasma gasification technology to produce electricity and hydrogen is not viable because it is not yet at a suitable stage of maturity.

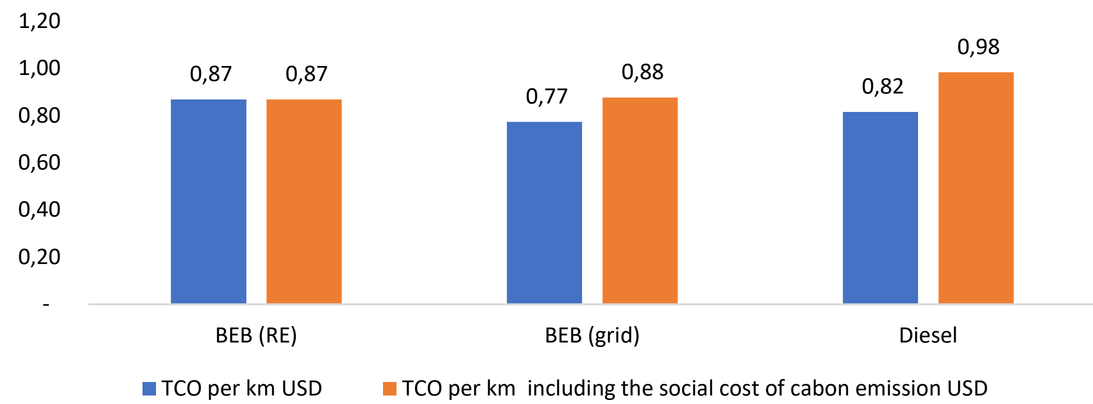
While these Waste-to-Energy technologies are not suitable for MBM's needs, they are all promising sources of renewable energy for further decarbonization of Jamaica's transportation sector in the future.

Battery electric buses powered by renewable energy are cheaper than battery electric buses powered by the grid and diesel buses when the social cost of carbon is included

Figure 1.1 compares the Total Cost of Ownership (TCO) of BEB powered by renewable energy, BEB powered by the grid, and diesel buses with and without the social cost of carbon.

Figure 1.1 shows that BEB charged with electricity from the grid is the least-cost option without considering the social cost of carbon with a TCO of US$0.77 per km. However, when the social cost of carbon is considered, BEB powered by renewable energy becomes the least cost option with a TCO of US$0.87 per km. When the social cost of carbon is included, the TCO of grid powered BEB becomes more expensive than TCO of BEB charged using renewable energy because electricity from Jamaica's grid is generated using mostly conventional power sources. Similarly, diesel buses become more expensive due to emissions from diesel fuel production and combustion when the cost of carbon is considered.

Figure 1.1: Comparison of TCO of different bus technologies, with and without the social cost of carbon



**Note: Social Cost of Carbon is assumed to be US$112/ tCO² e (Methodology for valuing Social Cost of Carbon is discussed in Section 4.2)*

A PPP structure and green finance can derisk the project

Five major risks to transitioning MBM's diesel buses to BEB powered by floating solar PV are:

- That NWC is unwilling to lease the Bogue treatment plant for the installation of solar PV
- That MBM is unable to adequately operate and maintain BEBs or a floating solar PV system
- The project cannot be financed because MBM is not creditworthy
- Revenue from bus fares will not cover the cost of the project
- The Government of Jamaica will prefer BEB powered by the grid because it is cheaper.

The risk that NWC is unwilling to lease the Bogue treatment plant can be overcome through early engagement with NWC by the Government of Jamaica.

Delivering the project as a Public Private Partnership (PPP), wherein a creditworthy and technically capable consortium would have a concession to operate MBM's bus routes, will mitigate the risks that MBM is unable to adequately operate and maintain BEBs or a floating solar PV system; mitigate the risk that MBM is not creditworthy; and can mitigate the risk that revenue from bus fares will not cover the cost of the project.

Green finance can assist in mitigating the risk that the project will not be seen as financeable. Further, green finance can mitigate the risk that the Government will prefer BEB powered by the grid by providing grants and concessional finance to close the viability gap with BEB powered by renewable energy.

Further, this project is an ideal candidate for green finance to close the viability gap because BEB powered by renewable energy has the lowest social cost, after accounting for the social cost of carbon. This makes BEB powered by renewable energy a suitable candidate for Jamaica's NDC+ and for support with from global green finance to offset the financial viability gap, de-risk the project, and provide the technical assistance necessary to develop all the details and make this innovative concept a reality.

Support of this nature can allow replacing MBM's diesel buses with BEB powered by renewable energy to become the pattern for similar projects all over the Caribbean, since the economics and structuring of this project are likely to be applicable with limited adaptation in many similar locations.

1 Introduction

This report assesses the technical and economic feasibility of a trailblazing project that would replace Montego Bay Metro's (MBM) aging diesel bus fleet with electric buses powered by 100 percent renewable energy. This project aims to achieve two key goals:

- Enhance the Jamaican government's e-mobility framework by providing a scalable, replicable pilot program for replacing diesel buses with electric buses, and
- Improve MBM's operational efficiency and customers service by replacing its aging diesel fleets with modern cost-efficient buses.

Assessing the feasibility of this project to achieve those two goals required:

- Assessing the operational capabilities of battery electric buses (BEB) and hydrogen fuel cell electric buses (HFCEB) to determine if they can meet MBM's operational requirements (Section 2)
- Assessing the technical and economic viability of BEB and HFCEB combined with potential renewable energy sources to power the bus fleet to determine that BEB powered by floating solar PV is the option that can meet MBM's needs for the least cost (Section 3)
- Comparing the CO^2 emissions of BEB powered by floating solar PV with BEB powered by the grid and diesel buses to determine the potential emissions reductions and their value based on the social cost of carbon (Section 4)
- Determining if BEB powered by floating solar PV is economically justified by conducting a Total Cost of Ownership (TCO) analysis—including sensitivity analysis. The TCO analysis compares BEB powered by renewable energy, BEB powered by grid electricity, and diesel buses based on each option's capital cost, energy cost, maintenance cost, and the social cost of each option's emissions. This analysis determined that BEB powered by renewable energy is the least-cost option when the social cost of carbon is considered and BEB powered by the grid is the least-cost when it is not (Section 5)
- Analyzing the major risks to the project and proposing mitigation strategies to allow the project to overcome those risks (Section 6).

In addition to the analysis required to assess the feasibility of replacing MBMs diesel buses with electric buses powered by renewable energy, this report looks beyond MBM's needs by:

- Considering additional renewable energy options that provide future opportunities for renewable energy to power the continued decarbonization of Jamaica's transport sector (Section 7)
- Identifying opportunities to scale and replicate this project in Jamaica and the Caribbean (Section 8).

2 Technical analysis of electric bus options

This section determines the technical viability of BEBs and HFCEB's by comparing MBM's operational requirements with the operational capabilities of BEBs and HFCEBs. Section 2.1 determines MBM's operational requirements by analyzing:

- The number of buses required to replace MBM's existing fleet with electric buses, and
- The number of kilometers on the routes that MBM metro runs and would like to run.

Based on the assessment of MBM's needs, Section 2.2 analyzes the technical viability of available BEB and HFCEB to meet those needs.

2.1 Montego Bay Metro's bus requirements

This section shows that MBM requires six buses to cover a total of 2,219km per day to replace MBM's existing diesel buses. To complete its routes, MBM operates eight bus routes using six diesel buses. MBM's existing buses:

- Were produced by Volvo between 2010 and 2013
- Are 12m long and seat around 53 people
- Have an average diesel consumption is approximately 0.59 L/km (Li, Gao and Song, 2020).

MBM's operational requirements are based on information provided by MBM on their current routes. Table 2.1 provides detail on each of MBM's routes.

Table 2.1: MBM bus route information

Montego Bay routes	Distance for the whole route	Frequency of route operation	Number of buses operating the route	Total distance traveled per day
Unit	*km*	*times/day*	*#/day*	*km/day*
Route 2 Falmouth	68	10	2	680
Route 3 Cambridge	56	5	1	280
Route 5 Sandy Bay	58	5	1	290
Route 6 Lucea (school pickup route)	84	2	Operated by Route 5 Sandy Bay bus	168
Route 7 Spot Valley (school pickup route)	50	2	Operated by any available bus	100
Route 8 William Knibb (school pickup route)	68	2	Operated by one of the Route 2 Falmouth buses	136
Route 10 Goodwill	50	5	1	250
Route 21 Mackfield	63	5	1	315

Total	**2,219**

Source: Montego Bay Metro

Table 2.1 shows that all buses have combined travel of approximately 2,219km per day, with an average daily distance of 370km per bus. The shortest bus route is 50 km, and the longest route is 84km. The time to complete a round trip for each route is between 100 to 120 minutes with an average dwell time—time spent in the bus depot in between routes—of 15-20 minutes.

Bus routes in the table are divided into public routes and school routes.

- **Public routes**—Routes 2, 3, 5, 10, and 21 are public routes, meaning that they are routes that are accessible to all commuters. Public routes are all covered by one bus per route—except for route 2, which is covered by two buses. Public routes complete four to five round trips per day depending on road and traffic conditions. Public routes are operational six days per week as MBM does not operate buses on Sunday.
- **School routes**—Routes 6, 7, and 8 are school routes. School routes are routes designed to drop off and pick up children from school. School routes do not have dedicated buses. Generally, route 6 is covered by the bus that operates route 5; route 8 is covered by one of the buses from route 2; and route 7 is typically covered by any available bus. Buses covering these routes are required to complete two round trips five times per week—one trip to pick up children and drop them off at school before returning to the bus depot and another route to pick up the children from school and drop them off at home.

2.2 Technical assessment of battery-electric and hydrogen fuel cell electric buses

This section shows that BEB and HFCEB technologies are technically viable to meet the MBM's operational needs described in Section 2.1. Further, this section shows that BEB with smaller battery capacity are better suited to MBM's routes and cost less than BEB with large battery packs.

2.2.1 Battery electric buses are technically viable

BEB are technically viable and BEB with smaller battery packs are best suited to MBM's needs.

All BEBs considered are technically viable; however, buses with smaller battery packs will require top-up charging during the day

Several BEB manufacturers are capable of a one-for-one replacement of MBM's existing buses based on their offerings. One-for-one replacement means that:

- They offer buses of a similar size to the buses currently used by MBM
- They can cover the required range in terms of total distance per day and distance of each route.

This section includes details of buses offered by Proterra, Ankai, and Yutong to show that BEBs readily available to MBM are suitable for MBM's operational needs to show that all three buses can meet MBM's needs. Ankai and Yutong are included because they are two of the largest producers of BEBs in the world and have representative offices in the Caribbean. Proterra is included because it is one of the largest producers in North America that offers bus models with a range sufficient to cover MBM's longest daily route distance of 340km on one charge. Table 2.2 compares the characteristics of Ankai, Yutong, and Proterra's buses.

Table 2.2: Characteristics of BEB Reviewed

Producer	Model	Battery	Price	Nameplate driving range	Actual driving range*	Bus length	Seats
		kWh	*US$/bus*	*km*	*km*	*m*	*#*
Proterra	ZX5 40-foot bus	675	1,400,000	530	371	12	40
Ankai	HFF6129G03E V6 Low Entry City Bus (RHD)	383	236,700**	300	210	12	40
Yutong	E12	350	360,000**	350	245	12.5	40-49

Source: Proterra ZX5 40-foot bus specification, Motowheeler, Proterra Zx5 40-Foot Bus, Industry expert consultation

** Actual driving range refers to the fact that batteries should not be fully discharged before the next charge to minimize battery performance degradation. In addition, there should be a security margin for backup during emergencies and unforeseen delays. As a result, the usable energy is approximately 70 percent of the nameplate driving range. (Source: NREL, 2021, Electrifying transit: a guidebook for implementing battery electric buses, p.8)*
***Landed cost in Jamaica excluding taxes*

All three companies offer 12-meter city buses that have 40-49 seats. MBM's current buses are also 12-meter city buses; however, MBM's current diesel buses are configured to seat 53 people. The buses reviewed may need to be reconfigured to meet MBM's needs. Determining the required seating and layout of each bus requires information about average bus occupancy and the average number of passengers traveling per day that can then be used for modeling seating requirements. This is beyond the scope of this assignment; however, this is an area for further consideration during the detailed feasibility study.

Table 2.2 also shows that the driving range and the price of BEBs vary greatly depending on the electric battery of the bus. For example:

- The Proterra ZX5 40-Foot Bus model with a battery capacity of 675kWh battery has a maximum actual driving range of 371km and a landed price in Jamaica excluding taxes of US$1,400,000 per bus (Motowheeler, 2022).
- Smaller battery buses produced by Ankai and Yutong, with a battery capacity of 383kWh, have an actual driving range between 210-245km and a landed price in Jamaica excluding taxes ranging between US$240,000 and US$360,000.

All options have the required range to operate any of MBM's routes; however, the buses with smaller batteries will require topping up during the day to complete multiple routes. The analysis does not include buses with swappable battery packs because none of the major producers reviewed offered this option.

Choosing the best battery electric bus requires considering which charging strategy to employ

This section shows that using BEB with smaller battery packs combined with a fast charger will meet MBM's needs and cost less than buses with larger battery packs.

The type of bus best suited to replace the current diesel bus fleet largely depends on the charging strategy. There are two common BEB charging strategies:

- Using only overnight depot/plug-in chargers
- A combination of overnight and daytime recharging—also called opportunity charging. Opportunity charging means that buses with a smaller range receive a top-up charge during their dwell time with a fast charger.

The first strategy requires MBM to purchase more expensive buses, such as the Proterra ZX5 Max 40-Foot Bus because the buses will only be charged at night and must have sufficient range without top up charging during the day. Proterra's buses have an operational range sufficient to cover average daily travel distance of 370km.

The second strategy allows MBM to purchase less expensive buses with a shorter range, such as those offered by Ankai and Yutong. Like the first strategy, these buses would charge overnight using 30-50kW chargers. However, to compensate for the lack of operational range, MBM would also have to use a faster charger to replenish the battery charge during the dwell time.

Fast chargers are typically available in a size range between 150 and 600kW. Table 2.3 provides details on the amount of time required to charge buses using each type of charger.

Table 2.3: Comparison of different types of chargers (NREL, 2021 (a))

Type of charger	Charging power	Charging speed (full charge)	Cost
Overnight charger (slow)	30-50 kW	4-6 hours	US$2,000-US$100,000
Opportunity charger (fast)	150-600 kW	7-30 minutes	US$$330,000-US$600,000

There is a range of charging power within each charger category – which impacts the amount of time it takes to charge a bus and the price of the charger. Another factor affecting the charging time is the size of the battery. Larger batteries require more time to charge fully.

Therefore, a charging strategy must determine the power of the slow or fast charger in addition to determining which charging strategy to use based on the amount of time that a bus has to charge overnight or during its dwell time in the bus depot. For this reason, a final decision on the optimal bus and charging strategies requires complicated, precise modeling, which is outside this pre-feasibility study's scope. As an example, the box below describes Foothill Transit's charging strategy using a 500kW charger.

Box 2.1: Conductive on-route charging in Foothill Transit in California's San Gabriel and Pomona Valleys

Foothill Transit has used BEBs in conjunction with Proterra fast-charging equipment since 2010. Foothill Transit uses a 500-kW on-route charger with Proterra EcoRide BE35 buses equipped with 88-kWh battery packs. The buses can be fully charged in 10 minutes, but typical charge times are around 7 minutes. The charging time is reduced to optimize the frequency of operating the route while maintaining a safe charge level.

Figure 2. Foothill Transit overhead 500-kW fast charger

Source: NREL, 2021, Electrifying transit: a guidebook for implementing battery electric buses, p.13

BEB with smaller battery packs charged using opportunity charging are the best option for MBM despite the need to top up

To determine which charging strategy makes most sense for MBM, Table 2.2 compares the cost of purchasing six Proterra buses and the cost of purchasing six smaller buses and a fast charger. It shows that using buses with smaller battery packs plus a fast charger will cost significantly less than using buses with larger battery packs and longer ranges.

Table 2.4: Cost comparison of charging strategies

Charging strategy	Average bus price	Number of buses	Cost of a fast charger, including installation	Number of fast chargers	Total cost
Unit	*US$*	*#*	*US$*	*#*	*US$*
Strategy 1 (overnight charging only)	1,400,000	6	0	0	8,400,000
Strategy 2 (opportunity charging)	298,350	6	698,447	1	2,488,547

In the case of MBM, a 450kW fast charger—which would cost US$698,447, including installation costs (NREL, 2021 (a))—would be sufficient to allow MBM to purchase BEB with smaller battery packs. A 450kW charger can add approximately 21 miles or 33.6km of range in 10 minutes (Proterra, 2022).

During the 15-20 minutes of dwell time that MBM's buses average, a 450kW fast charger can add a range of 50.4km to 67.2km. Even buses with smaller battery packs would still retain over half of their charge even after completing MBM's longest route and would not be fully discharged. The additional range added by a 450kW fast charger during any of MBM's buses' dwell time would be enough to guarantee that the bus will be able to complete its route with a safe margin of battery charge.[1]

This conclusion is in line with desktop research that suggests that overnight charging using only less powerful chargers is more economical for shorter daily travel distances of less than 150km/day. Meanwhile, for longer daily travel distances over 300km/day, the balance flips toward opportunity charging using faster more powerful charger. Research shows that for longer routes, opportunity charging saves 10-20 percent of the total cost of ownership (McKinsey, 2018). MBM's longer daily average of 370km means that existing literature supports that conclusion that BEB with smaller battery packs employing opportunity charging, would be more cost-effective for MBM.

2.2.2 Hydrogen fuel cell electric buses are technically viable

HFCEB can replace MBM's existing diesel buses on a one-for-one basis given the operational similarities between diesel and hydrogen buses. The HFCEBs analyzed are also 12-meter city buses with 40-49 seats, and a landed price in Jamaica excluding taxes ranging between US$490,000 to US$1.3 million.[2] Further, commercially available HFCEB have a driving range of around 480km that can be fueled in less than 4 minutes, which is similar to conventional internal combustion engine vehicles.

[1] This analysis is indicative and there would need to be an optimal charging schedule to allow buses to operate effectively. BEB producers, such as Yutong, can perform a detailed analysis of bus routes and design the best-suited charging schedule for a specific bus operator.

[2] Source 1: Yutong sales manager in Trinidad Tobago; Source 2: Castalia intel for 2021; Source 3: NREL, 2021, Fuel Cell Electric Bus Progress Report

3 Assessment of potential renewable energy/electric bus combinations

This section determines the least-cost option for replacing MBM's diesel buses with electric buses powered by renewable energy.

In many countries, procuring the renewable energy required to meet MBM's requirements could be achieved by contracting with a utility-scale renewable energy producer to provide electricity for the project over the existing transmission and distribution network. However, Jamaica's Office of Utility Regulations (OUR) has not approved the mechanism—known as a "wheeling charge"—that would allow for MBM to enter into such an agreement. Further, the timing of when Jamaica's OUR will approve a wheeling charge for MBM is highly uncertain. As a result, this section assesses the cost of options to deliver renewable energy directly to buses, alongside the costs of the buses themselves, to find the most cost-effective combination.

Waste-to-Energy technology and Solar PV are feasible options for delivering renewable energy to MBM buses directly. Various Waste-to-Energy technologies were considered. While Waste to Energy is a promising future option, they are not currently viable sources of renewable energy for buses, as explained in Section 7.

As result, this section assesses the following renewable electricity generation options:

- Floating solar PV in the Bogue wastewater treatment plant's oxidation ponds
- Rooftop solar PV installed over the entire MBM depot area
- Land-based solar PV located reasonably close to MBM.

All three types of solar PV are proven technologies that are in commercial operation around the world. The key consideration for technical viability of each type of solar PV is the availability of a suitable site near the MBM bus depot:

- Solar PV for BEBs must be located within or near MBM's bus depot because, as shown in Table 2.2, BEBs have a maximum effective driving range of 371km[3]. This range just covers the average daily driving range for MBM's buses of 370km, leaving no remaining battery charge for driving to and from a solar PV installation for overnight charging[4]
- HFCEB would need to fill up with hydrogen at the place where hydrogen is produced to avoid the prohibitive cost of transporting hydrogen to the bus depot[5]. The range of an HFCEB bus on a

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[3] Even when fitted with a larger than standard battery pack to increase range

[4] It has been proposed that BEB could be driven to an offsite facility to charge overnight; however, even if a BEB had a large enough range to cover MBM's routes and the drive to the offsite facility, this option would require complicated logistics, which makes it non-viable: Bus drivers would need to be ferried to and from the offsite facility to pick up the buses in the morning and after dropping them off in the evening; driving the buses to and from an offsite facility in the morning and evening would reduce their available range for operating MBMs routes; and an offsite facility would preclude the ability to use a fast-charger to opportunistically charge buses during their dwell time in the MBM depot. This is particularly important as it would require either purchasing much more expensive buses or additional buses to meet MBM's requirements

[5] Analysis conducted for the New Zealand market shows that there are two methods of transporting green hydrogen: Compress and Liquify. The total transport costs per kg of hydrogen are US$0.26 per kg (compress) and US$ 1.39 per kg (liquify). These are only Capex and Opex (per kg) for transport infrastructure. However, the total costs also depend on transport distances. For example, a transportation distance of 20km would incur an additional cost of over US$0.12 per kg (compress) and US$0.02 per kg (liquify).

single tank of hydrogen means that a Solar PV plant and associated hydrogen production facility must be no more than 40km from MBM's bus depot. Considering the 480km range of HFCEB and the 370km average daily requirement, 40km would allow for a round trip for fueling of 80km and leave 400km for routes (370 and a safety margin of 30km).

Meeting the MBM's needs assessed in section 2.1 requires calculating the required area of solar PV to charge BEB or produce enough hydrogen for HFCEB. It also requires determining if there is a large enough site close enough to MBM's bus depot for the solar PV installation. The required area is calculated by: 1) calculating the amount of electricity needed to either charge BEB or produce enough hydrogen for HFCEB; and 2) the size of the area needed to meet that requirement (based on IRENA's estimate that a one MW solar system requires an area of 1.9 hectares):

- **BEBs**— MBM's bus fleet accounting for losses incurred in storing and discharging the electricity, requires a renewable energy installation providing 2.8MWh per day

  A daily distance of 2,219km for MBM's bus fleet requires 2.6MWh of electricity because a BEB consumes around 1.18 kWh of electricity per kilometer (Auckland Transport, 2018). In addition, overnight charging with electricity generated by solar PV during the day means that BEBs require a battery energy storage system (BESS). BESSs incur losses in storing and discharging electricity increasing the required amount of electricity. For example, the Round-Trip Efficiency (RTE)[6] of a Tesla Megapack BESS is 93.5 percent(Tesla, 2022). Accounting for losses, BEB would require a renewable energy installation providing 2.8MWh per day

  Given Jamaica's solar PV capacity factor of 22 percent (CCREEE, 2018), the daily production of 2.8 MWh would require a solar PV facility with a capacity of around 0.5MW[7] covering an area of approximately 10,035m^2

- **HFCEBs**—approximately 184kg of hydrogen would be required for HFCEB to travel the 2,219km required to serve MBM's routes because an HFCEB consumes around 0.083kg of hydrogen per kilometer.[8] Producing 184kg of hydrogen requires 9,761kWh of electricity[9] because the production of 1kg of hydrogen requires approximately 53kWh of electricity.[10] As a result, daily hydrogen consumption of 184kg requires 9.8MWh per day to produce. A 9.8MWh requirement means that HFCEB requires a solar PV installation with a capacity of approximately 1.85MW covering an area of 35,126m^2.

Considering the requirement for the size and location requirement of the solar PV facility, Table 3.1 shows that BEBs powered by floating solar PV is the best option for MBM. For each combination of electric buses and solar PV options, Table 3.1 compares:

- **Bus cost (US$)**—this includes both the cost of the bus and the infrastructure required to charge or refuel the buses, such as depot and fast chargers

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6 Round trip efficiency is the ratio of energy put in (in MWh) to energy retrieved from storage (in MWh) is the expressed in percent (%). The higher the round-trip efficiency, the less energy is lost due to storage.

7 Calculated: 2.788MWh/(22%*24hours) =528KW

8 The fuel consumption is an average derived from three sources. Source 1: Economic Case for Hydrogen Buses in Europe, Ballard 2017; Source 2: SunLine Transit Agency American Fuel Cell Bus Progress Report, NREL, 2020; Source 3: Orange County Transportation Authority Fuel Cell Electric Bus Progress Report. NREL 2021

9 Calculation: 184.18kg*53kWh=9,761kWh

10 IRENA Renewable Technology Innovation Indicators states that 1 MW solar system would require approximately 1.9 hectares

- **Energy Cost (US$/km)**— this is a sum of the Levelized Cost of Energy (LCOE) of the solar PV installation required to produce electricity for the bus option and the cost of additional infrastructure such as the BESS required to store electricity for BEB or the cost of the electrolyzer and hydrogen storage for HFCEB expressed as a cost per kilometer travelled.

Table 3.1: Comparison of Electric Bus and Renewable Energy Source Options

Energy source	Battery-electric bus	Hydrogen fuel cell electric bus
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Rooftop Solar	Bus Cost (US$): 465,307 Energy Cost: (US$/km): 0.44 (does not include the cost of constructing a roof) **Physical Configuration:** Buses charge at depot overnight and opportunistically during the day using a fast-charger	Not technically viable due to insufficient area of the MBM bus depot****
Land-Based Solar PV	Not Technically viable due to lack of a suitably large piece of land near the MBM bus depot***	Bus Cost (US$): 814,688 Energy Cost: (US$/km): 1.43 **Physical Configuration:** Buses travel to refuel with hydrogen produced at the land-based PV installation

**Capital cost of the bus is an average of observed prices for each type of bus*
***Cost of energy on bus includes the full cost of energy—for solar PV options this includes the full cost the PV installation as well as required energy storage—required to power the bus*
****Even BEB with a larger battery pack and larger possible range (for example, the Proterra ZX5 40-Foot Bus model with a battery capacity of 675kWh battery and a significantly higher price of US$1,400,000 per bus) has a maximum effective driving range of 371km which would only just be enough to cover the average daily km for MBM's buses of 370km. There would be no remaining battery charge for driving to and from a land-based solar PV installation for overnight charging.*
*****HFCEB requires 35,126.18m3 of area to generate enough electricity to create the required amount of hydrogen and the MBM bus depot has only 10,000m3 of potential roof space.*

Table 3.1 shows that the BEB options are lower cost than either of the HFCEB options. Both the cost of the bus and the energy cost are lower for BEB than for HFCEB.

Comparing the two BEB options, the option that uses floating solar PV has lower energy costs than the option that uses rooftop solar PV; the cost of electricity from floating solar is less than the cost of rooftop solar (while the cost of the buses is, of course, the same). This suggests that BEB powered by floating solar PV is the best option for electric buses powered by 100 percent renewable energy.

The following sections explain how the bus cost and energy cost for each option in Table 3.1 was calculated. Floating solar, rooftop solar, and land-based solar generation are considered in turn. How each renewable energy generation option would work is briefly described, and the viability and cost of combining that option with either BEB or HFCEB analyzed.

3.1 Assessment of floating solar PV options

Floating solar PV located on the Bogue wastewater treatment plant is technically viable for both BEB and HFCEB and is the cheapest option for BEB. Section 3.1.1 and Section 3.1.2 contain the calculation of the energy cost for BEB and HFCEB using floating solar PV, respectively.

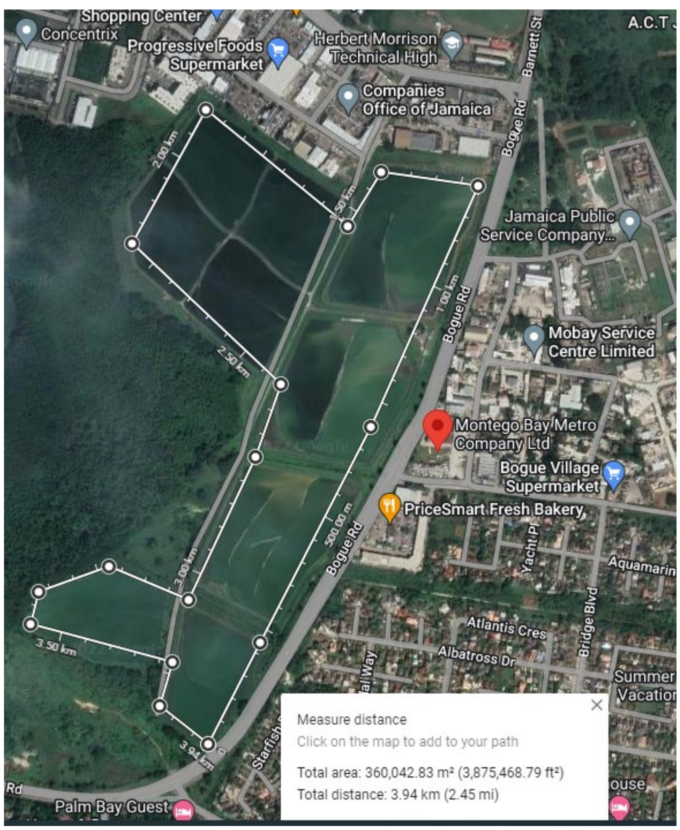
The Bogue wastewater treatment ponds are across the street from the MBM bus depot. Electricity can be generated by floating solar PV installations on the ponds and transmitted directly to the MBM bus depot.

If battery electric buses are used, the electricity would be stored in a battery electric storage system (BESS) in the depot. Buses would be charged through a fast charger during dwell times in the depot during the day and through overnight chargers when the buses are out of service at night.

If HFCEB are used, electricity generated by the floating solar PV installation would be used to run an electrolyzer at the depot during the day to produce green hydrogen. Hydrogen would be stored in a tank at the depot, and the buses would refill with hydrogen as needed.

The Bogue wastewater oxidation ponds have a surface area of around 360,000m sq. (Gray, 2003) providing sufficient space for either the 10,035m^2 floating solar PV facility required for BEBs or the 19,425m^2 facility required for HFCEB. Figure 3.1 shows the space available on Bogue's treatment ponds for floating solar PV.

Figure 3.1: The Bogue Wastewater Treatment Plant



Source: Google Maps

International experience suggests that floating solar PV facilities will not face any technical difficulties operating on Bogue's treatment ponds or prevent the ponds from functioning to treat wastewater. For example, D3Energy installed 1MW floating solar PV facility in the Rosedale Wastewater Treatment Plant in New Zealand. This is the largest solar project of any type in New Zealand.

The shallow depth of the oxidation ponds (1-1.5m) would also not be an issue. The floats can function even if the pond completely dries out and sits on the floor of the reservoir. Floating solar PV installations can also withstand hurricane-force winds meaning they are suitable for Jamaica (PV Magazine, 2020; Interesting Engineering, 2021).

The NWC has expressed concerns that installing floating PV panels would block the sunlight and wind required for the ponds to carry out their function in treating wastewater. These are valid concerns; however, the large space of the ponds allows for installing small islands of floats that would have a minimal impact on the pond's functioning and algae growth. Floating solar installations required to satisfy MBM's energy needs using battery-electric buses would cover one percent or less of the surface area of the ponds and be spaced out such that some sunlight will reach the area under the float.

3.1.1 Energy cost of floating solar PV for battery electric buses

The energy cost of US$0.427 per km shown in Table 3.1 for floating solar PV for BEBs comprises the LCOE of the floating solar PV itself and the additional cost of the BESS system.

- The LCOE of a floating solar PV facility to charge BEBs is calculated using the following assumptions:
  - Capital cost of US$3,000 per kW. [11] This means a 0.528MW[12] floating solar PV facility would cost around US$1.58million
  - Annual operating cost of US$15.5 per kW (NREL, 2021)
  - A lifetime of the facility of 30 years (NREL, 2021)
  - Operational days per year – 312 days, as the electricity is only used six days per week
  - A capacity factor of 22 percent—this is in line with other Solar PV in Jamaica; however, floating solar PV typically has a higher capacity factor due to the cooling effect of the water on the PV panels which means that the capacity factor of 22 percent is a conservative estimate

  Based on these assumptions, the LCOE of floating solar PV is US$0.184kWh
- The cost of the BESS system that would charge and store electricity from the solar PV during the day so that buses can charge at night is based on the cost of the Tesla Megapack BESS (power 0.8MW, energy 3.1MWh). The Tesla Megapack's capacity is large enough to fully charge the six buses that MBM would require. The price of this Megapack, including installation cost, is approximately US$1.5 million (Tesla, 2022). Further, the annual maintenance cost is assumed to be two percent of capex (Tesla, 2022). Based on these assumptions, the additional cost of the BESS results is an additional US$0.178kWh.

As a result, the energy cost for BEB from floating solar PV is US$0.362 per kWh or US$0.427 per km based on BEB electricity consumption of 1.18 kWh of electricity per kilometer (Auckland Transport, 2018).

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[11] Provided by D3Energy

[12] The capacity of the floating solar PV facility accounts for the Round-Trip Efficiency (RTE) of 93.5%

3.1.2 Energy cost of floating solar PV for hydrogen fuel cell electric buses

The energy cost of US$1.73 per km for HFCEBs shown in Table 3.1 is calculated based on the LCOE of electricity from the floating solar PV and Castalia's existing model for the cost of hydrogen developed for the Port of Auckland in New Zealand.

The LCOE of floating solar PV is slightly lower than for BEBs because economies of scale mean that the larger size of the facility results in a lower price per installed kW of US$2,400 per kW. All other assumptions remain unchanged. As a result, the LCOE of a floating solar PV facility for hydrogen production is US$0.126 per kWh.

Castalia's model of hydrogen costs for the Port of Auckland includes consideration of all additional infrastructure required to create and then deliver hydrogen to HFCEBs. Using the LCOE of electricity generated by the floating solar PV, Castalia's model calculates a hydrogen cost of US$20.896 per kg. Based on the hydrogen cost and average hydrogen consumption of 0.083 kg per km,[13] the energy cost is US$1.73 per km. Box 3.1 provides a more detailed explanation of how Castalia's existing model calculates the cost of hydrogen.

Box 3.1: Cost of hydrogen

This analysis used a financial model of hydrogen production Castalia developed for Port of Auckland in New Zealand to calculate the price of hydrogen because there are no green hydrogen producers in Jamaica.

Except for the cost of electricity, all the inputs used in the model—including water, labor, capital cost and discount rate—are based on the New Zealand market. This means that the cost of hydrogen is likely understated given that New Zealand likely has lower water and capital costs as well as more efficient labor.

As a result, the finding of the US$1.73 per km, which is significantly higher than BEB, cannot be less in the Jamaican context. Table 3.2 provides estimates of how the cost of hydrogen changes when the cost of electricity changes, leaving all other variables constant.

Table 3.2: How the cost of electricity affects the cost of hydrogen

	Unit	Cost of electricity in New Zealand	Cost of electricity from utility-scale solar PV	Cost of electricity from floating solar PV
Cost of electricity	US$/kWh	0.054	0.085	0.126
Cost of hydrogen	US$/kg	14.430	17.258	20.896
Energy cost	US$/km	1.20	1.43	1.73

Table 3.2 shows that using New Zealand's cost of electricity of around US$0.054 per kWh, the cost of hydrogen is US$14.430 per kg. Using data from Eight Rivers Energy Company (EREC) in Jamaica–where electricity from utility-scale solar PV costs US$0.085 per kWh–the cost of hydrogen is US$17.258 per kg. Using the cost of electricity from floating solar PV, US$0.126 per kWh, the cost of hydrogen is US$20.896 per kg.

One of the key factors affecting the cost of hydrogen is the size of the plant. The economies of scale of larger plants can substantially reduce the costs. For example, in the New Zealand model, a small-scale hydrogen production facility producing 83kg per day would result in a hydrogen price of approximately US$27 per kg. Whereas the cost of hydrogen for a medium-scale facility is approximately US$14.43 per kg. Table 3.3 illustrates the relationship between capacity and price.

[13] Source 1: Economic Case for Hydrogen Buses in Europe, Ballard 2017; Source 2: SunLine Transit Agency American Fuel Cell Bus Progress Report, NREL, 2020; Source 3: Orange County Transportation Authority Fuel Cell Electric Bus Progress Report. NREL 2021

Table 3.3: Economies of scale of hydrogen production

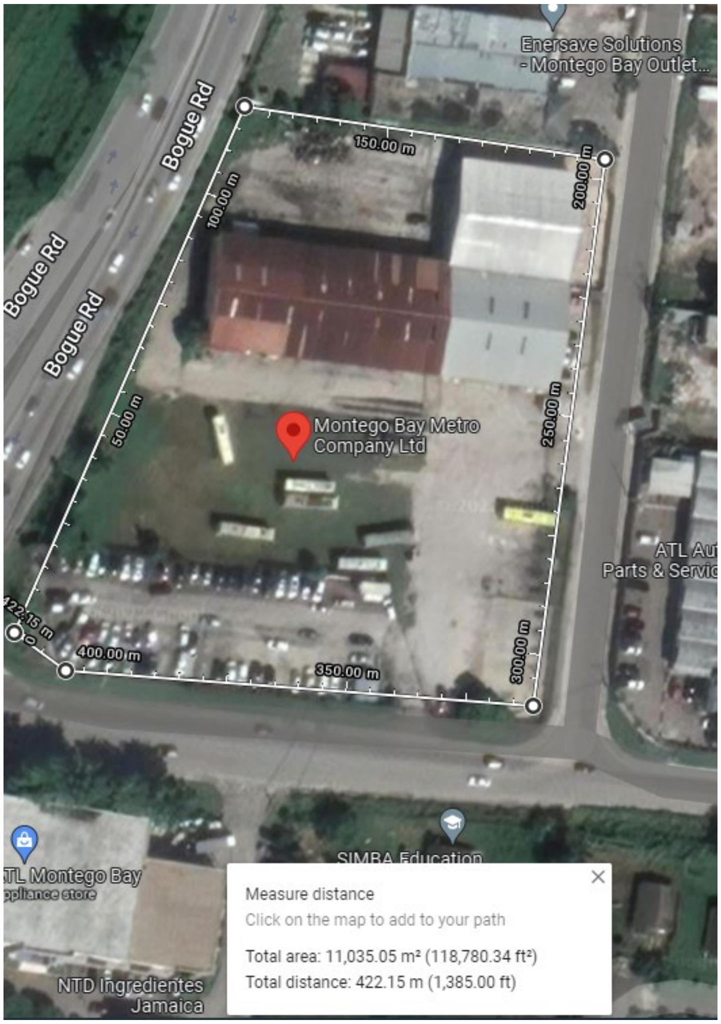
Approximate System Size	Small Scale 250kW	Medium Scale 950kW
Daily production capacity	83 kg	410 kg
Approximate heavy vehicles	2 bus/truck	19 bus/truck/fork hoist
Approximate small vehicles	15 cars	10 cars
Levelized cost per kg	Around US$27 per kg at full utilization	Around US$17.258 per kg at full utilization

3.2 Assessment of rooftop solar PV options

Rooftop solar PV is technically viable for BEB and is not technically viable for HFCEB because the area of the MBM bus depot is not large enough for a solar PV installation that HFCEB would require. Further, the energy cost of US$0.44 per km of rooftop solar PV, without considering the cost of roof construction, is higher than the cost of floating solar PV.

Rooftop solar is viable for BEB and not HFCEB, because the area of the MBM depot is roughly 10,000m^2 as illustrated in Figure 3.2. While 10,000m^2 is sufficient for BEB, it is insufficient for the 35,126m^2 required to produce hydrogen for HFCEB.

Figure 3.2: MBM area that needs to be covered with a roof



Source: Google Maps

Locating solar PV on the rooftop allows electricity to be generated at the MBM bus depot and stored in a BESS onsite to be discharged into the BEB. As a result, the energy cost of US$0.44 per KM shown in Table 3.1 for rooftop solar PV for BEB includes the LCOE of rooftop solar PV itself and the additional cost of the BESS system.

- Rooftop solar PV's LCOE of US$0.19 per kWh[14] is based on the reference price of the tender won by Eight Rivers Energy Company (EREC) for of US$0.085 scaled up by 123 percent. The scaling factor is based on analysis by LAZARD, which publishes an annual report on the LCOE of renewable energy technology, that shows that commercial and industrial rooftop Solar PV is approximately 123 percent more expensive than utility-scale land-based solar PV (LAZARD,

[14] Calculation: 0.085*(1+1.23) = 0.19

2021). Further, this price is in line with previous Castalia research on rooftop solar PV in the Caribbean[15]

- Similar to floating solar PV, the incremental cost of infrastructure for rooftop solar PV is the BESS cost, which adds US$0.18 per kWh to the total cost of electricity
- Additionally, the solar PV system would need to be installed on top of the MBM depot area, as illustrated in Figure 3.2 which requires building a roof that can hold the solar panels. However, the energy cost does not include the cost of building the roof itself because roofing costs are highly uncertain. Further, the energy cost of rooftop solar was already higher than floating solar PV and cannot be the lowest cost option for electrifying Montego Bay's bus fleet.

Without accounting for the cost of a roof, which can be substantial given the required size, the total cost of electricity from rooftop solar is US$0.37 per kWh or US$0.44 per km based on electricity consumption 1.18 kWh of electricity per km (Auckland Transport, 2018), which is greater than the energy cost from floating solar PV.

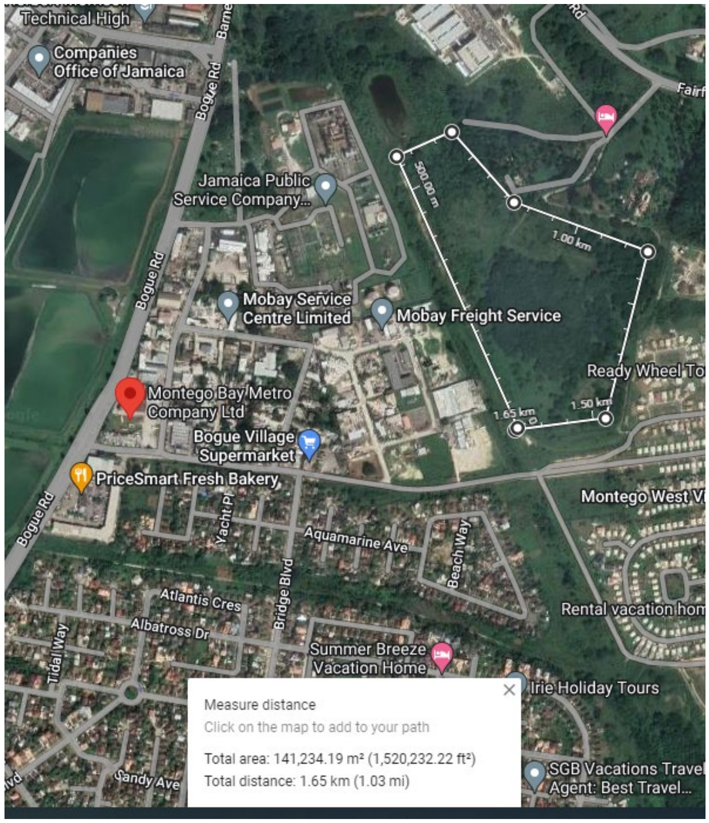
3.3 Assessment of land-based solar PV options

Assuming it can be sited within 40km of the MBM bus depot, land-based PV's energy cost of US$1.43 per km is the least-cost option for HFCEB. However, land-based solar PV is not viable for BEB because there is no suitable piece of land in the immediate vicinity of the MBM bus depot.

Figure 3.3 shows that there is only one area of sufficient size for a solar PV installation large enough to power BEB in the immediate vicinity of the MBM bus depot. The area of around 141,234m^2 is located 750 meters from MBM and would provide sufficient space for installing a land-based solar PV system. However, the landlord is not interested in leasing the land for a land-based solar PV facility.

[15] According to Castalia report, (Castalia, 2019, CARICOM Sustainable EnergyPath Final Report, p.16) calculated LCOE (US$0.19/kWh) is in the range between a utility scale (US$0.11/kWh) and residential (US$0.25/kWh) solar PV

Figure 3.3: Montego Bay Metro's surrounding areas



Source: Google Maps

The energy cost for HFCEB with land-based solar PV is based on the price of the competitive tender won by Eight Rivers Energy Company (EREC) of US$0.085 per kWh (Eight Rivers Energy Company, 2019). That price per kWh produces a hydrogen price of US$17.26 per kg when input into Castalia's existing model for the cost of hydrogen (as shown in Box 3.1). Based on that price of hydrogen and HFCEB consumption of 0.083kg of hydrogen per kilometer, the energy cost for HFCEB powered by land-based solar PV is US$1.43 per km.

Using hydrogen as a source of power would not require any additional infrastructure costs for energy storage. However, because utility-scale, land-based solar PV would be located further away from MBM, buses might have to travel up to 40km per day to refuel. This option would incur additional costs of US$0.096 per km in present value terms over 12 years based on additional driver time, additional fuel costs to cover the 80km round trip, and additional wear and tear on the bus—particularly if the solar PV installation is located in an area that is not served by well-maintained roads (as is often the case).

4 Comparison of CO^2 emissions

This section assesses well to wheel CO^2 emissions for diesel buses and BEB and quantifies the Social Cost of Carbon (SCC) to determine the global benefits of replacing MBM's diesel buses with electric buses from the perspective of CO^2 emissions reductions. The analysis in this section shows that:

- Diesel buses produce approximately 1.488kg of CO^2 per km. Given annual average km per bus of 111,887 diesel buses produce 166,487kg of CO^2. As a result, switching MBM's entire diesel bus fleet to:
    - BEB charged with renewable energy would lead to a CO^2 reduction of 998,924kg per year
    - BEB charged from the grid would lead to a CO^2 reduction of 381,309kg per year
- Using a SCC of US$112.4/ tCO^2 e, diesel bus emissions cost US$0.17 per km.[16] BEB powered by renewable energy produce zero carbon emissions and no social cost. This means that switching to BEB powered by renewable energy has a global social benefit worth US$18,709 per bus per year.

While this section quantifies the SCC, electric buses also significantly reduce noise pollution. The internal combustion engine of a diesel bus can generate up to 80 decibels of noise. This is almost 100 times louder than a quiet residential street. Due to the high social cost associated with noise, adopting electric buses offers substantial further social and health benefits.

4.1 Calculating emissions per kilometer for each bus technology

This section calculates emissions reductions through Well-to-Wheel (WTW) analysis to compare the emissions of BEB powered by renewable energy, BEB powered by grid energy, and diesel buses. WTW analysis includes all emissions that occur during energy production, processing, and use in a vehicle. The analysis does not include analysis of emissions in bus production due to a lack of reliable information on emissions generated in bus production.

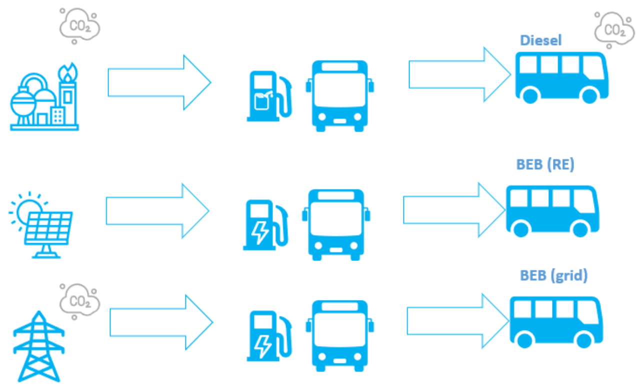
WTW analysis is divided into two stages:

- Well-to-Tank (WTT) – the emissions from producing the energy source (diesel or electricity) and transporting it to the fuel supply point (transport to the charging point or fuel pump)
- Tank-to-Wheel (TTW) – the emissions that result from burning the fuel while driving.

Figure 4.1 illustrates WTT to TTW emissions for diesel buses, BEB powered by renewable energy, and BEB powered by the grid.

[16] Calculated:0.167* 111,887=US$18,709

Figure 4.1: Conceptual illustration of WTW (WTT & TTW) emissions for diesel, BEB and HFCEB.



Source: Adapted form [Comparative Assessment of Zero Emission Electric and Hydrogen Buses]

BEB powered by renewable energy generates no WTW emissions, BEB powered by grid electricity generates WTT emissions and no TTW emissions, and diesel buses produce emissions at both stages. Using WTT analysis:

- BEB powered from the grid generates around 0.924kg[17] of CO^2 per kilometer based on the Jamaica's grid emission factor of 0.783kg CO^2 per kWh (IGES, 2022) and electricity consumption of 1.18kWh per km[18]
- Production of diesel fuel for diesel buses generates approximately 162g of CO^2 per kilometer (Hensher, Wei and Balbontin, 2021).

Further TTW analysis found that BEB would produce no emissions and diesel buses would produce around 1.3kg of CO^2 per km (Hensher, Wei and Balbontin, 2021).

Table 4.1 summarizes CO^2 emissions at each stage of WTW analysis. It shows that CO^2 emissions generated by diesel buses are approximately 1.488kg per km; BEBs powered by grid electricity generate emissions of 0.924kg per km; and BEB powered by renewable energy have no WTW emissions.

Table 4.1: Well-to-Wheel emission summary, ***kg*** CO^2***/km***

	BEB (RE)	BEB (grid)	Diesel
Well-to-Tank (WTT)	0	0.924	0.162
Tank-to-Wheel (TTW)	0	0.000	1.3

17 Calculation: 0.783*1.18=0.924kg CO^2 /km

18 Calculation given energy consumption of 1.18kWh per km: 0.783* 1.18=0.0924 kg CO^2 per km

Well-to-Wheel (WTW)	**0**	**0.924**	**1.488**

Source: Comparative Assessment of Zero Emission Electric and Hydrogen Buses in Australia, p23.

Further, the total amount of carbon produced by MBM's existing fleet of diesel buses is 998,924.16kg of carbon per year given the MBM diesel bus fleet's annual mileage of 671,320 km. 100 percent of these emissions can be avoided by switching to a BEB fleet powered by floating solar PV and 38 percent or 381,309kg of carbon per year can be avoided by switching to BEB powered by the grid.

Box 4.1: CO^2 emissions associated with lithium-Ion battery production are likely immaterial

Manufacturing any type of bus generates emissions because it involves sourcing materials, using large amounts of electricity from the grid, etc. The incremental carbon emissions during the manufacturing of BEB compared to diesel buses is limited to the production of Li-Ion batteries because all other parts of the bus would generally be made of the same materials as diesel buses—for example, steel frames of the bus, plastic seats and so on.

As Ankai and Yutong's buses are manufactured in China, emissions from battery production in China are most relevant. A study that analyzed CO^2 emissions related to the production of three types of Li-Ion batteries in China showed that the production of Li-Ion batteries in China results in carbon emissions between 96 and 127 kg CO^2e per kWh, depending on the battery chemistry.

Ankai and Yutong do not specify the battery chemistry. However, average carbon emissions of 112 kgCO^2e/kWh and an average battery capacity of two bus models of 366.5kWh results in Li-Ion battery production emissions of approximately 41,048kg per bus. This amount to emissions of 0.031kgCO^2e per km or US$0.0034 per km* over a 12-year life cycle of a BEB. As a result, the SCC of US$0.0034 per km associated with the production of Li-Ion batteries is too low to substantially impact the TCO comparison of bus technologies.

Source:

Hao Han,Zhexuan Mu, Shuhua Jiang, Zongwei Liu and Fuquan Zhao, 2017, GHG Emissions from the Production of Lithium-Ion Batteries for Electric Vehicles in China, MDPI

The International Council on Clean Transportation, 2018, Effects Of Battery Manufacturing On Electric Vehicle Lifecycle Emissions

** Given the SCC of US$112* t$CO^2$ e

4.2 Calculating the value of avoided emissions

This section calculates the global social value of GHG emissions avoided by switching to BEB powered by renewable energy or by the grid. The calculations are based on an estimate of the SCC of US$112/ t$CO^2$ e derived from an average of a range of estimates of the SCC.

Research shows that the SCC has a wide range of estimates. Sources sampled provided estimates between US$43 and US$302 per tCO^2 e. The range of the SCC is explained by the fact that integrated assessment models (IAMs) used to estimate the cost of reducing emissions use multiple inputs that can vary significantly. For example, the SCC changes considerably depending on the discount rate, warming temperature, and estimated climate damages and adaptation costs. The average SCC of US$112/t$CO^2$ e [19] is derived from several data sources as illustrated in Table 4.2.

[19] Source 1 ADB: US$43.2/ t$CO^2$ e, Source 2 IRENA: US$54.7/ t$CO^2$ e, Source 3 Goldman School of Public Policy, University of California, Berkeley: US$49.6/MT, Source 4 The UK Government: US$302/tCO2

Table 4.2: Sources of the SCC, US$/kg$CO^2$

Source	Social cost of carbon
Asia Development Bank	0.0432
IRENA	0.0547
Goldman School of Public Policy, University of California, Berkeley	0.0496
The United Kingdom Government	0.302
Average	**0.1124**

Source: Source 1 ADB;, Source 2 IRENA, Source 3 Goldman School of Public Policy, University of California, Berkeley; Source 4 The UK Government

The estimate of the SCC of US$112/ t$CO^2$ e is based on SCC estimates for recent years. However, the SCC will only increase over time as the impacts of climate change accumulate and the physical and economic systems become more stressed. As a result, in the future the social benefit generated by switching to battery-electric buses charged from renewable energy sources would also increase.

Based on the total amount of emissions generated by BEB powered by the grid and diesel buses, Table 4.3 shows the dollar value of avoided CO^2 emissions generated by these two options.

Table 4.3: The value of avoided emissions

Social cost of CO^2 emissions	Unit	BEB (RE)	BEB (grid)	Diesel
Social cost of CO^2 emissions	USD/km	0.00	0.104	0.167
Social cost of CO^2 emissions	USD/year/bus	-	11,616.94	18,709.02

Battery Electric Buses (grid)

The dollar value of CO^2 emissions avoided by BEB would be US$0.10per km[20] based on the average SCC of around US$0.112 per kg and WTW CO^2 emissions of 0.924kg of CO^2 per km generated by a BEB charged from the grid. Switching from diesel buses to BEB powered by the grid would result in an annual savings per bus of US$7,093; however, BEB powered by the grid would still generate emissions with a global social cost of US$11,616.

Diesel buses

Similarly, based on the total amount of CO^2 emission of 1.488kg of CO^2 per km generated by a diesel bus, the dollar value of carbon emissions would be US$0.167 per km for diesel buses.[21] As a result, switching from diesel buses to BEB powered by RE would total an annual savings of around US$18,709.

[20] Calculation given the total BEB (grid) CO^2 emissions of 0.924kg CO^2 /km: 0.112*0.924=0.104

[21] Calculation given the total diesel bus CO^2 emissions of 1.488kg CO^2 /km: 0.112*1.488=0.167

5 Total cost of ownership comparison of diesel buses and battery electric buses

This section compares the TCO of diesel buses, BEB powered by grid electricity, and BEB powered by renewable energy. The analysis in this section shows that BEB powered by renewable energy is the least-cost option for MBM when considering the SCC. It also shows that when not considering the SCC BEB powered by the grid is the least cost option of MBM. The TCO consists of four components:

- Capital cost—the cost of the type of bus identified in Section 2 and any related charging/fueling infrastructure (Section 5.1)
- Energy Cost—the cost of the least cost renewable energy option for BEB—floating solar PV—identified in Section 3, the cost of electricity from the grid, and the cost of diesel for diesel buses (Section 5.2)
- Maintenance cost—the cost of maintaining each type of bus and any associated charging or fueling infrastructure (Section5.3)
- Social cost of carbon—the SCC calculated in Section 4.

Based on these four components, Section 5.4 calculates the TCO for each bus option with and without the SCC. Further, it provides sensitivity analysis on key variables that impact the results of the TCO analysis.

5.1 Capital cost

This section shows that BEB have higher capital costs than diesel buses. Capital cost comprises the cost of each bus technology including any cost of installing the charging or fueling infrastructure:

- Cost of buses:
  - **BEB**—as noted in Section 2, MBM should purchase BEBs with a smaller battery that cost less than BEBs with larger batteries. For this reason, the price of the BEB is the average price of smaller buses produced by Ankai and Yutong of US$298,350
  - **Diesel bus**—the cost of diesel buses ranges between US$120,000 and US$184,935 [22]with an average price of US$152,500 per diesel bus
- Cost of charging or refueling infrastructure:
  - **BEB**—the total cost of charging equipment for a six BEB bus fleet is US$1,001,747 or US$166,957 per bus. This cost of charging equipment:
    - Assumes a combination of two charging methods: depot/plug-in charging and a fast charger. BEBs would charge overnight in the depot, each using its own plug-in charger, and all buses would "opportunity charge" during the day sharing a fast charger. Consultation with industry experts and desktop research recommends using one plug-in charger per bus for overnight charging. The cost of one charger ranges between US$17,000 and

[22] Source 1 Yutong: USD120,000; Source 2 Higer Klq6129g : USD184,935

US$50,000[23] with an average price of US$33,500. The depot charger installation cost is approximately US$17,050 (NREL, 2021 (a)).

    - Assumes that MBM will only require one fast charger. The cost of a fast charger is approximately US$495,636, while the installation cost is around US$202,811 (NREL, 2021 (a)). This cost is evenly split amongst the six BEB required to meet MBM's needs

- **Diesel bus**—operation of diesel buses would not require any additional infrastructure because diesel fueling infrastructure already exists to service the existing buses.

The combination of the capital cost for the bus and charging infrastructure for BEB is US$465,308 per bus. As diesel buses do not require additional fueling infrastructure, the total capital cost for diesel buses is US$152,500 per bus.

5.2 Energy cost

This section compares the energy cost of diesel fuel with the cost of electricity from the grid and floating solar PV. Table 5.1 shows that the grid would provide electricity at the lowest cost of US$0.28 per km, followed by floating solar PV, and diesel is the most expensive.

Table 5.1: Energy cost comparison, US$/km

	Energy from the grid	Floating solar PV	Diesel
Energy Cost (US$/km)	0.28	0.44	0.61

Energy costs are calculated based on:

- **Energy cost from the grid**—in September 2021, the cost of electricity for businesses was US$0.24 per kWh or US$0.28 per km (Global Petrol Prices, 2021). Given the average daily bus distance of 370km and the number of operating days of 312 per year, the annual energy cost of a BEB charging with grid power is approximately US$31,554
- **Energy cost from renewable energy**—The most cost-efficient source of renewable energy for BEB is electricity from the floating solar PV, which would cost US$0.36 per kWh or US$0.44 per km, as demonstrated in section 3.1.1. Given the average daily bus distance of 370km and the number of operating days of 312 per year, the annual energy cost of a BEB charging with renewable energy is approximately US$$49,230
- **Energy cost from diesel**—the price of diesel in Jamaica was US$1.52 per liter in May 2022 (Global Petrol Prices, 2022). Average fuel consumption of 0.4 l/km is based fuel consumption data for diesel buses from 10 countries (Li, Gao and Song, 2020). Diesel consumption of 0.4 l/km equates to an energy cost of US$0.61 per km. Given the average daily bus distance of 370km and the number of operating days of 312 per year, the annual energy cost of a diesel bus is approximately US$68,027

  Diesel consumption in diesel buses can vary substantially due to factors such as the extent of air conditioning use, the slope of the road, driving behavior, fuel quality, vehicle age and others. For example, MBM reported a fuel efficiency of 0.59 l/km, which is relatively high but not surprising

[23] Source 1 Yutong: USD17,000; Source 2 NREL, 2021, Electrifying transit: a guidebook for implementing battery electric buses : USD50,000

given the buses' age. Average fuel efficiency in other developing countries ranges between 0.266 l/km (India) and 0.467 l/km (Brazil) (Li, Gao and Song, 2020). For this reason, sensitivity to fuel consumption per liter is included in sensitivity analysis.

5.3 Maintenance cost

This section compares the cost of operating and maintaining each type of bus and the maintenance cost of charging infrastructure for BEB.

Table 5.2: Maintenance cost comparison, US$/km

	Energy from the grid	Floating solar PV	Diesel
Maintenance Cost (US$/km)	0.40	0.40	0.55

5.3.1 Maintenance cost of battery electric buses

The maintenance cost of BEB is approximately US$0.64 per mile or US$0.40 per km (NREL, 2020). Given the average daily bus distance of 370km and the number of operating days of 312 per year, the annual maintenance cost of a BEB is approximately US$46,176 per bus.[24] Further, in addition to the maintenance cost of the bus, the annual maintenance cost of the charging infrastructure is approximately US$3,496 per bus (Ballard, 2017).

BEBs have simpler propulsion systems with fewer moving parts that generally require less regular mechanical maintenance than traditional diesel buses. BEBs do not require oil changes; there are no diesel particulate filters as there are no tailpipe emissions; and no fuel or oil filter because neither fuel nor oil is used. However, BEBs do need motor coolant and transmission fluid refills (NREL, 2020). As a result, BEBs have lower maintenance costs relative to diesel bus maintenance costs.

Maintenance costs do not include battery replacement because BEB batteries can last 12 years of and would not have to be replaced within the 12-year commercial life of a bus. This assumption is based on both recent studies and industry consultations which show that batteries for BEB can last up to 12 years (NREL, 2020).[25] In addition, some bus producers, such as Proterra, offer 12-year warranties on their batteries, guaranteeing that batteries can last that long without additional investment.

5.3.2 Maintenance cost of a diesel bus

The annual maintenance cost of a diesel bus is calculated based on the assumption of an average cost of US$0.88 per mile or US$0.55 per km (NREL, 2020). Given the average distance covered by the MBM per day of 370km during the 312 operating days per year, the annual maintenance cost per bus HFCEB is US$63,492.[26]

The maintenance cost of diesel buses assumes that the cost of diesel refueling station maintenance is included in the retail price of diesel used to calculate the energy cost. Any savings MBM would make on the difference between purchasing diesel at wholesale prices and fueling its buses in the bus depot and

[24] Calculation: 0.4*370*312=US$46,176

[25] Yutong sales manager in Trinidad Tobago

[26] Calculation: 0.55*370*312=US$63,492

paying the retail price for diesel is assumed to go towards maintaining the fueling infrastructure in the bus depot (NREL, 2020).

5.4 Comparison of the total cost of ownership

TCO analysis uses inputs from Sections 5.1, 5.2, and 5.3 to determine whether BEB powered by renewable energy, BEB powered by grid electricity, or new diesel buses should replace the existing fleet of diesel buses. TCO analysis shows that BEB powered by renewable energy is the least-cost option when the SCC is included in the TCO analysis.

5.4.1 The total cost of ownership calculation process

The TCO methodology allows comparing the present value of all costs that occur over the 12-year life span for diesel and electric buses. TCO is calculated using the following formula:

$$TCO\ per\ bus = A + \sum_{i=1}^{12} \frac{O}{(1+r)^i} - \frac{S}{(1+r)^{12}}$$

In the equation above:

- *A* = Capital cost (buses, charging infrastructure),
- *O* = Annual operations and maintenance cost which includes energy and maintenance costs)
- *r* = Discount rate—calculated based on a discount rate of 8.82 percent based on JPSCo's cost of capital of 8.82. The cost of debt for JPSCo's is 8.07 percent and the cost of equity of 12.25 percent. The debt to equity is assumed to be 50 percent and a tax rate of 33.33 percent (Ministry Of Science, Energy & Technology, 2020)
- *i* = Year *i*
- *S* = Salvage value of the bus.

The TCO per KM is calculated by dividing the TCO of a bus by the total number of kilometers that one bus covers during its 12-year operational life, using the following formula.

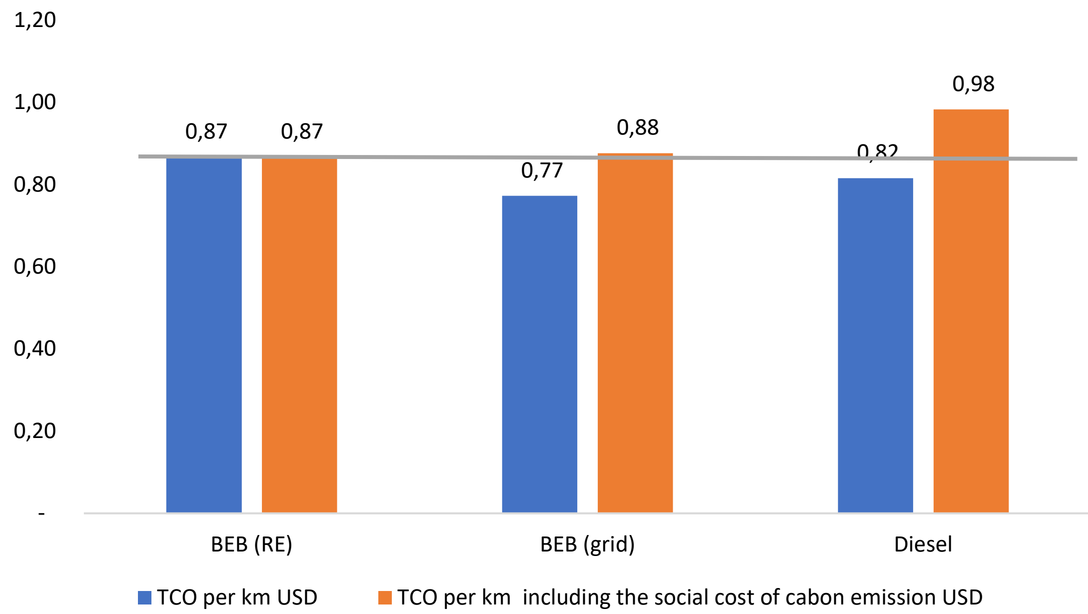
$$TCO\ per\ km = \frac{TCO\ per\ bus}{N}$$

In this equation, *N* = Total amount of km over the 12 years lifespan of a bus, which is 1,342,640km.

5.4.2 Comparison of total cost of ownership of different bus technologies

Figure 5.1 illustrates the comparison of TCO of different bus technologies with and without considering the SCC.

Figure 5.1: Comparison of TCO of different bus technologies, with and without the SCC



Without considering the SCC:

- **BEB charged from the grid have the lowest TCO of US$0.77 per km**–although BEB (grid) has high capital cost compared to diesel buses, BEB (grid) saves on O&M costs over the total life span of the buses
- **Diesel buses have the second highest TCO of US$0.82 per km—**although diesel buses have significantly lower capital costs than BEB, they have much higher O&M costs
- **BEB charged using renewable energy have TCO of US$0.87 per km—**similar to BEB (grid), BEB (RE) have high capital cost compared to diesel. Although O&M costs of BEB (RE) are lower than diesel, it is not as low as BEB (grid). As a result, BEB (RE) is more expensive than both BEB (grid) and diesel buses.

Based on the analysis in Section 4, diesel buses generate emissions that have a social cost of US$0.167 per km and BEBs charged from the grid generate carbon emissions that have a social cost of US$0.104 per km that is added to the TCO per km. As a result, when the SCC is included in the TCO:

- **BEBs charged using renewable energy have the lowest TCO of US$0.87 per km—**BEB powered with renewable energy has no TTW emissions. Thus, its TCO does not change
- **BEBs charged from the grid have the second highest TCO of US$0.88 per km—**TCO per km for BEB powered by the grid increases due to grid emissions from the electricity used to charge the buses
- **Diesel buses have the highest TCO of US$0.98 per km—**Diesel buses generate the greatest amount of carbon emissions per km and, as a result, there is a significant increase in the cost per km when the cost of carbon is included in the analysis.

5.5 Sensitivity analysis

This section includes sensitivity analysis of the TCO to changes variables which are highly uncertain to ensure that the TCO analysis is robust. These uncertain variables covered in the sensitivity analysis are:

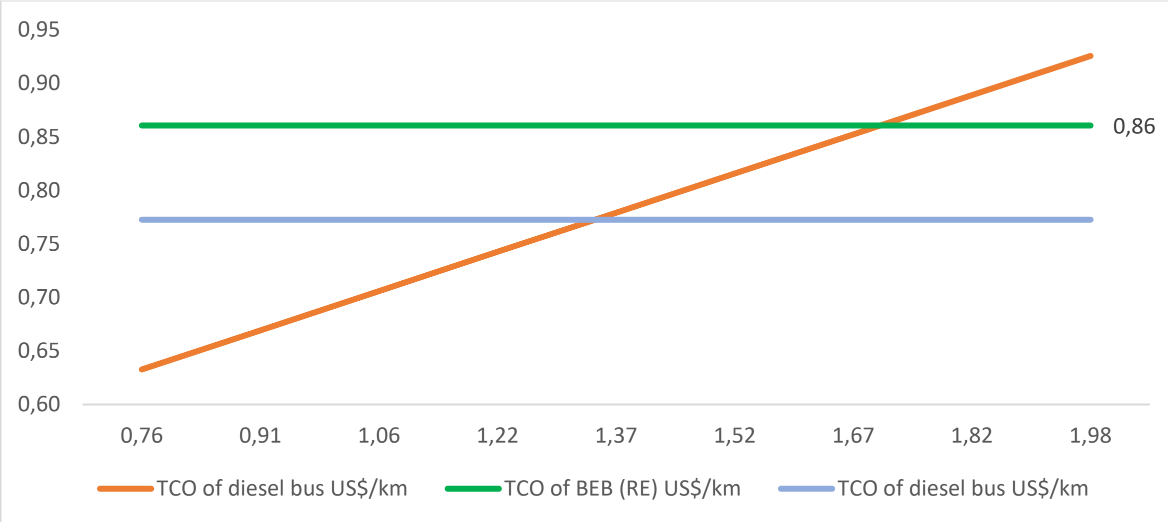
- Diesel price
- Fuel efficiency of diesel buses
- Cost of electricity delivered to the BEB
- Social cost of carbon.

Further, changes in some of these inputs may significantly affect the TCO and the outcome of the analysis. Sensitivity analysis ensures that MBM can make a sound decision about the most cost-effective bus technology and power source to replace diesel buses.

5.5.1 Diesel price

The price of diesel is the most volatile variable affecting the TCO of diesel buses. Due to the large fluctuations of the price of oil between US$16 and US$120 in the past two years (Trading Economics. 2022), diesel prices in Jamaica also fluctuated between US$0.73 per liter to US$1.66 per liter in the same period (Petrojam Limited, 2021). For this reason, Figure 5.2 shows the impact of diesel prices between US$0.70 per liter and US$2.00 per liter on diesel buses as compared to BEB (RE):

Figure 5.2: Sensitivity of the TCO to cost of diesel



The diesel price of US$1.52 per liter used to calculate energy costs for diesel buses results in a TCO of US$0.82 per KM which is cheaper than BEB (RE) and more expensive than BEB (Grid) before considering the SCC. However, a diesel price of around US$1.70 per liter is when the TCO of diesel buses and BEB (RE) are almost equal. The analysis shows that if the price of diesel increases above US$1.70 per liter, the TCO of diesel buses becomes higher than the TCO of BEB (RE). Further, as long as the diesel price stays above US$1.37 per liter, BEB (Grid) remains cheaper than diesel buses.

5.5.2 Fuel efficiency of diesel buses

The rate of diesel consumption by diesel buses also significantly affects the TCO of diesel buses. However, the rate of diesel consumption is highly uncertain and fuel efficiency of diesel buses varies widely across different countries.

Figure 5.3: Sensitivity of the TCO to fuel efficiency of diesel buses

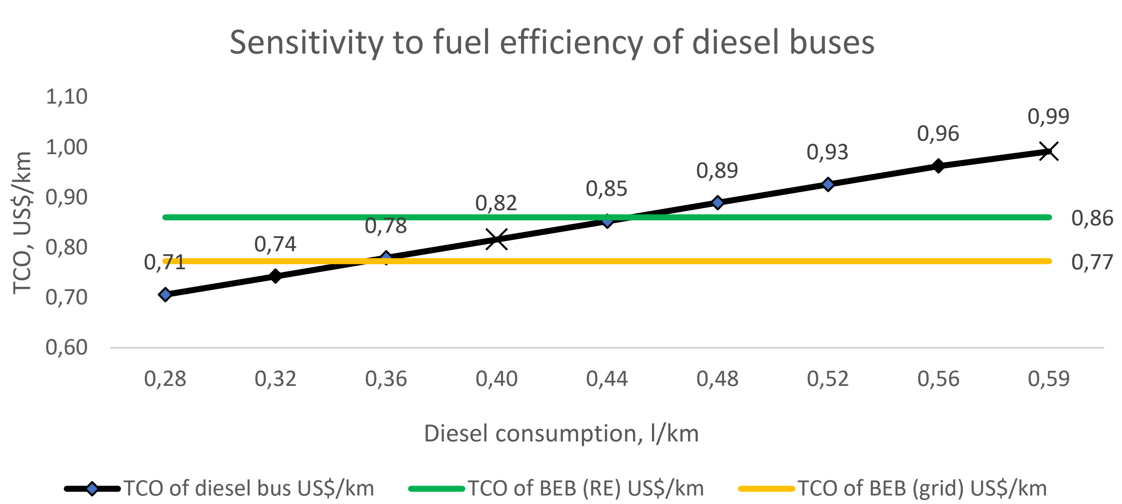


Figure 5.3 shows that with the average fuel consumption of 40L/100km or 0.4L per km, the TCO of diesel buses is lower than the TCO of BEB (RE), but higher than the TCO of BEB (grid) before considering the SCC. However, using fuel consumption of 0.59L per km, which corresponds to the current level of fuel consumption of MBM buses, the TCO of diesel buses would be US$0.99 per km, which is much higher than the TCO of BEB (grid) of US$0.77 and the TCO of BEB (RE) of US$0.86 per km. Further, as long as diesel consumption remains above 0.36L per km BEB (Grid) remains cheaper than diesel buses.

5.5.3 Cost of electricity

For BEB (grid), the cost of electricity has a significant impact on the TCO. However, the tariff structure of JPSCo allows for the pass-through of fuel costs to customers. This means that the cost of electricity can fluctuate significantly with the cost of fuel. Figure 5.4 show how different electricity cost from the grid would affect the TCO of BEB (grid).

Figure 5.4: Sensitivity of the TCO to cost of electricity delivered to the BEB bus

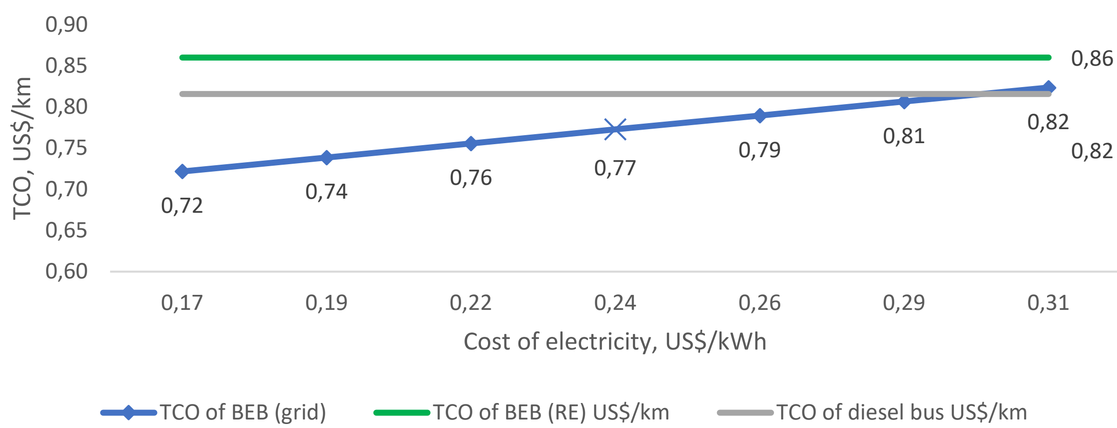


Figure 5.4 shows that even with a 30 percent increase in the electricity cost, the TCO of BEB (grid) would be lower than the TCO of BEB (RE) before considering the SCC. However, the same increase in the price of electricity would make the TCO of BEB (grid) equal to the TCO of diesel buses before considering the SCC.

5.5.4 Social cost of carbon

As discussed in Section 4, estimates of the SCC vary significantly. For this reason, it is essential to understand how a different SCC would impact the TCO of buses. Figure 5.5 illustrates the results of fluctuations in the SCC.

Figure 5.5: Sensitivity of the TCO to the SCC

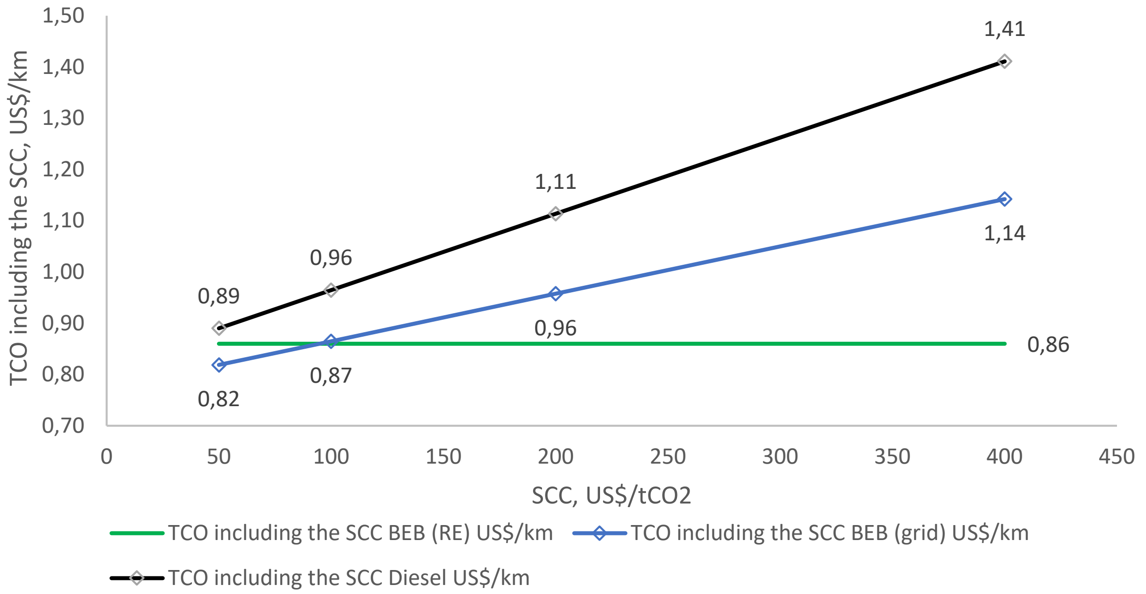


Figure 5.5 shows that with the SCC of US$50 tCO^2 e the TCO of BEB (grid) is the lowest relative to BEBs (RE) and diesel buses. However, as the assumption about the SCC increases and crosses a US$100 tCO^2e mark, BEB (RE) becomes cheaper than BEB (grid). This is a particularly important finding because, as discussed in Section 4.2, as the impacts of climate change accumulate and physical and economic systems become more stressed, the SCC is expected to increase over time.

6 Risk management strategy

Replacing MBM's diesel buses with BEB powered by floating solar PV would be a trailblazing project. Trailblazing projects are risky and this one is no exception. This section presents five major risks and strategies to mitigate them—including using green finance.

6.1 Major risks to electrifying MBM's bus fleet

Five major risks that must be overcome to transition from MBM's diesel buses to BEB powered by renewable energy are:

- **NWC is unable to lease the surface of the Bogue oxidation ponds for the installation of floating solar PV**—there is no guarantee that NWC will agree to lease the surface of the ponds as NWC has expressed concerns that the facility would prevent operation of the wastewater treatment ponds
- **MBM is unable to operate and maintain BEBs and/or the floating solar PV system**—Given MBM's unfamiliarity with BEBs, there is a risk that MBM employees will not operate and maintain the BEBs correctly, perhaps shortening the operational life of the buses or leading to costly repairs. Given MBM's lack of knowledge and experience in operating a power system, there is a considerable risk that the facility would not receive adequate maintenance and would be operated incorrectly. This would result in inconsistent electricity supply, which is crucial for the normal operation of the buses, and expensive repairs
- **The project cannot be financed because MBM is not creditworthy—**Regardless of the economic and financial benefits of replacing MBM's diesel buses with BEB powered by renewable energy, the project will not be able to go forward without financing to cover the high up-front cost of BEB. However, MBM is unlikely to be viewed as a creditworthy by financiers
- **The risk that revenue from bus fares will not cover the cost of the project**—the government of Jamaica may determine that the bus fare that customers should pay is less than what would be required to recover the full cost of the project
- **The risk that the Government of Jamaica will prefer BEB powered by the grid because it is cheaper**—given that the Government of Jamaica may decide on a bus fare that is not adequate to cover the full cost of the bus network, it will have to cover the difference. As a result, the Government will prefer the least cost option to reduce the funding it would be required to provide.

6.2 Risk mitigation strategies

The risk that NWC is unwilling to lease the surface of the Bogue oxidation ponds can be mitigated through early engagement with NWC by the IADB and the Government of Jamaica, should it decide to proceed with the project.

Delivering the project as a PPP will mitigate the risks that MBM is unable to adequately operate and maintain BEBs or a floating solar PV system; mitigate the risk that MBM is not creditworthy; and can mitigate the risk that revenue from bus fares will not cover the cost of the project.

Green finance can assist in mitigating the risk that the project will not be seen as financeable. Further, green finance can mitigate the risk that the Government will prefer BEB powered by renewable energy by providing grants and concessional finance to close the viability gap.

6.2.1 Mitigating NWC's unwillingness to use solar PV at the Bogue oxidation ponds

Early and constructive engagement with NWC to assure NWC that floating solar PV would not affect the ponds' ability to treat wastewater can relieve NWC concern.

The Government of Jamaica can arrange for NWC to meet floating solar PV developers and wastewater treatment plant operators with experience operating floating solar PV in their treatment plants. At these meetings, practitioners can explain how the space between the floats allows sunlight to penetrate all parts of the pond and that the small size of the floating solar PV relative to the ponds would allow for installing small islands of floats that would have a minimal impact on biological treatment processes in the pond.

In addition, the project can be structured to provide incentives to the NWC. For example, the project can be structured to offer electricity to NWC to run its pumps and other equipment at a lower cost than the grid cost. As explained above, the cost of electricity from the grid is US$0.24 per kWh, whereas the LCOE of floating solar PV is expected to be US$0.18 per kWh, offering savings for NWC.

6.2.2 PPP structure to reduce operation, maintenance, and financing risks of BEB and solar PV

There are many potential PPP structures. A full concession of MBM would be particularly effective at mitigating the risk that MBM is unable to operate and maintain BEBs and/or the floating solar PV system, the risk that the project cannot be financed because MBM is not creditworthy, and the risk that revenue from bus fares will not cover the cost of the project.

Under a concession contract, the risk that BEBs and floating solar PV will not be operated and maintained properly is mitigated because the winning concessionaire must be technically capable to own and operate the solar PV facility and the buses under a PPP contract.

The winning consortium would operate and maintain the BEB and floating solar PV installation itself. The concessionaire would take over responsibility for operating Montego Bay's bus routes, under a contract to MBM and using the current staff. The concessionaire would be responsible for training MBM's existing drivers on how to operate the buses.

Providing training for drivers and mechanics can smooth the transition to BEBs and minimize the unavoidable learning curve for BEB operation. The Battery Electric Buses—State of the Practice survey reported that BEB suppliers predominantly provide operations and maintenance training for the BEB and charging infrastructure. Transit agencies, equipment providers, and third-party organizations are also reported as sometimes providing additional training for bus operators and bus maintenance staff (National Academies of Sciences, Engineering, and Medicine. 2018).

Training drivers on the differences between diesel bus and BEB operations is vital for safety and efficiency. Training for BEB operators is necessary to ensure proper docking, braking, and shut down. It is also essential for a general understanding of BEB operation. For example, drivers must understand how the battery charge relates to the range and how environmental factors affect the range.

Under a concession contract, the risk that MBM will not be seen as creditworthy can be addressed by procuring a creditworthy consortium that already has financing arranged at the time of their bid. Further, under the concession contract the risk that revenue from bus fares will not cover the cost of the project is mitigated in two ways:

- The concessionaire is responsible for collecting fares and will be strongly incentivized to ensure that all fares are collected
- If the government of Jamaica determines that the bus fare that customers should pay is less than what would be required to recover the full cost of the project, the concession contract can be structured to include an availability payment based on the gap between the cost of operating MBM—including the cost of the floating solar PV and BEB—and expected fare revenue. To minimize the payment from the Government of Jamaica, the availability payment can be bid factor in the PPP transaction that determines which consortium is selected.

Procuring the BEBs and floating solar PV through a PPP would not create regulatory or legal hurdles. The Government of Jamaica has a well-developed a PPP Policy and PPP framework.[27] Further, the development and implementation of PPPs in Jamaica is supported by the PPP unit in the Privatization Division of the Development Bank of Jamaica and a PPP node located in the Ministry of Finance and Planning (Seureca, 2022; Commonwealth Governance, 2022). This unit has already successfully procured PPP projects, including in the transport sector. As such, the existing PPP framework in Jamaica should enable a smooth development and implementation of a PPP project, including appraising bids, selecting, and negotiating with a winning consortium, and finalizing contractual agreements.

6.2.3 Green finance can close viability gap and improve the projects creditworthiness

Green finance can mitigate the risk that the project is not seen as creditworthy by derisking the project and can mitigate the risk that the Government of Jamaica will prefer BEB powered by the grid because it is cheaper by providing grants and concessional loans that close the viability gap between BEB powered by the grid and BEB powered by renewable energy.

The government, assisted by development partners, should seek climate finance offered by the Green Climate Fund and the Global Environmental Facility which provides concessional loans and grants for the purchase of buses and/or infrastructure (Jattin, 2019) because this project is an ideal candidate. It is an ideal candidate because BEB powered by renewable energy is the least cost option when the SCC is considered, but it is not least cost when the SCC isn't considered. This means that the cost of offering climate finance to make BEB powered by renewable energy viable will be justified by the value of GHG emissions avoided. The project is also a good candidate for NDC+ funding from developed countries to support developing countries such as Jamaica in achieving greater GHG emissions reductions than they would otherwise achieve.

Green finance can reduce the risk that the project is not seen as credit worthy by providing grants and risk-facilities for de-risking the project. For example, green finance can be used to establish a first loss facility that can be called on if the Government of Jamaica fails for make availability payments under the concession contract.

Green finance can also reduce the risk that the Government of Jamaica will prefer BEB powered by the grid, by providing grants and concessional finance equal to the viability gap between the two BEB options. Grant funding would be key for carrying forward a full feasibility study—including more advanced modelling of MBM's transport system—and providing transaction support to prepare the PPP transaction.

[27] Called the Government of Jamaica Policy and Institutional Framework for the Implementation of PPPs

Further, concessional loans can help close the gap between the economic benefits delivered by BEB powered by renewable energy when the SCC is considered, and the negative financial benefits delivered by switching from diesel buses to BEB powered by renewable energy instead of switching to BEB powered by the grid by lowering the costs of capital.

7 Waste-to-Energy for further electrification of Jamaica's transport sector

This purpose of this section is to explore exciting Waste-to-Energy technologies that could become viable in the future to support Jamaica's continued electrification of its transport system and explains why due to high costs, uncertainties about commissioning timing, or technical infeasibility they are not feasible at this stage. This section explores:

- **Wastewater from the Bogue wastewater treatment plant and cruise ships docking in Montego Bay Cruise Port**—the option of covering the Bogue wastewater treatment plant's oxidation ponds to capture methane is not technically viable. collecting wastewater from cruise ships is not a reliable enough fuel source for MBM's needs; however, it is a potential source of renewable energy in the future
- **Generating electricity from municipal solid waste (MSW)**—generating electricity from MSW has great potential as a source of renewable energy. However, due to the uncertainty around the commencement and location of a proposed plant in Montego Bay's parish, it is not suitable for MBM at this stage
- **Thermal plasma gasification and pyrolysis technologies for generating electricity and hydrogen**—Plasma reactors that can produce electricity, heat or hydrogen from organic and inorganic waste have been implemented in several countries (Deloitte, 2022). However, this technology would require large capital investments (approximately US$7.4 million for 1MW power capacity), which would result in a higher cost of electricity compared to floating solar PV (approximately US$0.23 per kWh (Deloitte, 2022). Further, waste to hydrogen technology is still in the demonstration stage with only a few pilot projects in the United States.

7.1 Waste to energy using wastewater as a fuel source

There are two possible sources for wastewater in Montego Bay—the Bogue wastewater treatment plant and cruise ships that dock in Montego Bay. Both are not suitable for MBM's energy needs; however, wastewater from cruise ships is a potential source of renewable energy.

7.1.1 Wastewater from the nearby Bogue wastewater treatment plant

Wastewater from the Bogue wastewater treatment plant is the largest and easiest potential source of fuel for WTE technology. Collecting methane from the Bogue wastewater treatment plant's oxidation ponds would require covering the ponds to capture methane-rich biogas. The biogas could can be used:

- To power buses without further processing
- To generate electricity.

However, the Bogue wastewater treatment plant's nine ponds, including three facultative and six maturation ponds all require exposure sunlight and the wind to increase the growth rate of bacteria. Consultation with the National Water Commission confirms that the Bogue plant's ponds cannot be covered. As a result, generating electricity with methane captured from the Bogue Wastewater Treatment Plant is not technically viable(Gray, 2003).

7.1.2 Wastewater from cruise ships

Waste to Energy fueled by wastewater from cruise ships that dock in Montego Bay is an exciting potential source of renewable energy. Large cruise ships generate significant amounts of wastewater per day. For example, a large cruise ship with 3,000 passengers generates over 100,000 liters of human waste daily (Sahin and Vardar, 2020). The wastewater can be collected in Montego Bay and used to generate energy using an anaerobic digester to capture methane-rich biogas which is then burned to create electricity.

This option is not viable for MBM because it is unlikely to provide a consistent enough supply of wastewater to power electric buses in Montego Bay. Cruise ship schedules fluctuate seasonally and can be impacted by bad weather or changing trends in tourism. For example, the COVID-19 pandemic had a major impact on the operations of cruise ships worldwide. During the pandemic, the number of cruise ship calls in Montego Bay decreased from 148 in 2019 to only 53 in 2020 (Statista, 2021). As a result, Waste to Energy using wastewater from cruise ships is not reliable enough for MBM. However, this option has potential to provide renewable energy in the future.

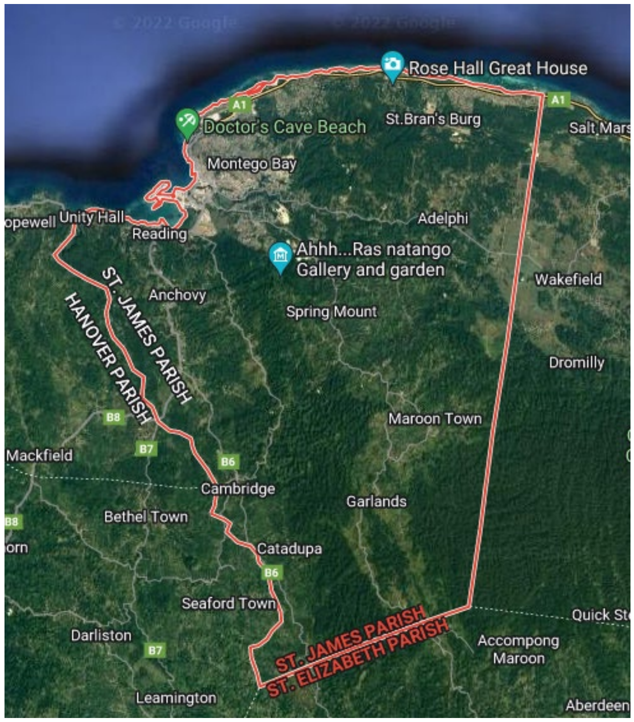
7.2 Waste to energy with municipal solid waste as a fuel source

The Government of Jamaica's Waste-to-Energy strategy includes developing a Waste-to-Energy plant fueled by municipal solid waste in St. James parish under a PPP framework that is currently at a feasibility stage. As such, it is a possible source of renewable energy for MBM. However, uncertainty about the location, cost of electricity, willingness to sell electricity directly to MBM, and price of the electricity means that this project is not suitable for MBM's needs.

The government of Jamaica's Waste-to-Energy strategy includes building an 18MW plant near Montego Bay in St. James Parish. A power plant with 18MW capacity would be more than large enough to provide sufficient renewable electricity to power BEBs and produce hydrogen for HFCEBs. However, the proposed plant is not a suitable source of renewable energy to power electric buses due to:

- **Location uncertainty—**the exact location of the plant in St. James Parish, which is a quite extensive area as illustrated Figure 7.1, is unknown.

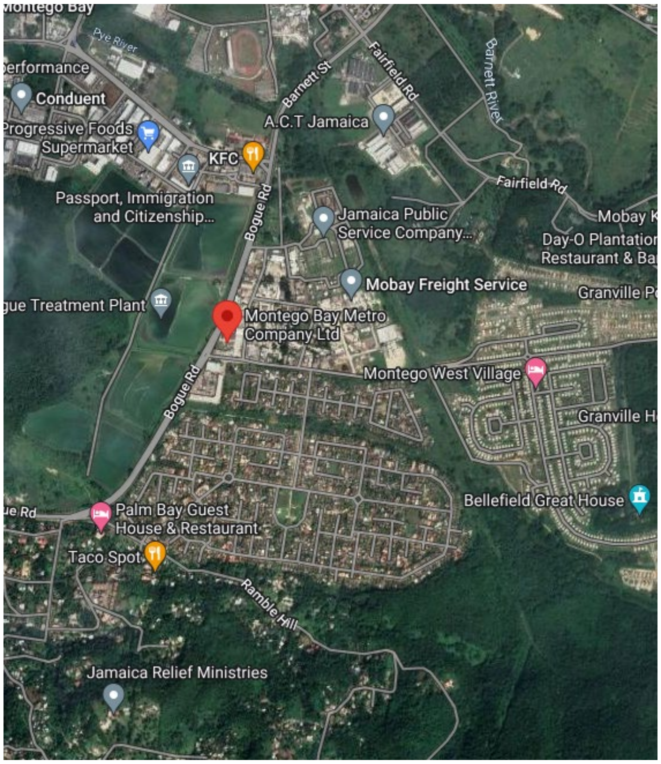
Figure 7.1: St. James Parish area



Source: Google Maps

The plant may be close enough to the MBM to refuel HFCEBs; however, it could not plausibly be located right next to the MBM for charging BEBs. The facility would require a relatively large piece of land to handle the project 850 tons of waste collected from five parishes each day (Seureca, 2022). The area surrounding MBM does not provide sufficient space, as illustrated in Figure 7.2. Further, if a suitable site were identified, it would likely encounter considerable community resistance to siting a large waste disposal facility near existing residences and businesses.

Figure 7.2: Montego Bay Metro area



Source: Google Maps

- **Timing uncertainty**—the commencement of the project is unknown. However, given that the planning process is still ongoing, it is likely several years away. Meanwhile, MBM is looking to replace its diesel buses in the short term
- **Uncertainty if the WTE facility can sell directly to MBM—**the electricity generated at the Waste-to-Energy plant is planned to be sold to the JPSCo (Seureca, 2022). As a result, it is uncertain if the plant would be able to sell electricity directly to MBM or if all electricity would be sold direct to JPSCo
- **Uncertainty around the cost of electricity—**the cost of electricity that JPSCo or the Waste to Energy would sell electricity to MBM is also uncertain. A report produced by the US Department of Energy states that generating electricity from municipal solid waste is 30 percent to 211 percent more expensive than solar PV. Further, determining the cost per kWh of electricity from WTE using MSW depends heavily on the tipping fee the Government of Jamaica is willing to pay in recognition of the value of avoided landfilling. Currently, the government has not made any decision on what if any tipping fee it is willing to pay.

As a result of these concerns, the 18MW Waste to Energy fueled by municipal solid waste in St. James will only become suitable for MBM's needs if:

- **The plant is built and a tipping fee agreed on**—this would remove timing uncertainty and a tipping fee would allow for calculating the cost of electricity generated by the facility

- **A wheeling regime is approved by the OUR**—approving a wheeling regime would allow for renewable energy produced at the facility to be wheeled over the transmission grid straight to MBM's depot for charging buses
- **A renewable energy certificate (REC) scheme is devised and implemented in Jamaica**—without a REC scheme it will not be possible for MBM to confirm that it is achieving the stated goal of this project of charging electric buses with 100% RE.

Until such time as these three conditions are met WTE using MSW will not be an appropriate technology for MBM to power electric buses with 100% RE.

Box 7.1: WTE using municipal solid waste for biomethanation

Biomethanation is another promising option for charging electric buses with waste to energy technology powered by municipal solid waste. Biomethanation is a process by which the organic waste component of municipal solid waste is separated from other waste and fed into a biogas digester under anaerobic conditions.

Within the biodigester organic waste undergoes biodegradation and produces methane-rich biogas comprising approximately 60 percent methane and 40 percent carbon dioxide and other trace gasses. The biogas can be utilized as a fuel for generating electricity in a conventional generator. Alternatively, it may be scrubbed to natural gas quality, used as a vehicle fuel, or injected into the gas distribution network (Seureca, 2022).

To determine if biomethanation is appropriate for MBM required calculating: 1) the quantity of waste required to produce enough electricity to meet MBM's operational needs and 2) the LCOE of electricity produced with biomethanation for comparison against other options.

MBM Would Require 3,675 tons of waste per year to meet its operational needs

Analysis conducted as part of Jamaica's ongoing effort to develop a national waste to energy strategy shows that municipal solid waste in Jamaica has the potential to create 260kWh per ton of waste (Seureca, 2022). Based on that statistic, a facility with an annual processing capacity of 3,150 tons of organic waste per year would be able to generate 819,000kWh per year. This would be sufficient to supply 2,625kWh per day (for the six days per week that MBM operates) which meets MBM's operational needs.[28]

Electricity generated from methanation has an LCOE of US0.418 per kWh

A facility with the capacity to meet MBM's operational requirements would require a total CAPEX investment of US$1,767,150 and have an annual OPEX of $151,200. Based on these costs, the LCOE of biomethanation is US$0.418 per kWh. This means that, similar to other waste to energy technologies, the LCOE of producing electricity with methanation is significantly higher that the LCOE of using floating solar PV of US$0.362. For this reason, methanation is not the best option for MBM to power BEB.

Further, an LCOE of US$0.418 per kWh is a generous assumption for methanation as this LCOE does not include the costs of waste segregation and byproduct management that would be required as part of the process of generating electricity from methanation. Biomethanation technology is only suitable for segregated organic matters and not suitable for mixed municipal waste. As a result, organic waste must be separated out from non-organic waste (Seureca, 2022). In addition, biomethanation would require both preprocessing and management of byproducts because organic wastes from multiple sources may contain silverware, other metals, rocks, and other non-desirable feedstock components. Thus, it would require preprocessing to remove contaminants from the feedstock (NREL, 2013). Additionally, biomethanation leaves combustible constituents as a byproduct after the screening and sizing process which require either incineration or gasification (Seureca, 2022).

The two tables below contain the assumptions and calculations used to determine the LCOE of biomethanation as well as the required amount of waste.

Table 7.1: LCOE calculation assumptions

Assumptions		
Food Waste Volume*	t/year	3,150
Electricity generation potential **	kWh/t	260
Capital cost*	US$/t	561
Operational cost*	US$/t/year	48
Useful life***	years	20

28 These figures are based on a facility with a processing capacity of 7,000 tons per year. As a result, the CAPEX and OPEX costs for a smaller facility needed by MBM could be much higher.

Discount rate	%	8.82%
Tipping fee****	US$/t	0

*Source: *NREL, 2013, Feasibility Study of Anaerobic Digestion of Food Waste in St. Bernard, Louisiana, p.33*
***Seureca Veolia, Development Bank of Jamaica, 2022, D2: Vision Statement Project Concept Cone, Transaction Advisor for the Structuring and Execution of an Integrated Solid Waste Management PPP Project in Jamaica, p.35*
****Fusi A., et al. 2016, Life Cycle Environmental Impacts of Electricity from Biogas Produced by Anaerobic Digestion*
*****We assume a tipping fee of US$0 per ton, as there is no information available on the tipping fees in Jamaica.*

Table 7.2: LCOE calculation

Annual electricity output	kWh/year	819,000
Daily electricity generation	KWh/day	2,625
Total capital cost	US$	1,767,150
Annualized capital cost	US$	$191,108.24
Annual operating cost	US$	$151,200.00
LCOE	US$/kWh	0.418

7.3 Waste to energy using thermal plasma gasification and pyrolysis technologies

Thermal Waste-to-Energy technologies, such a municipal solid waste plasma gasification and pyrolysis and gasification technologies, that can be used to produce hydrogen or generate electricity (Cedar Rapids, 2021) are exciting developing technologies that are not yet at a suitable stage of development for MBM.

7.3.1 Plasma gasification for electricity generation

Plasma gasification technology uses a plasma arc reactor that converts organic and inorganic waste into syngas (CO and H2) and vitrified material by exposing it temperature above 5,000ºC. Syngas can then be processed to either generate electricity or hydrogen.

However, it is still a relatively expensive option for producing electricity. A 1MW plasma gasification facility costs US$7.4 million and would have a useful life of only 10 years (Deloitte, 2022). This results in an LCOE of approximately US$0.23 per kWh, which is higher than the cost of electricity produced using any of the three types of solar PV considered.

7.3.2 Pyrolysis and gasification technologies for hydrogen production

Pyrolysis and gasification processes use high temperatures in an oxygen-free environment to convert any kind of solid waste into a gas and then extract the hydrogen in a separate process. The process does not require outside fuel to operate and produce hydrogen, as it self-supplies the energy and heat (The Digest, 2021).

Pyrolysis and gasification technologies for hydrogen production technologies present great renewable energy generation opportunity. However, based on information provided by the IADB they are not yet at a suitable stage of development for this project.

Commercial-scale gasification facilities are limited to a few facilities in Asia, particularly in Japan and a few in the European Union. In North America many of gasification facilities experienced difficulties scaling-up to commercial operations. As a result, gasification technologies in North America are limited to demonstration or pilot operations with limited operational history (Cedar Rapids, 2021).

In recent years, Ways2H, a joint venture between U.S.-based Clean Energy Enterprises and Japan Blue Energy Corporation, piloted a few waste-to-hydrogen projects. In 2021, Ways2H and Japan Blue Energy completed a facility in Tokyo that will be able to convert sewage sludge into renewable hydrogen. The system will process one ton of dried sewage sludge daily and convert it into 40-50kg of hydrogen daily. Also, Ways2H, in collaboration with Ford, Bacon & Davis, is designing the first US modular waste-to-hydrogen production facility (Power, 2020).

8 Opportunities for scaling and replicating this project

This report demonstrates that there are many opportunities to scale and replicate this project in Jamaica and throughout the Caribbean where the reduction in energy cost and maintenance cost that results from bus fleet electrification offsets the higher capital costs of BEB. Public and private operators can use this analysis to determine if electrifying their bus fleet will generate savings without considering the SCC and, where it will result in savings when considering the SCC, provides a strong argument for connecting public and private bus fleet operators to climate finance.

A successful demonstration of electric buses in Montego Bay could be scaled to include all of Jamaican Urban Transport Company (JUTC)'s operations. In Jamaica, the JUTC is renewing its fleet of diesel buses and piloting using BEB. In June 2022, JUTC purchased 50 buses from a Chinese producer Ankai, five of which are electric. JUTC is also constructing three charging stations. The acquisition of the five BEB is part of the Government's efforts toward greener, cleaner, and cheaper transportation. The analysis in this report shows that JUTC should dramatically expand its pilot BEB because it shows that BEB powered by electricity from the grid has a lower cost than diesel buses in Jamaica. Further, if JUTC can find a suitably large piece of land for land-based solar PV or floating solar PV to power its bus fleet, the analysis shows that BEB powered by renewable energy would be the least cost option when the SCC is considered. Finally, it is possible that BEB powered by land-based solar PV would save JUTC money without consideration of the SCC.

Also in Jamaica, Knutsford Express could save money by electrifying its bus fleet. Electrifying all or parts of Knutsford Express fleet is potentially viable given that their north coast route and south coast routes are 247km and 218km respectively. These distances are just within the range of smaller battery BEB buses as shown in section 2.2.1. Knutsford express should explore if BEB powered by grid electricity can save it money using the tool accompanying this report that allows any private bus operator to assess if electric buses are right for them.

Beyond Jamaica, there are likely many jurisdictions in the Caribbean where bus operators can save money by replacing their diesel buses with BEB. In Jamaica, BEB powered by the grid are less expensive than diesel buses assuming a price for grid electricity of US$0.24 per kWh. Electricity prices in the Caribbean average around US$0.25 per kWh and in some countries reaches over US$ 0.40 per kWh (Burunciuc, 2022). In many Caribbean countries, replacing diesel buses with BEB powered by the grid is likely already viable without considering the SCC. Furthermore, where wheeling charges exist or where tariffs and diesel prices are higher than in Jamaica, it is possible that BEB powered by renewable energy would also be viable without considering the SCC—particularly if there is available land for land-based PV or a suitable area for floating solar PV such as a wastewater treatment plant. A benchmarking study for the Caribbean region that compares the TCO of BEB powered by grid electricity, BEB powered by RE, and the TCO of diesel buses based on the cost of electricity and diesel in each country would demonstrate which jurisdictions in the Caribbean are likely to save money by switching to BEB. Therefore, a benchmarking study should be conducted to determine which jurisdictions should be considered for further detailed support developing a business case for replacing existing diesel buses with BEB.

Further, the benchmarking analysis should expand on the analysis conducted under this assignment to include an option to compare the TCO of battery electric mini-buses with the TCO of diesel or gasoline powered mini-buses. This assignment focused on larger 12m buses that matched the size and capacity of

MBM's existing buses and can provide a one-to-one replacement for MBM's existing buses. However, in many jurisdictions in the Caribbean mini-buses are the preferred mode of transport as a result of operational considerations such as smaller street. Therefore, the benchmarking study should include consideration of the TCO of diesel and BEB mini-buses as well as 12m buses.

9 Conclusion

BEB powered by floating solar PV would be the lowest-cost, zero-carbon solution, and lower cost than diesel buses replaced at current diesel prices and fuel efficiencies. However, the least-cost solution without considering the SCC would be BEB powered by grid-supplied electricity. Moreover, if MBM could improve diesel bus efficiency to 0.4L per KM in line with bus-operators elsewhere in developing countries, diesel buses would also cost less than BEB powered by renewable energy, provided the cost of diesel does not rise above US$1.70 per liter—something which has happened during the research period.

Despite non-renewable options possibly being lower cost, BEB powered by renewable energy has the lowest TCO, once the SCC is taken into account. Accounting for the SCC, BEB powered by renewable energy's TCO of US$0.86 per km is lower than BEB powered by the grid's TCO of US$0.88 per km, and diesel buses TCO of US$0.98 per km.

This makes BEB powered by renewable energy a suitable candidate for support with from global green finance and for Jamaica's NDC+ contributions to offset the financial viability gap, derisk the project, and provide the technical assistance necessary to develop all the details and make this innovative concept a reality. Support of this nature can allow the MBM's BEB powered by renewable energy project to become the pattern for similar projects all over the Caribbean, since the economics and structuring of this project are likely to be applicable with limited adaptation in many similar locations.

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