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Small Island Developing States and their suitability for electric vehicles and vehicle-to-grid services

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Highlights

1. Electric vehicles (EVs) offer Small Island Developing States (SIDS) solutions for electricity storage, grid services, reduced fuel imports, reduced pollution and associated health benefits, and the potential for improved resilience to natural hazard events.
2. Electrification of transport sectors, particularly given potential Vehicle-to-Grid (V2G) services, should be explored and incorporated into national energy planning strategies of Small Island Developing States.
3. Aging public vehicle fleets offer great opportunity for electric vehicle transition, substantially reducing cost of travel and subsidy support for the transportation sector.

Abstract: Small Island Developing States (SIDS), while at the forefront of international climate action, face a number of development challenges linked to their historic, geographic and socio-economic characteristics. Small populations and limited energy demand cap the penetration of renewable energy technologies. Electric vehicles offer solutions for electricity storage, grid services, reduced fuel imports, and reduced pollution with associated health benefits. This paper provides a comprehensive review of literature on island applications of electric vehicles, making the case for SIDS as an area of opportunity for further exploration, and presenting the southern Caribbean island of Barbados as a case study.

Keywords: Islands; electric vehicles; vehicle-to-grid services.

1 Introduction

The international electric vehicle market is growing exponentially, with over 1 million fully electric vehicles in operation globally (IEA, 2017). Experts conservatively predict that by 2040, 35% of new car sales globally and 25% of the world's car fleet will be electric cars (BNEF, 2017). One of the major barriers to their widespread adoption is cost, but with lithium battery prices dropping rapidly, experts expect the standard electric car to have cost parity by 2021 in Europe and China (BNEF, 2017). Small islands are a prime market for electric vehicles with limited road networks, high fuel costs and the need for direct grid storage solutions. Conversion of local passenger and public transportation fleets could have major cost savings and dramatic regional environmental benefits whilst bringing typically marginalized communities to the forefront of global technological advancement.

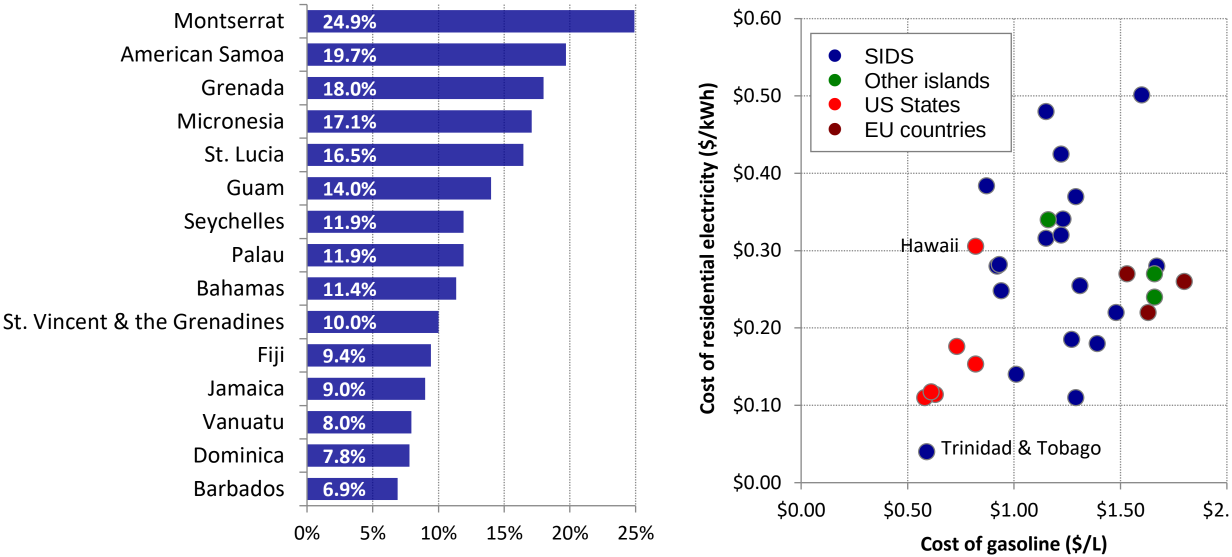
This paper provides a comprehensive review of recent studies that explore the effect of electric vehicle integration on isolated island grids. All the studies to-date focus on islands that are overseas territories or constituents of developed/industrialized countries. Small Island Developing States do share similar technical challenges in the design of their energy systems and the management of their electricity grids. However, they differ in several areas; including weaker governance structures and lower research and development capacities, but mainly in attracting foreign direct investment and domestic private finance (World Bank, 2017). This paper discusses the application of electric vehicles and vehicle-to-grid services to SIDS, highlighting the impact of electric vehicles on greenhouse gas emissions. The Caribbean island of Barbados is making substantial private sector-led headway in the creation of an electric vehicle market and a case study of this island is presented to relate the principles of vehicle-to-grid services to an existing SIDS context.

2 Special considerations of Small Island Developing States

2.1 Development challenges inherently connected to their energy systems

Small Island Developing States face many economic and technical challenges that differ to those of larger, more developed nations. These challenges primarily stem from their geography – specifically their limited areas, small populations and often-remote locations. Many also have limited natural resources, which hinder their ability to earn foreign exchange, resulting in economies that depend heavily upon imported goods and services (Weisser, 2004; IRENA, 2015). Their insularity and remoteness limit their market access for the trade of goods and services. The flight of human capital is also common with many professionals migrating to more developed countries in search of better prospects (Weisser, 2004). Fossil fuel imports, for electricity and transportation, comprise a large share of their GDP and limit their ability to develop. **Figure 1** and **Table 1** present an overview of some of the key statistics for SIDS and compare them with selected US States and EU countries. In an effort to pay for increasing fuel import bills, governments often sacrifice investments on infrastructure upgrades, improving local technical capacity and other important areas required for economic development, which can lead to 'locked-in' scenarios in times of high oil prices (IRENA, 2015).

The fact that their fossil fuel derived energy systems create 'locked-in' scenarios is often paradoxical given that many of these islands have plentiful renewable energy resources (Weisser, 2004; Dornan and Shah, 2016; Worldwatch 2015). As most SIDS are located in the equatorial regions, they have an abundance of solar resources. Exposure to trade winds can provide them with enviable wind resources (Scheutzlich, 2011), with the deployment of utility-scale wind often emerging as the cheapest way to generate electricity (Hohmeyer, 2015). Waste management challenges and declining agricultural sectors lead to strong bioenergy potential. They also have marine energy potential, be it wave, tidal and/or ocean thermal energy conversion, and many volcanic islands have the potential for geothermal energy production (Worldwatch, 2015; Hohmeyer, 2015; Wolf et al., 2016).



(a)

(b)

Figure 1. (a) GDP spent on fuel imports for selected SIDS. (b) Cost of electricity and gasoline for selected countries/US states (from Table 1)

Table 1. Key transport and energy statistics for SIDS (blue), other islands (green), selected US states (red) and selected EU countries (brown) (compiled from Ochs et al, 2015; NREL, 2015; Knoema, 2018; Numbeo, 2018).

	Cost of petrol (US$/L)	Diesel (US$/L)	Cost of electricity ($/kWh)	Fuel imports as share of GDP
Antigua and Barbuda	$1.29	$0.98	$0.37	5.76%
Bahamas	$1.15	$1.20	$0.32	11.35%
Barbados	$1.67	$1.40	$0.28	6.90%
Belize	$1.48	$1.43	$0.22	1.95%
Dominica	$0.87	$0.75	$0.38	7.79%
Dominican Republic	$1.27	$1.00	$0.19	3.51%
Fiji	$1.01	$0.86	$0.14	9.44%
Grenada	$1.22	$1.23	$0.43	18.00%
Haiti	$0.92	$0.71	$0.28	5.32%
Jamaica	$1.22	$1.21	$0.32	9.00%
Mauritius	$1.39	$1.23	$0.18	5.39%
Micronesia	$1.15	$0.79	$0.48	17.10%
Palau	$0.93	$0.59	$0.28	11.90%
Seychelles	$1.29	-	$0.11	11.92%
St. Kitts and Nevis	$0.94	$0.43	$0.25	3.99%
St. Lucia	$1.23	$1.15	$0.34	16.45%
St. Vincent & the Grenadines	$1.31	$0.41	$0.26	10.00%
Trinidad and Tobago	$0.59	$0.36	$0.04	13.58%
Vanuatu	$1.60	$0.84	$0.50	7.95%
Tenerife	$1.16	-	$0.34	-
Flores	$1.66	-	$0.24	-
São Miguel	$1.66	-	$0.27	-

Hawaii	$0.82	-	$0.31	-
California	$0.82	$0.80	$0.15	-
Florida	$0.63	$0.64	$0.11	-
New York	$0.73	$0.71	$0.18	-
Texas	$0.58	$0.65	$0.11	-
Ohio	$0.61	$0.68	$0.12	-
UK	$1.63	$1.99	$0.22	-
Spain	$1.53	$1.55	$0.27	-
Portugal	$1.80	$1.64	$0.26	-

2.2 The transportation sector in Small Island Developing States

Many of the development challenges that affect the energy sector in SIDS also impacts their transport sectors. As may be expected, challenges of remoteness and diseconomies-of-scale significantly impact island maritime and air transportation, and these are the subjects of several studies on island transport presented in UNCTAD (2014). These same development challenges also impact their road transport sectors. Worldwatch (2015) highlights a key observation in the Caribbean, in that road transport is often difficult to manage given a lack of available data on its status, which can subsequently lead to under-regulated and ill-designed transportation policies. This often results in negative impacts on local pollution levels, noise levels, congestion and subsequently human health. The World Bank's report on 'Climate and Disaster Resilient Transport in Small Island Developing States' (2017) makes similar observations for SIDS in other parts of the world.

3 Application of vehicle-to-grid services for Small Island Developing States

Whilst the prospect of increased electricity demand from electrification of transport systems may be attractive to utility operators, e-mobility, as it's often referred, will pose challenges to their grids. Weisser (2004) provides a useful background into the structure and operation of existing electricity grids for small island developing states. Here, we discuss the challenges of charging and charging strategies on these grids at the earlier stages of electric vehicle adoption, before discussing the potential benefits of more advanced charging capabilities to utility operators.

3.1 Charging and charging strategies

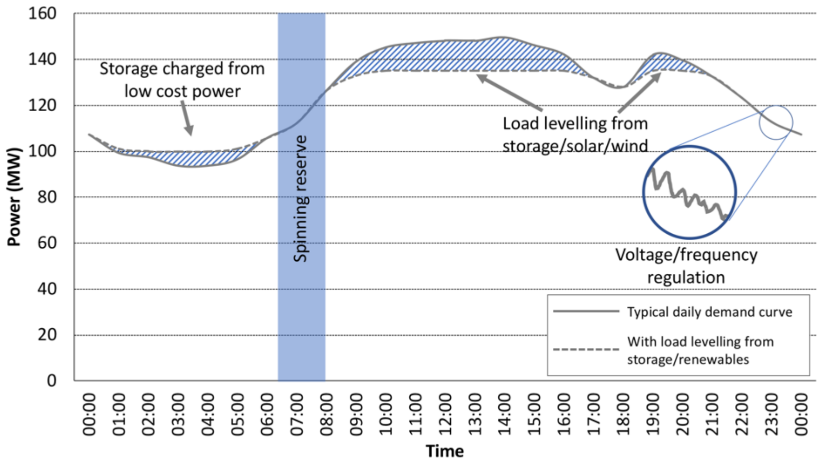
Given that the conventional energy demand of an electric vehicle is somewhere between 10kWh and 100kWh per charge, the cumulative charging of electric vehicles will have an impact on grid performance and stability. This is particularly so for relatively small, isolated grids whose installed capacities are below 200MW.

Due to the high capital cost of electric vehicles, early adopters tend to be clustered in more affluent neighbourhoods, or businesses with large vehicle fleets (couriers, delivery firms, etc.), and due to an early lack of public charging infrastructure, charging typically takes place at home or places of business during the evening and nighttime. Therefore, in the early stages of electric vehicle adoption, isolated overloading of the grid may occur (Waldron and Kobylarek, 2011; Boulanger, 2011; Muratori, 2014). Distribution transformers and feeders can quickly become overloaded since an electric vehicle can increase the home or business's demand by 25% or more whilst charging (Boulanger, 2011). This can result in unscheduled maintenance, early equipment replacement, and loss of revenue from increased outages. It is therefore in the interest of the electric utilities to investigate the economics of different incentive schemes and the legal processes involved in their implementation.

Grid operators have several options to ensure that vehicle charging minimises any impact on their grids. Known collectively as charge management, these options involve the operators applying demand charges, time-of-use rates and dynamic pricing, which are in widespread use today given their application to larger, industrial clients (Amjad et al., 2018). Due to recent technological developments, additional options are emerging for charge management and are introduced throughout the remainder of this section.

If charge management is not employed, as the number of electric vehicles increases the additional loads posed by charging can lead to a change in an island's daily load profile and an increase the demand peak (see **Figure 2**). Any change in the daily load profile can subsequently affect a utility's ability to manage generation, supply and distribution with respect to time and grid constraints, while increasing peak demand can put a strain on existing generating capacity (Dyke et al., 2010). The uncoordinated charging of a large number of electric vehicles could therefore compromise the grid's reliability, security, efficiency and economy.

The aforementioned charge management, or 'coordinated charging', is the simplest strategy to execute and is most suitable in the early stages of electric vehicle adoption (Ehsani et al. 2012). Coordinated charging can be implemented using unidirectional chargers with programmable timers, which can be set to charge the vehicle at pre-determined off-peak times. Utilities can encourage off-peak charging by offering incentives, such as preferential time-of-use rates, when demand on the grid is low or when there is excess renewable energy being generated. This method of charging can help ensure that no additional generating capacity is required and minimises the impact on the daily demand profile (Waldron and Kobylarek, 2011). Optimisation of charging times and energy flows can help reduce daily electricity costs with little effect on peak capacity, while coordinated charging can help flatten the load curve (see **Figure 2**) (Hota et al., 2014). This most basic form of grid-to-vehicle service is easy to incorporate into existing infrastructure and suitable for low electric vehicle penetration rates.



Load levelling – flattening of the demand curve to reduce need for new capacity.

Peak shaving – Long-term storage (hours) used to reduce peak demand, along with solar/wind.

Voltage/frequency regulation – short-term storage (seconds) used to improve power quality.

Spinning reserve - capacity available to the system operator within a short interval of time (seconds/minutes) to meet unplanned changes in demand.

Figure 2. Grid services that can be provided by electric vehicles and renewables, based on a 24-hour demand curve for Barbados (Hohmeyer, 2014).

Ioakimidis and Genikomsakis (2018) model the potential for Plug-in Hybrid Electric Vehicles (PHEVs) on the island of São Miguel in the Azores, an autonomous state of Portugal. They examine one-way grid-to-vehicle (G2V) charging strategies for different scenarios of electric vehicle market penetration (up to 32% penetration), in effect assessing the capability of electric vehicles for valley-filling in the island's daily demand curve. They found that a 32% share of electric vehicles in the island's vehicles fleet could be realized, yielding major benefits countering the environmental impact of their heavily fossil-fuel dependent energy system through allowing more intermittent renewables onto the grid. Importantly, this could be accomplished with no technical barriers to integration.

3.2 Provision for vehicle-to-grid services

At higher penetration rates, electric vehicles will have the potential to supply the grid with substantial amounts of power using bidirectional chargers, which enable the transfer of power and communication between the electric vehicle and the grid and vice versa (Waldron and Kobylarek, 2011; Ehsani et al., 2012; Hota et al. 2014). In the literature, this method is often referred to as 'smart charging' or 'vehicle-to-grid' services. Smart charging allows the electric vehicle's on-board battery to help maintain the quality of the electricity supply (Waldron and Kobylarek, 2011; Eshani et al. 2012). Excess energy from intermittent renewable energy sources can then be stored for later use. In energy systems with a high penetration wind and solar, research has found that engaging in smart charging can aid the grid operator's task of matching supply to demand (Fattori et al., 2014). Electric vehicles can also act as controlled storage, providing ancillary grid services such as spinning reserve, voltage and frequency regulation (see **Figure 2**). Electric vehicles can therefore increase the efficiency of power systems while at the same time reducing the emissions contribution and offsetting expensive fuel use in the transportation sector.

Colmenar-Santos et al. (2017) examine the adoption of an electric vehicle fleet employing a vehicle-to-grid arrangement and applies it to the island of Tenerife, an autonomous state of Spain. Their study uses an optimization model with a multi-objective function to establish whether a charge/discharge pattern is possible that facilitates the penetration of electric vehicles in an isolated grid. Their study concludes that island grids can incorporate a low level, described as a "transition" level, penetration of electric vehicles, whereby their use as a quasi-distributed storage system can accommodate a significant reduction in the amplitude difference between valleys and peaks (load levelling) of the Tenerife's demand curve.

Studies on the economic benefits of providing vehicle-to-grid services in developed countries are emerging in the literature. Due to its relatively recent development and a range of potential methods of application, a consensus has not yet been reached as to the most effective type of vehicle-to-grid system. Peterson et al. (2010) examine the economic feasibility of using electric vehicle batteries in energy arbitrage in the cities of Boston, Rochester and Philadelphia in the United States. In their model, grid energy was stored during off-peak hours, or when energy prices were low, and sold back to the grid during peak hours, or when energy prices were high. Their study revealed that the annual revenues received may not be attractive to most electric vehicle owners. Tomic and Kempton (2007) compare the profitability of two fleets of electric vehicles participating in five differently regulated markets, with one vehicle fleet providing regulation during the day and the other one at night. The conclusion drawn was that the use of electric vehicles to provide regulation services can be profitable and would help improve grid stability.

A study performed by Sioshansi and Denholm (2010) on the Texas electricity grid indicates that using electric vehicles to support spinning reserve will open up the possibility of savings to power system operators and electric vehicle owners. Pavic et al. (2015) created a generic computer model of a power system that could be configured to represent that of any national power system. Simulations using this model established that providing spinning reserve would result in savings to the power plant operators and reduce total system emissions. Building on their earlier study for Tenerife, Colmenar-Santos et al. (2017) analysed the economics of vehicle-to-grid electric vehicle integration for the Canary Islands through the application of time-of-use tariffs for residential electric vehicle owners. They concluded that vehicle-to-grid would benefit both the grid operator, through more flexible load management, as well as the electric vehicle owner, with potential for 50% reduction in mobility energy costs.

Vehicle-to-grid services are not without their disadvantages. Engaging in vehicle-to-grid services can shorten the useful life of the electric vehicle by increasing the rate of battery degradation. Studies by Ehsani (2012), Tomic and Kempton (2007), White and Zhang (2011) suggest that providing ancillary services, such as voltage and frequency regulation, do not significantly affect battery life and, with fair tariff structures, will be beneficial to electric vehicle owners. However, services that require large amounts of energy such as spinning reserve and peak shaving lead to significant depth-of-discharge of the batteries, thereby reducing battery life. This suggests that electric vehicles are currently more suited to vehicle-to-grid services that require fast response and reactive power, which do not require excessive depth-of-discharge. What is not known at present is how much the cost of electric vehicle-based energy-storage compares to the cost of the alternatives, such as static battery options, compressed air storage, pumped-storage hydro. Each alternative would be impacted differently when deployed on the electricity grids of small islands and this is therefore recognised as a future research need.

All studies reviewed thus far, regardless of their findings, are optimistic about the implementation of vehicle-to-grid services but advise that further research is still needed. Vehicle-to-grid services present particular opportunities in the SIDS. Small island energy systems are often owned and operated by a monopoly utility and only one energy market is available for trade. The generating capacity required to provide grid services, such as spinning reserve and regulation, is small in comparison to large power systems, so the possibility of electric vehicles being able to provide these services without seriously affecting the lifespan of the electric vehicle exists. Small island states therefore present a new perspective for research in this area.

3.3 Battery and End of life considerations

When electric vehicle batteries age and are no longer suitable for driving, vehicle-to-grid services are still possible. An electric vehicle's battery may be considered insufficient for use when it reaches between 70% and 80% of its original storage capacity. Cready et al. (2003) point out that, with minor refurbishment, the battery can then be used in stationary applications. Some stationary applications include storage for renewable energy installations, spinning reserve and localised voltage/frequency regulation.

The literature debates the feasibility of using expired electric vehicle batteries in large-scale stationary applications and appears to favour their use in residential installations. Hein et al. (2012) performed a study that compared electric vehicle batteries engaged in vehicle-to-grid services, old electric vehicle batteries used in stationary applications, and new electric vehicle batteries used in stationary applications. They concluded that in the long term, battery re-use would not be profitable due to the decline in capacity of the batteries and the corresponding decline in value. On the other hand, Cready et al. (2003) looked at eight possible stationary applications for used electric vehicle batteries and found that half of the re-use applications were in fact economically possible. Studies on electric vehicle battery reuse for domestic purposes show that battery buffer-packs help match the availability of household renewable energy systems to the household demand and in some cases completely eliminate the need for grid power, effectively making the property a stand-alone system (Knowles and Adrian, 2014). Stationary used electric vehicle battery packs also have the ability to reduce the strain on the electricity grid by shifting power from peak to off-peak times, an application that, as discussed in section 3.2, is not suited to the batteries whilst they are installed in electric vehicle (Heymans et al., 2014).

In small island developing states, roof-top solar photovoltaic installations presently make up the majority share of installed renewable energy capacity (Worldwatch 2015). Due to the high cost of battery systems, they tend to be grid-tied without battery backup. Battery systems can be attractive to homeowners in small island developing states for two main reasons. Firstly, as a method for further reducing electricity bills and secondly for improved reliability. Batteries offer security, especially in the event of power outages due to natural hazards, to which small island developing states are prone (see Section 3.5). There is therefore great potential for a thriving battery reuse market in small island developing states, which could help reduce the cost of ownership of electric vehicles while stimulating local economies.

3.4 Electric vehicle impact on greenhouse gas emissions

Early publications on electric vehicles suggest that they would help reduce greenhouse gas emissions from the transport sector, as opposed to relocating tail pipe emissions to the local power plant. A 2004 article by Chan and Wong (2004) reviewed the status of the electric vehicle market in the early 2000s and reported that electric vehicles can reduce global air pollution, even when the emissions from the power plant that supplied its electricity are considered. In 2011, Waldron and Kobylarek reviewed the introduction of electric vehicles and vehicle-to-grid services and further supported this position by demonstrating that a net reduction in greenhouse gas emissions is attainable through the adoption of electric vehicles, even if they are charged by coal-fired generation, their reasoning being that power plants will operate more efficiently than individual automobiles.

More recent studies explore the reduction in greenhouse gas emissions provided by electric vehicles and its dependence upon the original energy source. These studies also compare the efficiency of the internal combustion engine and different drive cycles of electric vehicles – efficient and inefficient driving styles (Sioshansi and Miller, 2011). More detailed analyses show that for the same energy mix, emissions depend on the time of day that charging occurs (Faria et al. 2013). For example, Abdul-Manan (2015) presents a life cycle assessment comparing electric vehicles with traditional internal combustion engine vehicles and demonstrates that when a country's generation mix is fossil fuel based, the use of electric vehicles does not result in reduced emissions. The study concluded that decarbonising the power plant sector, rather than converting to electric vehicles, could actually obtain a greater reduction in emissions.

Sioshansi and Miller (2011) investigated the effect of enforcing emission caps on the electricity used to charge electric vehicles in the Texas power system and found them to be successful in ensuring that electric vehicles are charged from cleaner sources. The case study on the Flores island, carried out by Pina et al. (2014), explored the impact of electric vehicles on Flores's small isolated grid with a high share of renewable energy and showed that having a high share of renewable energy does not guarantee a reduction in carbon dioxide emissions. The reason being that, mirroring other studies, the reduction in emissions depends on the time of day that the electric vehicles were charged and the amount of excess renewable energy available at the time. Therefore, it is apparent that electric vehicles should be directly charged from clean energy sources in order to guarantee significant reductions in GHG emissions.

Small island developing states have a predominantly fossil fuel-based electricity sector, with most employing low speed diesel engines to generate their electricity, resulting in emissions factors of around 760 gCO_2e/kWh (Honorio et al., 2003). This is in stark comparison to more developed countries, with averages for Europe of 340 gCO_2e/kWh and 499 gCO_2e/kWh for North America (Brander et al., 2011; Mora and Lonza, 2017). Many small island developing states also have favourable renewable energy resources, and renewable energy transition roadmaps are emerging (Worldwatch, 2015). Small island developing states are further boosted by their highly dispatchable low speed diesel engines, which can help support high penetrations of renewable energy generation (Hohmeyer, 2015). For example, with minimal modifications to its infrastructure, the Caribbean island of Barbados can accommodate at least 20% renewable energy penetration onto its grid (Emera, 2015). Due to their grid supporting measures the energy storage potential of vehicle-to-grid services can lead to an increase in this penetration potential.

Electric mobility should therefore occur in tandem with power sector reform to ensure that emissions are reduced rather than transferred.

Using data for a second-generation Nissan Leaf, **Figure 3** graphically represents the key issues around emissions reductions from an electric vehicle when considering the carbon intensity of an island's electricity source, 760 gCO_2e/kWh in this case. As the penetration of non-carbon sourced electricity increases, the grid's carbon intensity decreases, along with effective electric vehicle emissions. Emissions are particularly sensitive to how the car is driven, or in which 'mode' the vehicle is driven. Road networks on small island developing states tend to restrict the ability for cars to be driven efficiently. High ambient temperatures mean the use of air-conditioning may be necessary during the daytime, and congested road networks may lead to stop-go driving conditions, both of which place a strain on battery range and mean that efficient use of electric vehicle fleets can be difficult to maintain (see **Table 2**).

Figure 3 also compares the emissions of the different types of internal combustion engine vehicles (ICE). Due to the higher emissions factors for small island developing states, hybrid drive vehicles with good fuel economy may actually have lower greenhouse gas emissions than electric vehicles. Unless the electric vehicle achieves a range of 5.93km/kWh, a small family sized internal combustion engine car achieves similar greenhouse gas emissions. It's not until electricity generation has been decarbonised by 20% that electric vehicles start to make sense from an emissions perspective, and not until 50% renewable penetration that their transport systems may start to be considered as becoming decarbonised. This supports the earlier discussion that in order to expedite the decarbonisation of transport systems, electric vehicle introduction must be accompanied by the introduction of renewable energy sourced electricity. In reality however, many electric vehicle owners are often motivated to decarbonise their energy consumption and invest in renewable energy systems that offset their household and electric vehicle use.

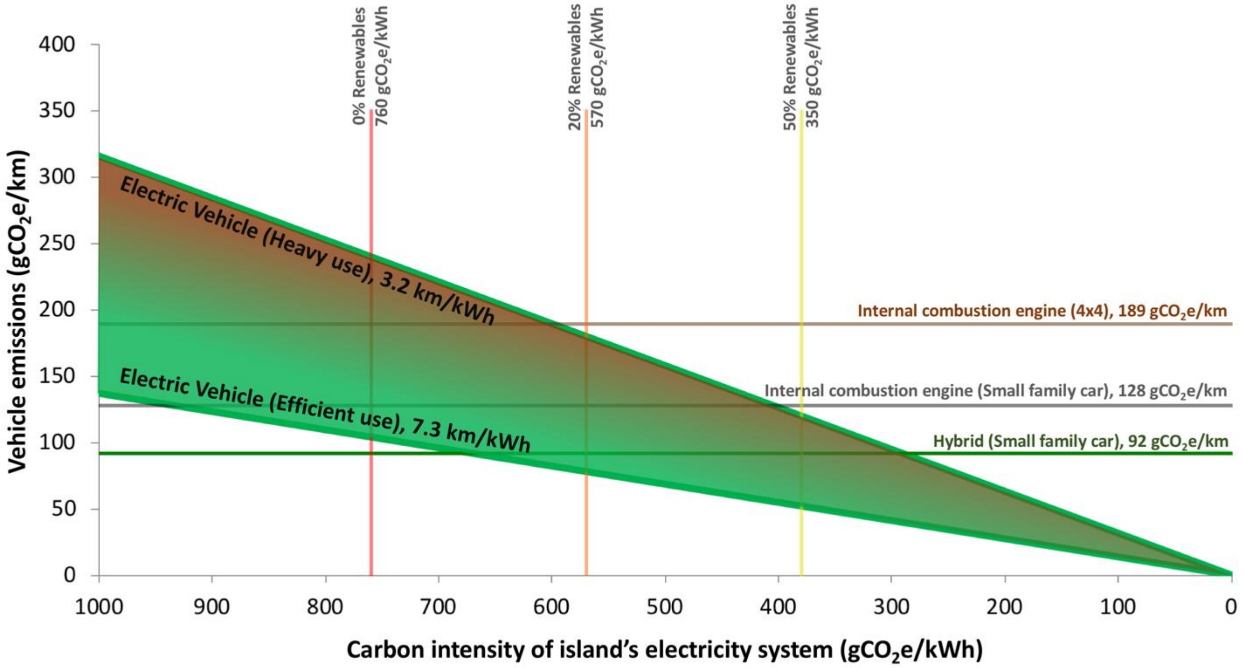


Figure 3. Emissions of different vehicle types and impact of carbon intensity of electricity supply for an island energy system.

Table 2. Summary of Nissan's results operating the 2011 Leaf under different real-world scenarios (Muller, 2010).

Driving conditions	Speed (km/h)	Temperature (°C)	Range (km)	Efficiency (km/kWh)	Air conditioner
Cruising (ideal conditions)	61	20	222	9.25	Off
City traffic	39	25	169	7.04	Off
Highway	89	35	110	4.58	In use
Heavy stop-go traffic	10	30	76	3.17	In use

3.5 Resilience to natural hazards

Small island developing states have always been vulnerable to natural hazards with many experiencing particular susceptibility to cyclones, heavy rain, storm surges, earthquakes, volcanoes and tsunamis. Strengthening their infrastructure resilience is of rising importance given increasing concerns over the impact of climate change (UNOHRLLS, 2015). According to the World Bank (2017), whilst the impact caused by natural hazards will often affect all economic sectors, damage to transport assets (air, marine and road) often accounts for a large share of economic losses. Damage to road transport will tend to impact infrastructure rather than vehicles. However, given vehicles play a key role before, during and after natural hazard events (for evacuation, emergency response and recovery), any substantial changes to an island's transport infrastructure, such as electrification, should be carefully considered.

At present, there has been minimal literature emerging in this area for SIDS. Adderly et al. (2018) raises awareness of the issues associated with electric vehicle use during potential evacuation events in Florida, which mainly relate to the availability of charging infrastructure during mass evacuations. SIDS will have different needs during natural hazard events, some of which may favour electric vehicles (using electric vehicles as mobile power sources during recovery) whilst others may prove problematic, such as a lack of mobility in the longer term if electrical power outages are prolonged. The question of electric vehicle integration and resilience to natural hazards feeds into a bigger conversation around the use of smart grids for SIDS. Colmenar-Santos et al. (2017) concludes that electric vehicles will play an active role in smart grids for isolated islands, in this case Tenerife. An observation that has been voiced by energy sector experts discussing the role of decentralised smart grids in improving resilience to natural hazard events after the 2017 hurricanes that affected much of the Northeast Caribbean (Mooney, 2017).

4 Case study: Barbados creating an island EV market

4.1 Progress in decarbonising its energy system

Barbados was one of 13 small island developing states to fully ratify the Paris climate agreement on the day it was signed in April 2016 and is a dominant player in encouraging increasingly aggressive country commitments during continued UNFCCC negotiations. Driven mostly by the private sector, Barbados serves as a strong example of a country that is working towards sustainable energy independence. The share of renewable energy in its electricity sector has been steadily increasing since 2010, primarily from solar PV. Distributed solar PV penetration has now exceeded 14MW, and a 10MW utility scale solar photovoltaic plant has been online since the last quarter of 2016 (Government of Barbados, 2017). This brings the total share of renewable energy in its electricity generation mix to approximately 10%, resulting in an estimated emissions factor reduction to approximately 680 gCO_2e/kWh.

Through its Intended Nationally Determined Contribution (INDC) Barbados intends to achieve an economy-wide reduction in greenhouse gas emissions of 40% by 2030 (UNFCCC, 2015). Part of this commitment involves renewable energy technologies contributing 65% of total peak electrical demand. Following its general elections in May 2018, the island's new Government has stated its goal of achieving 100% renewable energy supply by 2030. Given its low peak demand of 150MW, the Government has recognised that policies to encourage the business case for energy storage and demand response will be necessary to actualize large-scale deployment of intermittent resources like solar and wind in such a small and isolated power system (Government of Barbados, 2017).

Electric vehicles have been shown to represent both an energy storage and demand response solution, especially where the timing of charge can be aligned with solar and wind generation profiles. More specifically, the charging of electric vehicles during the day-time would create additional demand that matches solar generation (and wind generation in the evening/night-time), leading to less curtailment, increased renewable resource capacity deployment and lower system costs overall. According to IRENA's recent long-term capacity expansion analysis, transport electrification, where the electric vehicles are used to limit curtailment of intermittent renewable energy technologies, can be seen as a least cost pathway for Barbados to exceed a 65% renewable energy penetration (Taibi and del Valle, 2017).

The specific effect of electric vehicles depends on penetration and charging strategy. At low penetration levels electric vehicles are likely to have little impacts on generation, but at high penetration, different charging strategies can provide different types of grid services. Uncontrolled nighttime charging can lead to a need for significant additional capacity, such as wind power, which conveniently has a strong nighttime presence. Electric vehicles would act as nighttime storage, off-taking from wind power, which, for small island developing states like Barbados, would often be curtailed due to low nighttime demand. Daytime charging on the other hand, is another strategy. Charging is incentivized around central hours of the day to coincide with solar PV generation peak. Again, due to low demand, especially on small island developing states with low consumption, solar PV generation is often curtailed during the day. Thus, high electric vehicle penetration can increase renewable energy integration on grid by acting as storage, increasing consumption when cost of supply is lowest, therefore minimizing curtailment and reducing the levelized cost of energy. Further, with controlled charging, where the chargers are centrally or automatedly controlled, electric vehicles as a collective fleet can provide ancillary services to the grid (see Section 3.1), however charge controlling requires significant infrastructure investment.

Government support of the electrification of the transport sector is shown in the Barbados National Energy policy (Government of Barbados, 2017). The objectives and policy measures outlined in the document, such as the development of proper standards and introduction of a comprehensive information system, are geared towards the development of a framework to support the widespread adoption of electric vehicles. Linkages between sectors are also constantly highlighted and it is clear that the policy strives to tie together various elements of the developmental process to date with those planned for the future.

4.2 Electric vehicle market progress and future potential

Barbados' limited land area (431 km^2), its dense road network, generally flat topography and the relatively large size of its total vehicle fleet (132,000 registered vehicles for a population of 286,000) was enough incentive for the creation of a local company, Megapower Ltd, and for them to begin the importation of electric vehicles, quickly becoming the main stakeholder for electric vehicle adoption in Barbados. To date, they have deployed over 40 charging points, of which 34 are publicly accessible and the remainder located in the car parks of businesses (see **Figure 4**). In an effort to help decarbonise the transportation system, they have also installed solar PV covered car port infrastructure at two locations and support the installation of renewable energy projects within the country (**Figure 4**) (Plugshare, 2018). The began in 2012 and sold over 150 electric vehicles in less than two years of operation (predominantly Nissan Leafs), which highlighted both interest and demand despite limited regulatory financial incentive (Edgehill and McGregor, 2014).

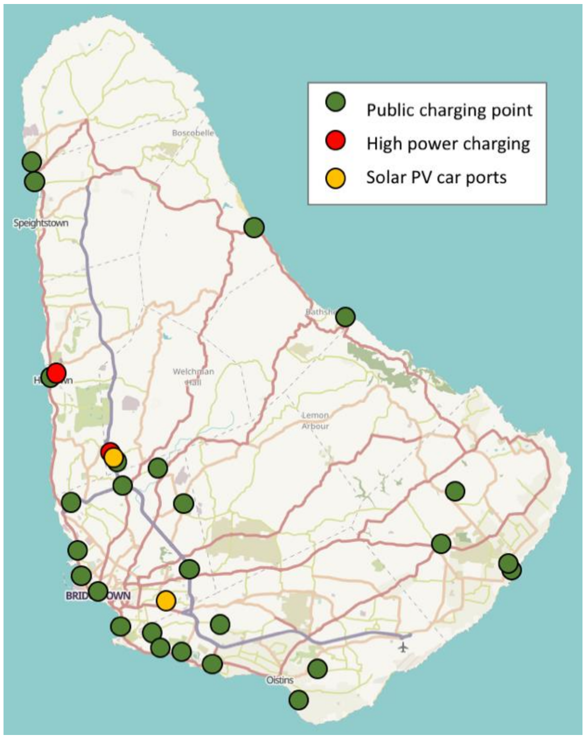


Figure 4. Map of Barbados with major roads and public charging points (Source: OpenStreetMap and Plugshare, 2018).

Across the entire passenger-vehicle fleet, electrification represents a major fuel saving to the individual car-owner in Barbados. Car owners in Barbados drive on average 40 km per day (Taibi and del Valle, 2017). At a cost of US$0.04/km, electric vehicles offer a cost savings of more than 50% over both petrol and diesel vehicles, as shown in **Figure 5**. Based on **Figure 3**, with a carbon intensity of around 680 gCO_2e/kWh, an electric vehicle (Nissan Leaf), driven efficiently, would be the mode of transport with the least emissions per kilometre (80 gCO_2e/km). Furthermore, with a battery capacity of 24kWh (Nissan Leaf), electrification of all 132,000 registered vehicles would potentially provide a distributed energy storage of 0.5GWh[1]. This additional storage would limit the need for curtailment of intermittent renewables (wind and solar), thereby helping to support higher levels of renewable energy penetration. If each parked and fully-charged vehicle is connected to a V2G charger, and each charger can discharge the vehicle's battery at 6.6kW (as per the Nissan Leaf's onboard charger) then the rated capacity, available for various grid services, would be 0.72GW, substantially higher than the island's peak demand of ~0.15GW.

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[1] This value assumes that all parked, fully charged electric vehicles are available for distributed storage and that cars are typically on the road for 1.5 hours and charging for 2.5 hours (so available for storage 83% of the time). It also assumes a 20% maximum depth-of-discharge for grid services in order to conserve battery life.

In reality the above calculations will be affected by issues caused by using electric vehicle batteries for grid services (discussed in **Section 3.2**) as well as system losses, charging/storage demand profiles and ongoing technology advancements. Charging and storage demand profiles are partly explored for Barbados by Taibi and del Valle (2017) and are discussed later as an area of further research.

Given the earlier 40km/day assumption for average mileage and an average vehicle efficiency of 5.25km/kWh (see **Figure 3**), the annual energy consumption for an all-electric vehicle transportation sector can be estimated at 367GWh, which represents a 40% increase to the island's current annual electricity consumption (Emera, 2015).

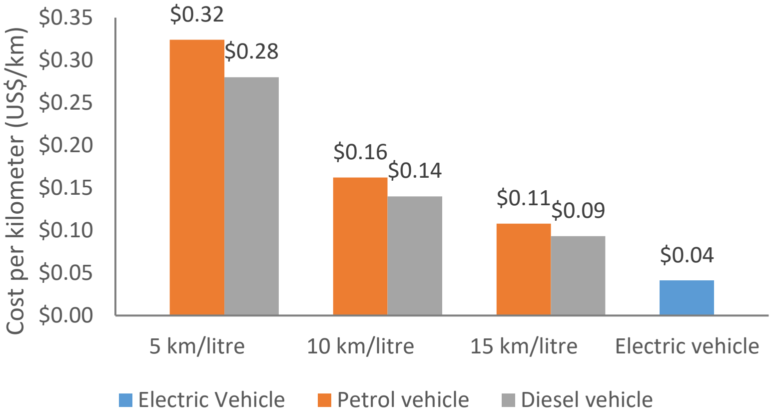

Figure 5. Comparison of cost per km for electric vehicles (Nissan Leaf), petrol and diesel vehicles in Barbados.

Although electric vehicles have emerged as a real option to meet future transportation needs, while at the same time supporting increased penetration of renewable energy technologies onto the grid, transport electrification needs to be carefully planned by both the utility and the Government. Given the abovementioned 40% increase in electricity consumption, the utility would need to prepare for localised overloading and a shift in the daily load profile as charging will initially take place at home in the night, beginning in the most affluent neighbourhoods (Taibi and del Valle, 2017). Time-of-use rates and similar incentives would need to be implemented as part of the overall coordinated charging plan, while keeping an eye on the profitability of its operation. The government would also have its share of planning and preparation. Besides the barriers of a lack of supportive legal and policy framework, along with the lack of charging infrastructure and technical capacity in the operation and maintenance of electric vehicles, there would be a need to consider the impact on its balance of payments. Presently, taxes on fuel sales, vehicle import duties and road tax are lucrative revenue streams for Government.

Further research is needed to determine the optimum solution of incentivisation and investment needed to support the market for both the Utility and the Government. The ability of electric vehicles to support intermittent renewable energy technologies through vehicle-to-grid services needs to be exploited and long-term indirect benefits, such as improved health because of reduced noise and air pollution, should be included in the analysis.

4.3 Targeting the public service fleet

Another proposal for further research would explore the benefits of a focus on public service fleet conversion. Public service vehicles typically have high mobility levels, lower fuel efficiencies and higher daily usage so that the diesel substitution per vehicle is higher. Replacing a single maxi-taxi bus with an electric bus in Barbados would yield equivalent diesel savings of 33 passenger vehicles (Taibi and del Valle, 2017). Comparing a diesel bus in Barbados with a conservative fuel economy of 2km/litre with a similar sized e-Bus (Proterra Catalyst XR), at $0.27/km the running cost of the e-Bus would be less than half that of the diesel bus ($0.70/km). Not only do fuel savings accrue faster but having plied routes and bus terminal locations allows for easier determination of optimal location for charging infrastructure, while predictability of daily use profiles allows for greater ease in controlling charging behaviour and fitting charging profiles to resource availability profiles for maximum renewable energy integration. It is also easier for governments to support the deployment of electric vehicles in public and fleet vehicles through legislation and/or regulation (e.g. mandates for public vehicle purchasing) without the additional complication associated with private market adoption. Finally, deployment of public and fleet electric vehicles also creates an excellent opportunity for public outreach and education programs that help familiarize the general public with clean transportation technologies and sustainable energy use behaviour.

In small island developing states, government run transportation is not normally a revenue stream. It is usually subsidized and used as a social benefit to promote economic development and ‘give back’ to society. This is the case in Barbados. Pensioners and school-aged children travel for free and the fare for all other passengers is fixed at US$1 regardless of destination. For privately owned route taxis, this affects the owner’s ability to recover the operation and maintenance costs of their vehicles, which results in overcrowding and leads to aggressive driving as bus drivers compete for passengers. In 2009, this translated into approximately 30% of all passengers travelling for free and the government funding over 60% of the costs through a subsidy of US$5 million (Robinson, 2012).

The importance of this social benefit however, cannot be underestimated. Surveys find that more than 20% of the population is entirely reliant on public transportation (Robinson, 2012). More than 75% of commuters using public transport do so on a daily basis and yet research estimates that even with approximately 24 million passenger trips being made annually, only 60% of total demand is being served. In particular, many rural parishes in Barbados are under-served in terms of total vehicle availability relative to demand (Robinson, 2012).

Thus, while the passenger car is the highest share of vehicles and fuel consumption in Barbados, the public service fleet - buses, taxis and hired cars – can be considered to be prime targets for early adopters. In addition to cost savings, upgrading to an electric fleet equates upgrading to a smart fleet – one with routes and vehicle dispatch optimised by demand and supporting real-time collection and dissemination of information for consumer and operator efficiencies.

Given its advances in renewable energy deployment and leadership in international negotiations, Barbados provides a promising proving ground for the rest of the Caribbean and other small island developing states for the promotion of electric vehicles as a sustainable, efficient and cost-effective solution to transportation and energy sector challenges for island communities. However, a significant amount of data collection and analysis is required to understand the benefits and inform planning strategy for fleet conversion. The current bus fleet of the Barbados Transportation Board consists of approximately 300 45-seater buses, mostly Mercedes Engines ranging in age from 10 to 20+ years. However, due to maintenance needs and high servicing costs, 50% of the fleet is out of service on an average day. This drastically limits passenger numbers, which totalled 17.5 million journies in 2015/2016. In addition to the Transportation Board's large maxi-taxi fleet, the public is also served by a fleet of privately owned taxis, mini-buses and 14-seater mini-vans (known locally as ZRs or route taxis). Public service vehicles alone form over 20% of Barbados' total fleet, so there is a major opportunity for rapid market adoption by focusing on this sector. The Alliance of Public Transport Operators (APV) represents the owners and operators of these vehicles and they note that fuel and maintenance costs are becoming increasingly prohibitive for drivers (Barbados Today, 2018). As such, there is voiced interest in exploring alternative technology within the Alliance.

Nevertheless, there are a number of challenges for e-Bus adoption, including the cost of buses, the cost of charging infrastructure and more. For instance, in order for e-buses to support increased share of renewables in the national energy balance, charging must come predominantly from renewables, and thus charging would need to directly align with resource profiles. For daytime (solar PV) charging infrastructure needs to be deployed across the island in the locations where vehicles spend significant periods of time parked during daylight hours. This requires the tracking bus routes and understanding trends to optimize public charging locations with respect to time and geography. Furthermore, the cost of public charging infrastructure is often double the cost of private charging for equivalent charge capacity (more complex infrastructure and maintenance). To determine the right balance of charge management strategies, further research is required on time-of-use tariffs, and how they can impact private charging profiles. Also needed is simulation of demand-side smart control technology on moderating charging during the evening peak; and research into billing strategies to encourage maximum use or investment returns for public charging infrastructure. These are critical research needs to understand the technical benefits of fleet conversion.

Finally understanding the economic benefits of fleet conversion itself will require further study. Economic equilibrium analysis is needed to understand the trade-off between revenue streams for government (i.e. scale of fuel import savings versus reduced fuel tax earnings, the impact of potential electric vehicle import tax reduction and exemption incentives on government revenues, and the indirect impacts on the local economy through sectoral interaction and jobs creation).

5 Conclusions

For the many small island developing states that depend heavily on imported fuel, the prospect of reducing dependency on fossil fuel imports and improving energy security can act as a key incentive towards transportation sector reform. These countries currently pay premium prices for they fuel and in many cases their transportation sectors represent a 50% share of fuel imports. Reducing the fuel demand of this sector will therefore save foreign exchange and improve their economies.

One of the main concerns of electrification of the transport sector is the impact of electric vehicles on the isolated electricity grids, at both low and high penetration levels. Without careful planning, electric vehicles may lead to overloaded distribution feeders and transformers and, at high penetration rates, could result in grid destabilisation. Strategies have been proposed to mitigate these impacts starting with coordinated charging, where electric vehicles are charged at a predetermined time of day, and ultimately leading to the adoption of vehicle-to-grid services, where electric vehicle charging and discharging is deployed centrally by grid operators to assist in matching supply to demand. The prospect of vehicle-to-grid services in small island developing states could result in electric vehicles going from being a grid liability to a key grid asset. However, to promote the decarbonisation of transportation sectors, transitioning to electric vehicles should develop in tandem with increasing the renewable energy share in the primary energy mix, which should be reflected in national energy policies. Many small island states have already set renewable energy targets and have begun the process of power sector reform. This has been brought about not only because of their need to reduce dependence on imported fuel but also because of their fragile environments. Climate change along with their growing energy demand threaten the health of their ecosystems, which form the backbone of their economy. Incorporating transportation sector reform by way of electric vehicles and vehicle-to-grid services will complement these overall goals.

Our paper provides a comprehensive review of literature on island applications of electric vehicles, making the case for small island developing states as an imminent area of opportunity for further exploration. Current literature mainly focuses on the economic aspects of vehicle-to-grid services for large interconnected grids. Due to the complexity of these grids and their energy markets, these studies are often unable to completely analyse all variables. With their small isolated grids and often monopoly electricity utilities (controlling generation, transmission, and distribution), small island developing states present an attractive environment for the exploration and successful adoption of electric vehicles and implementation of vehicle-to-grid services. It may be more useful to model these simpler systems, especially at this early stage of vehicle-to-grid development.

The present status of the Barbados electric vehicle sector captures some of the challenges that will be faced by small island developing states in the development of their electric vehicle markets and vehicle-to-grid services. Whilst the island is witnessing a successful uptake of electric vehicles in its private vehicle sector, an aging public transportation vehicle fleet with unsustainable subsidy support holds great potential for electric vehicle transition. This would result in substantially reducing the costs of travel around the island, whilst raising public awareness of the economic viability of a clean transport sector.

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