Transport Policy 138 (2023) 45–59

Contents lists available at ScienceDirect

Transport Policy

journal homepage: www.elsevier.com/locate/tranpol

Electrifying public transit benefits public finances in small island developing states

Zakia Soomauroo [a,*], Philipp Blechinger [b], Felix Creutzig [a,c]

[a] Sustainability Economics of Human Settlements, Technische Universität Berlin, Germany
[b] Reiner Lemoine Institut, Germany
[c] Mercator Research Institute on Global Commons and Climate Change, Germany

ARTICLE INFO

Keywords:
Electrification
Island
Public transport
Infrastructure factors
Fossil fuel dependence

ABSTRACT

Deep decarbonization of the transport sector in small island developing states (SIDS) can simultaneously address issues of energy security, high fuel import prices, and climate change mitigation measures while ensuring a reduction in air pollution and higher levels of wellbeing for citizens. Electrification plays a vital role in the decarbonization process. Here, we investigate potential transition pathways towards electrification, taking the public transportation system in Mauritius as an example, where there is vast potential in electrifying the old and overburdened bus system. We simulate a variety of public bus turnover scenarios, considering initial costs of investments, energy and fuel requirements, and reductions in greenhouse gas emissions. We demonstrate that optimized investment into electrifying public transit pays off, with annualized investments of about $5 million superseded by annual savings on fossil fuel imports of about $15 million. We suggest that international donors can accelerate this transition by providing loan guarantees and, by this, reducing the cost of capital.

1. Introduction and state of research

Climate change and energy security are two of the main issues in the transportation sector (García-Olivares et al., 2018; Azzuni and Breyer, 2018), with recent research pointing to the increased importance of urban transit and transport electrification in achieving a more rapid decarbonization process (Creutzig et al., 2016). Decarbonizing the energy and transport sector in small island developing states (henceforth SIDS) allows for advancing mitigation strategies, testing novel technologies on limited network testbeds, and aiding the global phase-out of fossil fuels (Soomauroo et al., 2020). The island states simultaneously face high levels of energy insecurity and high petrol prices, yet are responsible for less than 1% of global carbon emissions (UNFCCC, 2005; Wong, 2011; Thomas and Lindo, 2019). Given the limited reach and financial capabilities, their mitigation measures present them with a unique bargaining chip that allows them to act as frontrunners for faster uptake of sustainability by becoming leading voices in the global climate change advocacy movement (de ÁguedaCorneloup and Mol, 2014; Betzold, 2010; Ourbak and Magnan, 2018).

Their smaller resource bases and network chains result in less resilience to global catastrophes, affecting livelihoods, food security, and human health. The last years have seen the continued expansion of global threats, climate change, erosion of natural landscapes, and fluctuation in trade and finances – all factors to which SIDS are particularly vulnerable. This underlines the urgency for SIDS to become climate mitigation leaders to influence global transformation efforts. Due to their propensity towards accelerated decarbonization - given their constricted and demarcated network effects and the need to urgently consider extreme climate effects and energy resilience (Lammers et al., 2020) - SIDS serve as powerfully disruptive case studies.

With over 87% of primary energy needs met by imported petroleum fuels, islands are highly susceptible to price trends in the global oil market (Romano et al., 2016; Surroop et al., 2018; Raghoo et al., 2018). As a result, they often face periods of prolonged supply shortages (Surroop et al., 2018; Niles and Lloyd, 2013), with specific SIDS paying some of the highest fuel prices globally (Raghoo et al., 2017; Niles, 2013). This long-term reliance on imported fuels leads to a vicious circle of accumulated dependence on foreign capital and energy (Atteridge and Savvidou, 2019), thus leaving fewer means for investment in low-carbon infrastructure. Amongst others, land-use and road systems – due to their carbon-intensive, long lifetimes – become relevant factors for climate change mitigation (van Vuuren et al., 2017). The historical patterns of concentrated urban development along the coasts, with few primary roads stemming from the capital to smaller towns and insufficient

---

* Corresponding author.
E-mail addresses: zakia.soomauroo@rl-institut.de (Z. Soomauroo), philipp.blechinger@rl-institut.de (P. Blechinger), creutzig@mcc-berlin.net (F. Creutzig).

https://doi.org/10.1016/j.tranpol.2023.04.017
Received 14 June 2022; Accepted 29 April 2023
Available online 11 May 2023

resources, place additional stress on islands (Soomauroo et al., 2020; Urbanization and Climate Change in; Monioudi et al., 2018).

SIDS are confronted with particular climatic, energy, and transport-related issues (Atteridge et al., 2020; Prasad et al., 2017; Wolf et al., 2016). While transforming the power sector of islands is well understood, the transformation of the transport sector remains a considerable challenge. Using electrification of transport as a vector for decarbonization will escalate the synergies of the transport and energy sectors and improve mobility options and sustainability. This can create further benefits when combined with optimized mobility planning along improved public transport routes and systems. Public transport is rarely a revenue stream in the SIDS (Gay et al., 2018). It has been subsidized to provide a car-independent mobility option. Therefore, electrification and optimization of the public transport services have important implications for decarbonizing the transport sector and making it more accessible and equitable.

2. Problem & contribution

Reacting to climate change means global, deep decarbonization of the energy and transport sectors - as quickly and efficiently as possible. Despite this fact, the number of motorized urban passenger-kilometers is expected to nearly double to 48.4 trillion by 2050, while the number of motor vehicles on the road is estimated to grow – from the 2015 figure of 1 billion (Ronan., 2021) – to 2.4 billion within the same period. As a result, emissions from the transport sector are rising more rapidly compared to other sectors (Transport). Factoring in the high number of end-users, expensive low-carbon transport technologies, and the difficulty in substituting equally high energy-density carriers such as oil (Ueckerdt et al., 2021), the decarbonization process is particularly challenging. Furthermore, the transport sector has acquired seen a negative correlation in reaction to standard pricing measures – as can be seen by the Yellow Vest protest movement in France in 2018 and dependence on long-lived infrastructure – two factors further entrenching its dependency on fossil fuels (Jetten et al., 2020; Fisch-Romito et al., 2020; Javaid et al., 2020). Therefore, a key driver for change in the transport sector is using renewable energy, mainly through direct electrification and shifting away from individual car usage towards, for example, public transport.

SIDS have optimal characteristics that make them ideal for the early-stage adoption of electric public transit systems (Gay et al., 2018). Their limited road networks and high imported fuel costs necessitate rapid system change (Soomauroo et al., 2020). SIDS also feature specific characteristics similar to urban settings, which favor public transport with increased coverage and ridership connecting densely populated areas and reducing traffic jams by individual cars. The electrification of bus systems can be planned easier than that of private vehicles. Therefore we see electrifying and improving public transport systems of SIDS as a crucial first step towards the transformation of the respective transport sector (Lah et al., 2019). For this step, policies and frameworks are essential for small islands to fully capitalize on their potential as global frontrunners. While implementing such policies and framework is unequivocally conclusive and undoubtedly required, local decision-makers need more clarity on the transition process. A majority of the COP21 established Nationally Determined Contributions (NDCs) of SIDS pinpointed transport as a source of greenhouse gas (GHG) emissions and a vital area of action, with 23 NDCs aiming for reductions in transport emissions (INDC; Long-term strategies in SIDS, 2021)· However, most SIDS missed the chance to provide a cohesive link in their NDCs to transport (among other sectors), climate change, and development (Atteridge et al., 2020). Currently, there is a growing trend towards clean transportation in the national policy reviews of the SIDS; however, there are substantial island-to-island discrepancies towards enabling the policy landscape for electrification. Few systemic studies exist for small islands that study the linkages between transport, energy security, and environmental impact. This represents a significant knowledge gap concerning the understanding of island sustainability, which, in turn, inhibits effective policy.

The contribution of this study is to explore whether the transition phase of the transport system on such islands can be at the same time climate-friendly and economically viable. For this, we use electrification as a vector for decarbonization through simulation, optimization, and planning of renewable energy source integration into the public transport system. This investigation centers around the case of Mauritius, a SIDS located in the Indian Ocean. For this study, we analyze the current bus-based public transport system and address the following questions: i) what is the impact of partial and complete electrification of the bus fleet regarding costs and greenhouse gas emissions; ii) how can a metro line support sustainable transport on Mauritius; and iii) what recommendations can be given to accelerate sustainable transport on SIDS in general?

Our paper is a step in addressing the significant research gap on sustainable transport on islands and is organized as follows: Section 3 presents our literature review on bus fleet electrification processes. Section 4 outlines our conceptual framework and qualitative case study method. We further discuss the results and their implications. We conclude with Section 5 by making recommendations for future research and policy implications. This paper adds to the literature by accessing the potential of electrification of the public transport fleet regarding fuel savings, their role in mitigating climate change, and providing an adequate level of service.

3. Literature review

A growing body of literature explores sustainable development pathways for small island nations, focusing on high-share, renewable energy systems (Medina Warmburg, 2006; Cross-Call, 2013; Segurado et al., 2015; Blechinger et al., 2016). These studies include innovative approaches such as floating PV or wave energy (Keiner et al., 2022). Higher penetration of renewable energy sources brings local benefits such as sustainable jobs and educational opportunities (Shah et al., 2016). However, while transforming islands' power sector is well-studied, there is a shortage of studies on the transformation of the transport sector. Studies include a comparative analysis of 6 different urban areas across the SIDS (Khan and Gonzalez, 2021). A case study looking at potential alternative transport scenarios in the Cook Islands finds economic and social benefits in switching to sustainable transport solutions through increased local wages, domestic stimulus, decreased import consumption, and a substantial decrease in GHG emissions (Tyedmers et al., 2020). Through stakeholder analysis, Kougias et al. identify that island researchers expect technological breakthroughs and lessened RE production costs. At the same time, end-users are hesitant to buy electric vehicles (EVs)(Kougias et al., 2020) despite the short point-to-point travel distances. The case of Barbados, however, demonstrates how islands are ideal markets for EVs due to their limited road networks and the need for direct grid storage solutions. A private-sector movement has led to the island having the 3rd highest EV uptake per capita worldwide (Gay et al., 2018). Despite these interdisciplinary case studies on decarbonizing transport systems in island systems - with Dorotic et al. showing one of the first sector-coupled analyses of decarbonizing an island's power and transport sectors (Dorotić et al., 2019) - we identified a lack of analyses regarding the role of public transport for islands.

To find adequate recommendations for decarbonizing SIDS transport sectors, new ways of implementing technical solutions, new behaviors, and lifestyles in the transition process need to be considered (Hiselius and Rosqvist, 2016). The complexity of planning the synergetic transformation of different sectors requires different kinds of computer-based models to support decision-makers. Planning low-carbon transport modes requires that stakeholders are empowered with robust tools focusing on the peculiarities of transport system analyses (Grosso et al., 2017). Transport simulation tools enable stakeholders to appraise transport policies and schemes, forecast their outcome, and assess their economic and environmental impacts and effectiveness. Given the numerous transport issues society faces, tools need to consider different urban systems, high levels of mobility, sustainability goals, and accessibility. Numerous studies analyze the energy aspects of the transport sector, primarily through the use of bottom-up energy simulation tools (Grosso et al., 2017; Dodds and McDowall, 2014), for example, using the simulation tool Osemosys, the transition technologies for electrification and optimization of the bus transport systems in Curitiba, Brazil are analyzed (Dreier, 2020). Transport planning models typically simulate trips by origin and destination, trip purpose, mode of travel, and household demographics. Multinomial logit (MNL) modeling is often used to compute mode choice for trips between origin and destination (Modelling Transport). Aspects identified as crucial for transport modeling include enhancement in the disaggregation of the car market, the imposition of market shares for battery electric vehicles (BEV), plug-in hybrid electric vehicles (PHEV), diesel and diesel hybrid cars, and representations of infrastructures through lumpy investments (Final Report on DTI). In contrast, transport planning involves considering how investment and other interventions are most needed (Lovelace, 2021). Given that the increase of public transit ridership is predominantly constrained by travel time and the built environment (Liao et al., 2020), transport-specific parameters such as the Travel Time Budget (TTB) and the Travel Time Investment (TTI) have also been implemented.

Public transport infrastructure and services have the potential to significantly affect societal wellbeing since it shapes people's ability to access opportunities that are essential to human development, such as employment, healthcare, and education. However, studies have shown that public transport is still divided along the lines of spatial, income, and gender equity (Milan and Creutzig, 2017). Decisions about the built environment in the climate context intersect with human wellbeing (Klinsky and Mavrogianni, 2020). Investment in public transport improves access to low-carbon services, resulting in lower energy demand, with the proper mechanism of subsidies shielding poorer households from upstream fuel taxes (Lamb et al., 2020; Laizāns et al., 2016). However, long-lived infrastructure (Fisch-Romito et al., 2020) of the transport sector leads to increased carbon lock-in and delays sustainable mitigation actions due to stranded investments.

However, there is a shortage of research on the disparity between upfront investment costs in electrification and import of fossil fuel costs towards financing the incumbent system in transport planning models. Through design and form, built environments have substantial potential for reducing energy demand and achieving sustainability co-benefits (Creutzig et al., 2015). However, upscaling solutions and appropriate policies are challenging for shareable learnings across geographical locations. Urban mitigation solution approaches remain defragmented due to inconsistent planning methods and boundaries of analysis. Urban and island case studies add to our understanding of mitigation solutions, but comparative analyses are needed to organize these case study insights into quantitative systems of geographic locations. These case studies need to be reviewed with more detailed planning tools, thus moving away from top-down, macro-level planning towards a thorough assessment of infrastructure and mobility needs. In this paper, we focus on the role of low-carbon public transport to improve services and provide urban mobility that is safe, efficient, effective, and affordable for the community (Mugion et al., 2018).

3.1. Research scope and design

3.1.1. Case study area: Mauritius

Mauritius, shown in Fig. 1, is an archipelago located in the Indian Ocean, with 1.4 million inhabitants, mainly on the main island. Mauritius imports coal and liquid fuels to meet 83% of its energy needs, rendering it vulnerable to rising and volatile world energy prices. Increased energy security and diversifying income from exports are key policy concerns. Mauritius demonstrates a clear example of the transport system design of SIDS through its dense built infrastructure sprouting from the coastal capital cities and sporadic coastal towns and buses as the principal mode of public transport. The island has seen its private car ownership levels increase by 98% over the past decade, whereas buses have only seen a 9% increase between 2010 and 2019. The Mauritian case mirrors the transport situation in many urbanized islands or urban areas, such as worsening congestion, air pollution, traffic accidents, and high vehicle ownership and high vehicle density per kilometers (Enoch, 2003). This case moreover illuminates the high fuel costs of the transport system and the carbon lock-in trap. At the same time, Mauritius has been a leader among the African Group of countries to promote electric vehicles through reviewing their taxation structures and adopting policies and standards to promote EV uptake (Shah, Awojobi, Soomauroo) as well as restricting old, polluting second-hand vehicles through the feebate system (Environment, 2020).

To investigate the impacts and implications of technological changes of the public transport system and their potential contributions to lowering greenhouse gas emissions, road traffic, and local air pollution, we identify different potential trajectories focusing on electrifying public transport. Improving the public transit modes becomes even more urgent and focal, as developments in other emerging countries show a predictable correlation between the level of growth and the increase in the use of motorized transport, particularly private cars. The public

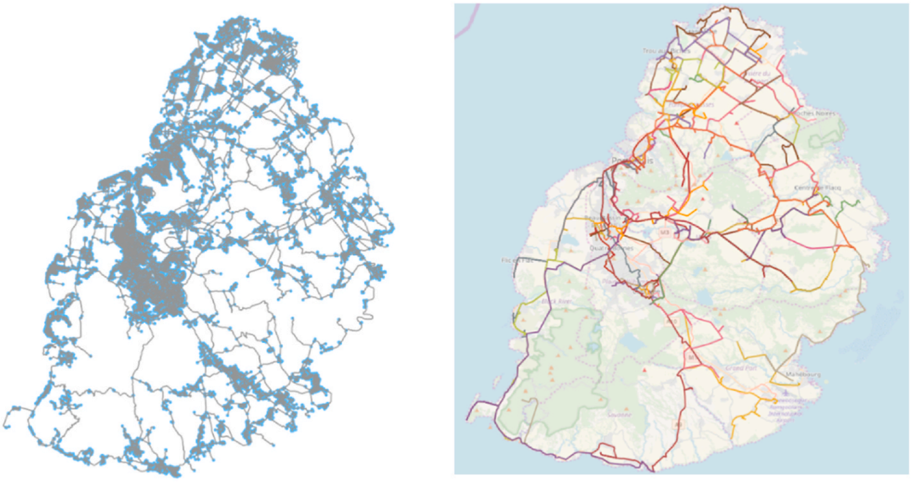


Fig. 1. Road network and human settlements (left) and current bus lines on Mauritius (right).

transit system on Mauritius and other SIDS is a low-hanging fruit for decarbonization through legislation and regulation regarding markets and infrastructure to deploy electric buses. Historically, SIDS have had larger public transport fleets (relative to population and comparable GDP per capita) than larger countries.

3.2. *Describing the public transport network*

In the context of energy usage and climate policy, the **transport sector** accounts for 48.6% of Mauritius' final energy use (Statistics Office Government of Mauritius, 2020) in 2020, down from 54% in 2019, a decrease most likely explained by the COVID-19 induced lockdown (Le Quéré et al., 2020). We can therefore envisage that the pre-pandemic numbers are more appropriate. The most significant energy resources in the country's transport sector are oil products, accounting for 62.1% of the total primary energy requirements (Statistics Office Government of Mauritius, 2019). A recent study shows that the most pressing transport issue for the Mauritian population is road congestion (Vencataya et al., 2018). More than 150,000 people travel to Port Louis every morning, and along with the planned metro line, there is an emerging movement in promoting public transportation and adopting a carpool culture. Despite the high car ownership level, a survey shows that 48% of respondents still selected "Bus" as their daily transport mode, partly promoted by the fact that students and the elderly population of over 60 years travel free of cost. According to research done by the Ministry of Public Infrastructure and Land Transport, the transportation system in Mauritius does not meet the expectations of the stakeholders, including the 750,000 passengers traveling daily by bus (Republic of Mauritius). This is exacerbated by the daily traffic congestions during rush hours, limited operating hours, lack of passenger comforts, and unhealthy exhaust fumes. The total cost of these congestions to the economy is estimated to swallow approximately 1.3% of the GDP (Government of Mauritius, 2018). Electric buses will become an important element for a sustainable transportation system, given the lack of space for developing tram systems. Providing adequate pedestrian and public spaces, especially if in alignment to the new light metro rail system, will also help to improve the situation and reduce the need for individual bus lines. These factors need to be considered when developing scenarios for electrifying and improving Mauritius' public transport sector.

Efforts to move beyond the current regime are laid out in the **new Renewable Energy Roadmap 2030** (Republic of Mauritius, 2030), outlining how the country will achieve its targets set out in the Nationally Determined Contribution (NDC). Regarding the uptake of renewables, there are plans for further wind farms and solar energy, biomass, and waste-to-energy projects, while a grid-code and incentive scheme for small power producers has been implemented. While there are no policies yet looking at the fuel economy or reduction of greenhouse emission within the urban corridor, both the roadmap and NDC list the introduction of electric vehicles as a sustainability measure. A transition can only go hand in hand with both decarbonization of national energy systems and mobility solutions. Their interactions are expected to increase significantly, especially with battery systems expected to achieve grid stability, given the generation to load profile mismatch.

By analyzing Mauritius's current bus lines (see Appendix for detailed Methodology), we see that different bus providers cover the same routes, resulting in heavy road traffic. The whole bus fleet covers nearly three times Mauritius's total road length (approx. 2000 km). We also see that 48% of the bus fleet is older than 1980, resulting in concerns regarding the pollutants (particulate matter, carbon monoxide, and nitrogen oxide) from the ICEVs exhausts, driving home the point that transport is also a public health problem. Currently, the **transport modes in Mauritius are predominantly fossil fuel and combustion engine-based.** The year 2020 has seen the introduction of a Metro light rail system, which is not yet fully operational and will be expanded in the future to cover the main settlement areas from the north to the south of the island. The **public transport networks use the existing, limited highway grid** and offer few connecting roads at medium altitude; they generally consist of parallel routes running from the densely populated central plateau to the capital city and the coastal strip (Soomauroo et al., 2020). Interurban and urban coaches/buses do not have dedicated bus lanes, so their performances are also affected by general traffic conditions. As things stand today, they have difficulties providing predictable quality services. Lastly, public transport users are mainly captive customers with no other means of travel: the public transport network is not seen as an attractive alternative to the private car. This can be changed by providing more effective, fast, and sustainable services.

3.3. *Research design*

The goal of our research is to find optimized and sustainable transport scenarios that offer at least the same level of service (in regards to accessibility, comfort, and punctuality) but at reduced costs and emission levels. Over 50% of buses on Mauritian roads were manufactured before 1981 (see Fig. 2). Since older buses need to be periodically replaced, this provided us with the opportunity to construct a transition pathway where those buses are switched with electric ones. We then played with the concept of charging those acquired e-buses with the current national grid and an on-site renewables-based mini-grid.

For the assessment, four scenarios are created in which the investment, maintenance, and operational costs are calculated. Furthermore, the impact of investments in electric buses is also evaluated against fuel imports. We supplement these insights with a further GHG emission reduction analysis and place these facts within the broader concept of the SIDS-wide energy transition process. To tackle the questions of renewables investment cost vs. reaching break-even and attaining a self-sufficient transport network, we use primary bus fleet data and real-time costs collected in Mauritius in 2019. We determine the respective costs by applying a self-coded simulation and financial tool based on the Open Energy Modelling Framework. Scenarios A, B, and C are generally available for all SIDS in that we compare replacing a certain amount of diesel buses with electric ones. For scenario D, we look specifically at Mauritius to see how bus transit changes with the implementation of the newly introduced metro line. The future scenarios account for high adaptation of electric busses in the public fleet by 50% and consideration of the metro line. In the following, we describe the narrative of the scenarios. Detailed assumptions can be found in the annex. We use 2019 as the weather year for solar capacity factors. The scenario development process occurred from a combination of expert opinions gathered via an in-person workshop in Mauritius in June 2019 and elaborated upon by the authors.

(A) *Base scenario, Business-as-usual (BAU)*, based on the current public transport fleet and grid capacity in the year 2021. In this scenario, there are 3086 diesel buses, of which 51% were acquired before 1980. In addition, there are currently two electric

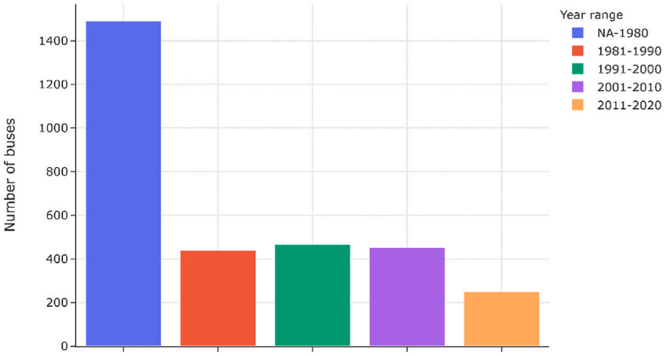


Fig. 2. Manufacturing year range of bus fleet.

buses as part of a pilot project run by Rose-Hill Transport.[1] This scenario defines the baseline of current cost and emission levels of the analyzed public transport system.

(B) *Grid-based scenario*, in which 1490 of the original 3086 buses are replaced with e-buses. The central power grid charges the e-buses at an industry electricity tariff (0.14 USD/kWh) and current power generation mix. We assess the investment costs of those e-buses and charging infrastructure and fuel costs for the diesel buses. We do not apply route optimization in this scenario but focus on electrification of existing busses.

(C) *Solar-based scenario*: Similar to scenario B, we replaced 1490 buses with e-buses and charging infrastructure; and simulated an energy autarky system with a resulting tariff of 0.179 USD/kWh with on-site PV generation. This helps to show an alternative way of charging the busses with renewable energy without changing the entire power supply system.

(D) *Integrated and electrified transportation system (IETS):* This scenario combines electrification of bus fleets with simultaneously introducing a rail-based axis, a new metro line. We modeled an optimal route algorithm with a new metro line to attain maximum synergy. For each route, we evaluated whether the current passenger demand can be met through the metro line and whether the number of bus lines can be reduced by the metro line, thus reducing the road traffic volume. We also consider the cost and energy requirements of the metro line. Here, we applied a routing algorithm, which required a line graph of the entire street network. Data from OpenStreetMap (OSM) database classified the different road networks into typologies of specific street types (residential road, agricultural road, highway, etc.). For each edge of the respective road, we implement attributes such as the maximum speed limit, road length, and the time a vehicle needs for this edge depending on the speed limit of the respective road type.

The introduction and ongoing implementation of the metro line in Mauritius has opened up new feasible avenues for the transport future of the island. The IETS scenario is in line with the Bus Modernization Program introduced by the Government of Mauritius in 2014. As a result, the metro line will become the primary choice for travelers within the urban corridor and for connecting tourists from the airport (as is planned in Phase 2) to the urban areas. The bus routes then become feeder services for last-mile access or focus on underserved, remote regions. Especially among small islands, this is an opportunity to make public transit more attractive by focusing on factors increasing speed and decreasing travel time (Liao et al., 2020).

We conceptually summarize the methodological approach in Fig. 3.

4. Results and discussion

4.1. Comparison of all transport system scenarios

Based on the previously defined four scenarios, we here assess the costs, fuel consumption, and GHG emissions of the different transport futures. The Base, Grid-based, and Off-grid solar-based scenarios find themselves within the same range of annual costs. The base scenario has the highest cost of $15 million per year and emits the highest GHG emissions (1132 tons/year). Both the grid-charged and the off-grid solar scenarios also result in high annual cost spending (investment, maintenance, and variable costs), amounting to $15,230,000 and $15,761,000, respectively. The current high cost of the base scenario is mainly due to fuel costs ($15,415,000), and for the off-grid solar and grid-charged scenario, higher costs were led both by investment into e-buses and charging infrastructure as well as fuel costs for 1604 diesel buses. While base, grid-based, and off-grid solar-based scenarios are similar, there is a difference in the cost breakdown within each respective scenario. The base scenario sees nearly 100% of its cost solely in fuel costs for buses. The majority of the grid-based scenario costs also go towards fuel costs (53%) with 47% into electric buses and electricity costs and approximately 1% in charging infrastructure. For the off-grid solar-based scenario, 61% of expenses are spent on fuel costs, with 38% in investments into e-buses and 1% in charging infrastructure. The IETS shows the steepest reductions in total annual costs, at approximately $5,000,000. A summary is presented in Table 1.

We find that the costs per kilometer also follow a similar pattern, with the base scenario at $2.31 and both the grid-charge and off-grid scenario slightly higher ($2.48 and $2.51 respectively) and the IETS substantially lower at $0.10. Reduced transportation costs from lower energy costs per kilometer are achieved through more efficient vehicles and lower fuel costs (Collett, Byamukama, Crozier, McCulloch). If we had not replaced diesel buses in the IETS scenario but still lowered the number of buses, the cost per kilometer would be $0.27 due to a more optimized routing network.

Investment costs in electric buses and sufficient charging infrastructure are the highest in the grid-base and off-grid scenarios, due to the need for upfront payment, with annuities calculated over 20 years. This is far less in the IETS due to fewer buses needed as a result of the optimized metro line. The same pattern is again found for maintenance costs, as well as in annualized investments. Fuel costs are the highest under the current base scenario, with all 3094 buses operating on diesel. The grid scenario sees this number lowered with a combination of both fuel and electricity. Electricity costs in this scenario are at $0.14, whereas in the off-grid scenario, it is at $0.17, explaining the slightly higher operational costs.

Investing in electric buses means a high capital cost for electrification and high utilization, resulting in a short payback time as much less expensive diesel fuel is used, after which national economies will begin to generate profit. Furthermore, investing in the scale-up of renewable energy generation and charging hub will provide low-cost energy and a better distribution network. Over time, this is then self-financed from reduced spending on fossil fuels.

4.2. Detailed analysis of Integrated and electrified transport system

The modeling results show that IETS scenario outperforms the other three scenarios in terms of costs and tailpipe GHG emissions. In terms of emissions, however, the study did not account for lifecycle emissions. The government's long-term goal is to restructure the entire public transport system in complete alignment with the metro line by replacing the bus fleet with electrified feeder service. For this, we further explore the IETS scenario, where the metro line is thoroughly analyzed, considering both expansion phases. The metro line will cover a total distance of approximately 26 km through 19 stations, which in the following sections will be referred to as "phase 1" (see Fig. 4). In the future, a north-south connection between the first section of the metro line will be extended to provide a direct connection to the airport, which, in this study, is referred to as phase 2 (see Fig. 4). For the first expansion stage, nineteen georeferenced stations were predetermined and taken from the Metro Express plans, and ten additional stations have been assumed for the second expansion stage. The selection was based on settlement areas and proximity to the airport.

Through a routing algorithm, **the future public transit network is conceptualized**. Using the bus electrification tool (TES), we replace the current bus network with electric buses. The energy demand is calculated for every bus line circulation depending on the kilometers driven. The charging infrastructure is assumed to be at the endpoints of a line, allowing for charging time during the scheduled breaks. Different bus configurations (table 6 in Appendix) are tested on the circulation to determine the optimal internal battery capacity. The criterion is the

---

[1] Interview carried out with the CEO and CTO of Rose-Hill Transport in June 2019.

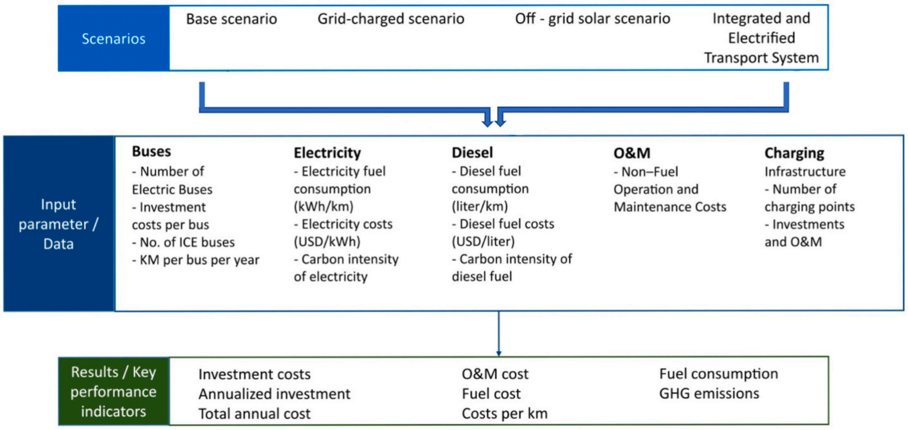


Fig. 3. Methodology of the study.

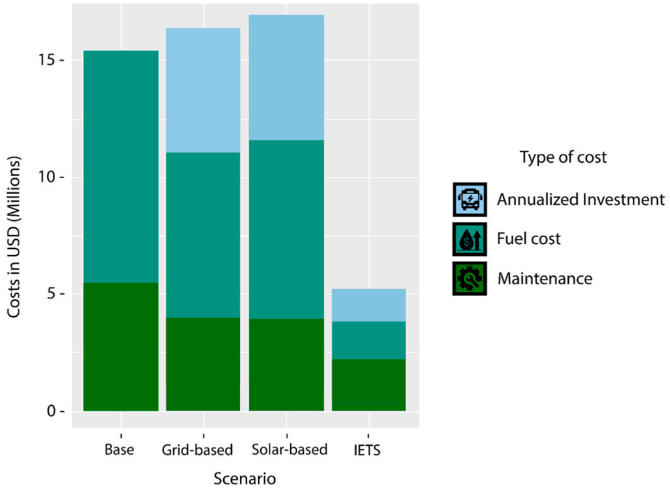


Fig. 4. Cost comparison of the scenarios.

minimal *State of Charge of the internal battery* during circulation.

Electric buses with internal batteries primarily have two charging methods. Firstly, plug-in charging using a connector and cable, usually in the depot overnight. Secondly, pantograph charging integrates charging with the operating time during the circulation and is done with special charging stations. Plug-in charging uses low charging powers of typically less than 150 kW pantograph charging, which, in contrast, requires a very high charging power of 450–600 kW.

The **full charge strategy** allows the electric bus to charge at each available opportunity at charging stations to its maximum charging level using the given break time as charging time. The strategy necessary charge minimizes the charging events by allocating charging times only when the State of Charge is too low for an entire journey completion. This, however, can exemplify a worst-case scenario in which charging stations are not operational due to technical difficulties. Therefore, the number of buses and charging stations is crucial information to determine the transition costs towards electric buses. We calculate the duration of a round journey from the start and back to the same point for every line. This information, combined with the intervals of each line scheduled to depart from the start point during the business hours (13 h), is then used to determine the number of buses needed to meet the daily demand. The charging infrastructure is assumed to be at every start and endpoint to ensure potential charging during the day. Charging stations at the depot are used as a backup possibility and overnight charging.

We then used the open-source **energy system optimizing tool SMOOTH to meet the energy demand of the transit fleet and its charging infrastructure**. The objective of the optimization is the lowest costs of electrifying public transport. For the energy system in Mauritius, an off-grid system is examined. As decision variables, the PV system's power potential and the battery storage capacity are selected. However, SMOOTH is highly sensitive to its input parameters, and minor variations can result in entirely different configurations. Therefore, the results must be considered as one possible configuration. To determine the PV power and battery capacity for the electricity demand of the transit fleet with the integrated metro line, the shares of the capacity of the PV system and the battery capacity in the total energy demand are calculated.

The **required energy demand can be calculated from the route length and the intervals**. In the case of the current transit fleet, the demand is calculated through TES at 460 GWh/a, and an hourly seasonal time series is generated, which is later used for the energy system design. In the case of the transit fleet with the metro line, with a consumption of 2 kWh/km, a demand of 263 MWh/a (phase 1, conservative) and 87 MWh/a (phase 1, ambitious) or 275 MWh/a (phase 1, conservative) and 92 MWh/a (phase 2, ambitious) is calculated. It can be seen that by replacing the current transit fleet with an additional metro line, the required route kilometers and energy consumption is significantly reduced by a factor of 1000. This is a heavy reduction of fuel and energy demand for bus services and a substantial reduction of street-based public transport through the introduction of the metro line and adapted optimized bus routes. Although the length of the metro line will almost double in phase 2, more routes will be needed for the feeder service, and therefore more energy demand for busses occurs (see Appendix for more details). In some cases, the feeder service has to make a slight detour to the metro line, resulting in more unique routes.

Assuming that every bus line has two charging stations at the start point and the endpoint, the current bus network requires 388 charging stations in total. Some lines may only need one charging station in the depot for overnight charging, but others need an extra one at the depot to get the buses functioning for the next day. **The number of charging stations can also be estimated** by assuming a distance at which charging stations are required. For opportunity charging, we assumed this distance to be 17 km, meaning that the current bus network of 6642 km requires 390 charging stations, roughly the same number as the first method. That means for the feeder services in phases 1 and 2, we use this approach to calculate the required charging stations with very robust results.

The analysis of the current bus lines in Mauritius shows that different bus providers cover the same routes, resulting in heavy road traffic. The whole bus fleet covers nearly three times the total road length of approx. 2000 km on Mauritius. Thus, one-to-one electrification amounts to high energy demand (460 GWh/a). With the implementation of the metro line, it makes sense to restructure the entire public transport system and use electrified buses, now functioning as a feeder service. The investigations show that even the installation of the metro line in the first phase can significantly reduce the route kilometers traveled of the bus fleet and thus in the energy volume (see table 4 in Appendix). The metro line extension over the entire North-South connection up to the airport means that additional parts of the routes can be entirely covered by bus in the first extension phase (Fig. 4). However, since parts of the bus lines are now being routed so that they reach the metro line relatively quickly, the route kilometers and the corresponding energy requirements of the electrified fleet only increase slightly.

The results of the optimization show that even if the current fleet is only electrified with a PV system (200 MW) and a battery system (490 MWh), the entire demand of the fleet can be covered at a low LCOE (10.79 ct/kWh). Furthermore, the demand can be met with significantly fewer PV systems capacity (40–120 kW) and battery storage capacity (100–300 kWh). Nevertheless, it should be noted that the energy requirements of the metro line were not included in the calculation of the PV and battery capacities.

In all systems, significant storage capacity is needed to store enough energy to meet the needs of the electrified fleet. Due to the high costs of the battery, the LCOE is also higher than the costs of the grid. Should an off-grid mini-grid be considered, it makes sense to connect further consumers to the grid to increase demand and thus reduce the LCOE. We consider the direct supply of the electrified busses with solar energy for supplying the busses with 100% renewable energy. More integrated and sophisticated energy supply scenarios for the transport system might reduce the LCOE at similar renewable shares.

In the IETS scenario, the simulation uses 100–150 kWh batteries to ensure a sufficient range to cover 100 km a day, making a fixed route schedule a necessity. To ensure optimization and lifespan, batteries should not be discharged to below 15%, and only be charged to 80% capacity. The e-buses will mostly charge overnight from the electricity grid (taking 5–6 h with a 125-kW charger). It must be kept in mind that simultaneously charging numerous buses will affect the electricity grid in that geographical area and require significant grid infrastructure upgrades. In the grid-based and solar-based scenarios, bus depots considering both the refueling of existing diesel buses and charging of the e-buses must be set up. Given their limited geographical land-use potential, space could be an issue because of the significant turning radius of buses. It should be considered together with land needs for bus depot rooftops, photovoltaic plants or offshore renewables floating technologies (Keiner et al., 2022).

In summary, the detailed view on the IETS scenario reveals that a systemic mobility transition is possible when different technological solutions work together. First, it is necessary to optimize routes and services to increase the overall efficiency of the public transport system. For the specific case of Mauritius, this means introducing the metro line for the main transport corridor in combination with centrally optimized bus feeder lines. For both metro and busses, full electrification – the second step - is needed to bring emission levels down. Finally, even zero emissions can be achieved when the electricity supply becomes 100% renewable as the third step.

4.3. Regulatory and policy implications for enabling electrified public transport

With electric buses, there is a greater need for the utility board - the Central Electricity Board (CEB) - to restructure their scheme thus far and allow commercial companies (and individuals) to install a corresponding capacity of grid-connected solar PV on net metering for each bus operated, beyond the current MSDG (or SSDG) allowance granted. Investment in green energy infrastructure and EV charging could become more attractive with reliable electricity demand from all-electric vehicles acting as an anchor load (Lukuyu et al., 2020). Due to the existing supply challenges, additional demand from e-buses will need to be met by additional, clean generation (likely distributed PV). This investment would act as positive feedback to reducing emissions.

Public support for the uptake of renewable energy and a more sustainable transition in Mauritius has increased with the Wakashio oil spill in August 2020. However, no transition will occur without addressing the particular challenges that the political economy of energy dependence places on small islands, which intertwines with the geopolitical (proxy, country's size and position) and the economic role they play. There also needs to be a more prominent alignment between energy security and climate change mitigation. While just as urgent, focus on environmental sustainability has been perceived as more important than questions of energy security. Our study shows that future investments have the potential to be more robust if there is coherence and integration of these two streams of policies, allowing smaller economies to make more efficient use of public funds. Also relevant is the critical examination of islands' geopolitical roles regarding international relations with existing complex power structures and assumptions behind energy policy decisions. Energy security means low vulnerability of vital energy systems (Cherp and Jewell, 2014), and the islands still face fuel shortages and black-outs regularly. Therefore, geopolitical security and energy security are seen as significant landscape threats.

The switch to an electrified fleet will also mean an automatic upgrade regarding the quality of public transit, as routes and vehicle dispatch time will be optimized concerning demand. Setting routes and bus depot locations also set locations for charging infrastructure. Public transit's more straightforward daily use profile (instead of private use) sets boundaries towards charging behavior and sets charging times to allow for maximum renewable energy integration. For this, there will also need to be more integration of different key stakeholders involved from the Ministry of Energy and Public Utilities, the National Transport Authority, the Mauritius Renewable Energy Agency, to name a few. These institutional bodies will have to work more in-silo for maximum usage of the limited national economy.

4.4. SIDS: Ideal candidates for escaping lock-in and policy coherence between energy security and environmental sustainability

Our study aims to guide decision makers in Mauritius and other SIDS. Although the 58 islands belonging to the SIDS are far from homogenous due to their varying territorial areas, governance systems, degree of economic development, and geographic features (Thomas and Lindo, 2019), certain features they share led to the UN defining them as a special group. These similar features have often been defined by the narrow resource base, dominance of economic sectors that are dependent on natural resources, limited industrial activity, geographical remoteness, and limited economies of scale. Also in their transport systems, SIDS show several similarities: their road configuration with the ring road along the coast, the main highway crossing the built infrastructure, smaller main road roads connecting all other towns, and sporadic highways to smaller, rural areas. Mauritius is chosen as a case study to represent the myriad islands and congested coastal cities faced with developmental issues, climate change issues, and an urgent need to kick-off their sustainable transition. For example, certain aspects of this study can be considered for the Maldives, where road transport, mainly buses, accounts for 23% of the diesel consumption (Keiner et al., 2022) and in this comparative case study of urban transport across SIDS (Khan and Gonzalez, 2021), the same issues are found.

Somewhat paradoxically, SIDS are both one of the most prominent symbols of the need for climate action and fossil fuel exploitation. There is a belief that, with the dramatic decline in the cost of renewables and the abundance of natural resources such as photovoltaics, it will be much easier for the developing world to decarbonize. However, one of the biggest challenges in the sustainable energy transition is likely to be precisely in developing countries, given the difficulties that many of these countries have in accessing and securing capital on the same terms (Ameli et al., 2021). The cost of capital is far higher in developing countries, owing to the enormous differences in everything from macroeconomic conditions to business confidence and legal infrastructure. Additionally, the SIDS face a variety of constraints in accessing international funding, such as through the Green Climate Fund. This is then combined with the high level of debts burdening the public finances of the SIDS; further reducing financial capacity available for climate change adaptation and mitigation projects. As the transformation towards low-carbon futures require tackling myriad crises simultaneously, this is an opportune moment to restructure financing structure for capacity building and large-scale projects struggling to find funding. Debt-for-swaps, cancellation, rescheduling, and suspension all offer synergistic interventions to boost commitment to cooperative climate finance, in alignment with the Paris Agreement which pledges to embed financial flows 'with a pathway towards greenhouse gas emissions and climate-resilient development' (Article 2.1(c)). Loan guarantees can also facilitate bridging this financial divide when coupled with low-carbon investment deemed as high-risks. As these guarantees tend to reduce default risk, these measures will enable institutions to lend to counterparties at reduced rates, at higher volumes and reducing the liquidity premium. A high liquidity premium hinders project feasibility due to the substantial amount of upfront capital required to set up mitigation measures. This is illustrated in our case study, where upfront investment in the off-grid solar-based and IETS scenarios are substantial compared to lifecycle investment.

Alongside our analysis of the decarbonization process of the public fleet, we explore the role that this reliance on fossil fuel has had on SIDS. The policy landscape integration and coherence between energy security and sustainability transition is insufficiently addressed at the governmental level. Fossil fuel imports, both for electricity and transport, comprise a large share of their GDP and limit their capacity for ability building. Fig. 6 (in the Appendix) presents the percentage of GDP the SIDS pay on fossil fuel imports, resulting in a vicious cycle of imported capital through loans and aid and imported fossil fuels (Niles and Lloyd, 2013). The current need for decarbonization of energy and transport sectors provides SIDS with an opportunity to break out of this cycle. Decreasing their reliance on imported energy and future financial support must aim to make the islands more self-sufficient in the medium to long term. Future decarbonization transition planning must emphasize capacity building, training, and institutional strengthening.

Most SIDS are found along the equatorial line; therefore, solar PV results in high generation output. For example, a sunny day in Mauritius sees a solar generation of 4450 $Wh/m^2.d$. When looking at SIDS, most of their emissions come from the energy and transport sector. This makes a case for phasing out diesel and gasoline in the transport sector and diesel fuel and fuel oil in the energy sector, paving the way for solar PV and wind and geothermal, biomass, and hydropower. The solar-based and IETS scenarios show that overall, increasing penetration of renewable technologies can lead to significant decreases in emissions and costs.

Driven by cost reductions, renewable electricity is increasingly cost-competitive with conventional thermal power plants. In some regions, RE cost is lower than running costs of existing fossil and nuclear power plants (Bogdanov et al., 2021), and solar PV has emerged as the least-cost source of electricity production in the history of humanity (Ram et al., 2018). Benefits of the RE system are not limited to radical declines in GHG emissions and low energy system costs but also lead to lower social costs and additional jobs (Teske et al., 2019; Jacobson et al., 2019). Thus, the opportunities for SIDS to decarbonize both energy and transport sectors improve with technological developments along with solar PV, battery systems, and electric vehicles. In addition, digitalization and optimized routing can significantly improve the service level of public transport. The suggested measures for Mauritius can be a blueprint for many other SIDS towards a more sustainable mobility future.

5. Conclusion

We mapped out Mauritius's current public transport system to identify the energy requirements for complete electrification. Thus far, existing literature and white papers offer unsubstantial insights into the electrification process. We seek to enhance the understanding in an open-access method and aim to point out what the individual islands under the SIDS umbrella can learn from each other and what they might still have to learn. By illustrating the long-term development of investments in low-carbon infrastructure, we aim to provide insights into the conjuncture of the process of electrification transition in terms of achieving fossil fuel independence.

Our study focused on the transportation sector, which contributes disproportionately to SIDS emissions and energy demands. The public transit system offers itself as some low-hanging fruits for decarbonization, but this requires planning and funding for large-scale and systemic changes to infrastructure and public choices. Our results allow for an overview of electrification investment scenarios for Mauritius. The present scenarios pathways for achieving decarbonization goals in the transport sector, split into an intermediate strategy and full electrification. We explored four scenarios to meet those goals with different combinations of parameters. We looked at electric buses to play a significant role in the global decarbonization transition. The buses release no tailpipe emissions, emit lesser noise pollution, and are cheaper to operate, requiring a substantial initial investment in charging infrastructure.

Additionally, electrification does not require a completely new infrastructure system but offers synergies with the existing electricity system; nevertheless, this still requires joining the two previously siloed systems. We find the electrification of the current public transport already offers emission reduction potential, especially when combined with on-site solar generation. But the real game-change is introducing an additional mode of transport – the metro line – for the main transport corridor. This is a significantly more efficient mode of transport compared to busses. It allows reducing the number of bus kilometers traveled by factor 1000 when using busses only in optimized feeder routes. Powering these busses in an integrated scenario offers emission and cost reductions. Due to the lack of data, we do not consider the energy requirements and costs of the metro line in this study. For future research, it would be interesting to explore metro cost data to obtain clearer insights. We also call for a more systematic approach to data collection in the SIDS as a critical enabler for the global transition, especially given the prevalence of informal and privately-owned "public transport".

With several SIDS already successfully introducing electric bus pilot projects, they can benefit more through synergies between sustainable public transit and other sustainable development goals such as further embedding the tourism sector and resilience goals in long-term planning. To achieve this, the islands need to break silos in governance, policy, implementation, and legislation. Simultaneously, novel financial instruments must be leveraged to restructure sustainable financing costs with lower costs of capital enabling and accelerating equitable low-carbon transitions. This will require the coordinated commitment of international donors, as envisaged under the Paris Agreement, by enabling SIDS to access the global capital markets at lower interest rates and longer maturity periods.

With transport in SIDS becoming increasingly privatized, inequities in access to transportation will become a significant social justice issue. Individual (and electrified) transportation remains accessible for the privileged, while lower levels of accessibility and difficulties in commuting fall to low-income communities. Investment in radical transformation of the transport system, from mass transit to electrification and shared vehicles, is a necessary disrupter. An upheaval of the public transit system on SIDS has the potential to curb growing inequalities within the SIDS population without mentioning wellbeing and environmental health. We urge leaders to recognize that restructuring transport planning, technologies, and investment is a monumental opportunity to connect accessibility, economic justice, and climate mitigation.

Author contributions

Zakia Soomauroo: Conceptualization, Methodology, Investigation, Resources, Writing – original draft, Writing – review & editing, Visualization. **Philipp Blechinger:** Methodology, Investigation, Resources, Writing – review & editing. **Felix Creutzig:** Conceptualization, Methodology, Validation, Writing – review & editing, Supervision.

Funding

This material has been produced under the Climate Compatible Growth programme, which is funded by UK aid from the UK government. However the views expressed herein do not necessarily reflect the UK government's official policies.

Declaration of competing interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Acknowledgments

Z.S. acknowledges the financial support of the Reiner Lemoine Foundation and the TUB PAS scholarship.

The authors are grateful to Aneeque Javaid, Christoph Muschner and Oskar Kirsch for useful feedback on the manuscript.

Appendix

Table 1
Assumptions

Parameters	Sources
Cost of electric bus	Zhongtong shiteng series pure electric Customized city bus[1]
Km per bus per year	Bus electrification tool
Electric fuel consumption (kWh/km)	Smooth model
Electricity costs (USD/kWh)	Industry tariff Mauritius
Diesel fuel consumption (liter/km)	https://www.motor-talk.de/forum/was-verbraucht-ein-bus-nahverkehr-innenstadt-auf-100-km-t1724289.html
Diesel fuel costs (USD/liter)	Mauritius Energy
Non-fuel O&M electric buses	2% CAPEX
Non-fuel O&M conventional buses	2% CAPEX
Number of charging points	Smooth model
Investment costs per charging point	Zhongtong shiteng

1 The Rose-Hill Transport bus company currently has two electric buses; our assumptions are based on the parameters of those buses.

Table 2
Parameters used in greenhouse gas emission reduction calculation

Parameters	Unit
Average distance traveled by vehicles	38,000 km/year (Base, Off-Grid, Solar) 141,985 km/year (IETS)
Passenger occupancy	35
Fuel density	0.85
Fuel intensity	0.0368 L(diesel)/tonne.km

Table 3
Speed limit of the different road types in Mauritius

Road Type	Speed Limit
Town and city	40 km/h
Open roads	80 km/h
Motorways	110 km//h

Table 4
Three exemplary bus lines of the current transit system and the respective energy demand

Bus line	Length	Interval	Energy demand
Route Nr. 133	72 km	40 min	143 kWh
Route 1A	44 km	9 min	88 kWh
Route Nr. 194	28 km	25 min	56 kWh

Table 5 shows the route length both with and without taking into account the intervals of the current transit fleet and the feeder service with the metro line in phase 1 and phase 2.

Table 5
Route lengths

	Current transit fleet	Phase 1	Phase 2
Without interval consideration	6642 km	1487 km	1639 km
With interval consideration (conservative)	629,514 km	131,644 km	137,967 km
With interval consideration (ambitious)	629,514 km	43,978 km	45,875 km

Table 6
Bus configurations for electric buses

Bus configuration	Capacity in kWh	Charge type	Charge power in kW	Consumption in kWh/km
1	120	Pantograph	350	2
2	150	Pantograph	450	2
3	395	Plug-in	150	2
4	292	Plug-in	150	2
5	440	Plug-in	150	2
6	350	Pantograph	300	2
7	288	Pantograph	450	2

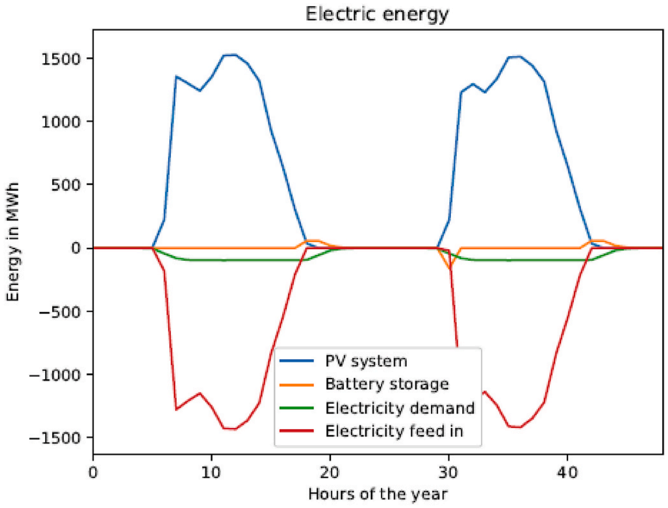


Fig. 5. Grid stability of electrification

Table 7
Percentage of the interval of the current transit fleet in Mauritius

Interval	Percentage of bus lines
3–10 min	16%
10–30 min	49%
30–60 min	31%
60–120	5%

The required power of the PV system is calculated to approximately 115 kW (phase 1, conservative), approximately 40 kW (phase 1, ambitious) while the results for the second phase is 120 kW (phase 2, conservative) and 40 kW (phase 2, ambitious) respectively and the capacity of the battery storage is calculated to circa 285 kWh (phase 1, conservative) and 95 kWh (phase 1, ambitious) respectively and 300 kWh (phase 2, conservative) and 100 kWh (phase 2, ambitious) respectively.

Table 8
Required power of the PV system calculation

Type of feeder service	PV system power requirements
Phase 1, conservative	115 kW
Phase 1, ambitious	40 kW
Phase 2 conservative	120 kW
Phase 2, ambitious	40 kW

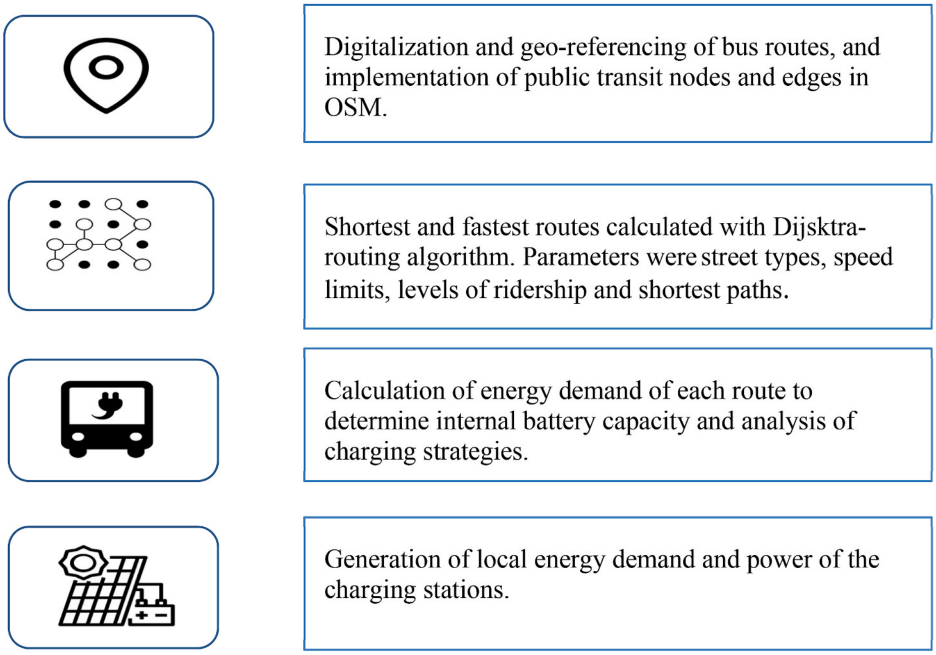
Table 9
Capacity of battery storage

Phase 1, conservative	285 kWh
Phase 1, ambitious	95 kWh
Phase 2 conservative	300 kWh
Phase 2, ambitious	100 kWh

IETS in-depth Methodology

For the IETS scenario building, we took the following steps:

The simulation framework is composed of distinct elements interacting among each other, with different input data and objectives. In order to calculate the energy requirements for a complete electrification, input data regarding the distance of the routes between the respective bus stations and the frequency of the buses is essential. Yet, for the current bus lines in Mauritius, these were not centrally digitalized nor made publicly available, of which the detailed steps are given in the Appendix. Fig. 4 provides a graphical representation behind our IETS scenario.



Digitalization and geo-referencing of bus routes, and implementation of public transit nodes and edges in OSM.

Shortest and fastest routes calculated with Dijsktra-routing algorithm. Parameters were street types, speed limits, levels of ridership and shortest paths.

Calculation of energy demand of each route to determine internal battery capacity and analysis of charging strategies.

Generation of local energy demand and power of the charging stations.

Since the integration of the metro line will make the demands of the overlapping routes from the current bus network obsolete, it is essential to reexamine the current bus routes and to reconstruct the network to ensure maximum optimization in meeting demand with interplay with the metro line. Bus lines can instead work as a feeder service for the metro line, and in turn, improving accessibility to public transport for more people. To take this into account, commuter traffic is considered. This data specifies the number of people commuting from one village area council (VCA) to another point. The VCA were then weighted according to their population density, in order to extract the starting and end points of commuter routes from this information. The weighting thus indicates a georeferenced point. A routing algorithm is then used to find the fastest route for the first and second phase of the implementation of the metro line.

Steps taken for the bus electrification

For the current bus lines in Mauritius, which are not centrally digitalized and made publicly available, the following steps were undertaken:

1. Visualizing the bus route numbers, the individual bus stations and the intervals names of the individual bus lines and the respective bus stations with their intervals and durations from
2. Georeferencing the individual bus stations via names with the batchgeo plug-in
3. Converting the resulting KML files (with the geographic annotation and visualization) into a shape file in order to generate the longitude and latitude of each bus station
4. Routing between the individual bus stations to obtain a bus line with its kilometers, using open-source python packages

Routing algorithm

The routing algorithm requires a line graph of the total street network. Data from OpenStreetMap (OSM) database classified the different road network into typologies of specific street type (residential road, agricultural road, highway, etc.). For each edge of the respective road, we implement attributes such as the maximum speed limit, road length, and the time a vehicle needs for this edge depending on the speed limit of the respective road type (see Appendix). The metro line is given preference over the road network by the routing tool. Therefore, it allocates a speed limit of 200 km/h, which is then specified as an attribute to the metro line and its edges.

The resulting two weighted graphs, (i) solely for the street network and, (ii) for the street network with the integrated metro line (Phase 1 and 2 respectively), are used to route the current bus lines and commuter routes using the Dijkstra-routing algorithm. Parallel bus lines within the commuter routes using the same routes which are integrated into one bus line in order to reduce the traffic volume and create a seamless traffic flow.

To determine the time intervals for the feeder fleet with the metro line, the percentage of intervals depending on the kilometers per route is taken from the current transit fleet in Mauritius and transferred to the simulated scenario with the metro line. A conservative scenario (lower boundary of the interval) and an ambitious scenario (upper boundary of the interval) are considered (see table 3).

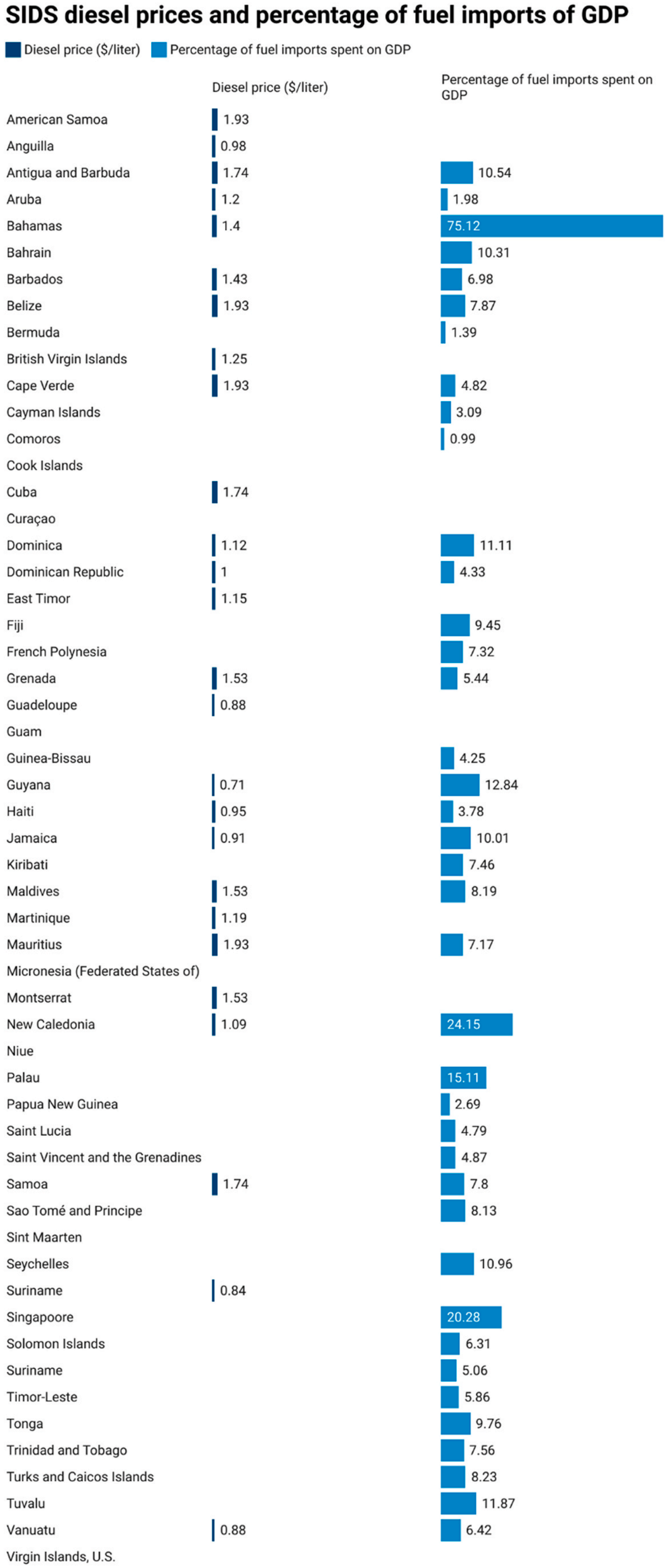


Fig. 6. SIDS diesel prices and percentage of fuel imports of GDP

References

Ameli, N., et al., 2021. Higher cost of finance exacerbates a climate investment trap in developing economies. Nat. Commun. 12, 4046.

Atteridge, A., Savvidou, G., 2019. Development aid for energy in small island developing states. Energy Sustain. Soc. 9, 10.

Atteridge, A., Verkuijl, C., Dzebo, A., 2020. Nationally determined contributions (NDCs) as instruments for promoting national development agendas? An analysis of small island developing states (SIDS). Clim. Pol. 20, 485–498.

Azzuni, A., Breyer, C., 2018. Definitions and dimensions of energy security: a literature review. WIREs Energy Environ. 7, e268.

Betzold, C., 2010. 'Borrowing' power to influence international negotiations: AOSIS in the climate change regime, 1990–1997. Politics 30, 131–148.

Blechinger, P., et al., 2016. Global analysis of the techno-economic potential of renewable energy hybrid systems on small islands. Energy Pol. 98, 674–687.

Bogdanov, D., et al., 2021. Low-cost renewable electricity as the key driver of the global energy transition towards sustainability. Energy, 120467. https://doi.org/10.1016/j.energy.2021.120467.

Cherp, A., Jewell, J., 2014. The concept of energy security: beyond the four as. Energy Pol. 75, 415–421.

Collett, K.A., Byamukama, M, Crozier, C, McCulloch, M. Energy and Transport in Africa and South Asia. GOV.UK https://www.gov.uk/research-for-development-outputs/energy-and-transport-in-africa-and-south-asia..

Creutzig, F., et al., 2015. Transport: a roadblock to climate change mitigation? Science 350, 911–912.

Creutzig, F., et al., 2016. Urban infrastructure choices structure climate solutions. Nat. Clim. Change 6, 1054–1056.

Cross-Call, D.F., 2013. Matching Energy Storage to Small Island Electricity Systems : a Case Study of the Azores. Massachusetts Institute of Technology.

de Águeda Corneloup, I., Mol, A.P.J., 2014. Small island developing states and international climate change negotiations: the power of moral "leadership". Int. Environ. Agreements Polit. Law Econ. 14, 281–297.

Dodds, P.E., McDowall, W., 2014. Methodologies for representing the road transport sector in energy system models. Int. J. Hydrogen Energy 39, 2345–2358.

Dorotić, H., et al., 2019. Integration of transport and energy sectors in island communities with 100% intermittent renewable energy sources. Renew. Sustain. Energy Rev. 99, 109–124.

Dreier, D., 2020. Transition Technologies for Electrification and Optimisation of Bus Transport Systems.

Enoch, M.P., 2003. Transport practice and policy in Mauritius. J. Transport Geogr. 11, 297–306.

Environment, U.N., 2020. Global Trade in Used Vehicles Report. UNEP - UN Environment Programme. http://www.unep.org/resources/report/global-trade-used-vehicles-report.

Final Report on DTI-defra scenarios and sensitivities, using the UK MARKAL and MARKAL-MACRO energy system models. http://www.ukerc.ac.uk/publications/final-report-on-dti-defra-scenarios-and-sensitivities-using-the-uk-markal-and-markal-macro-energy-system-models.html.

Fisch-Romito, V., Guivarch, C., Creutzig, F., Minx, J.C., Callaghan, M.W., 2020. Systematic map of the literature on carbon lock-in induced by long-lived capital. Environ. Res. Lett. https://doi.org/10.1088/1748-9326/aba660.

García-Olivares, A., Solé, J., Osychenko, O., 2018. Transportation in a 100% renewable energy system. Energy Convers. Manag. 158, 266–285.

Gay, D., Rogers, T., Shirley, R., 2018. Small island developing states and their suitability for electric vehicles and vehicle-to-grid services. Util. Pol. 55, 69–78.

Government of Mauritius, 2018. Road Transport and Road Traffic Accident Statistics. Island of Mauritius.

Grosso, D., Gerboni, R., Cotugno, D., 2017. Modelling urban transport sector: a methodology based on OSeMOSYS model generator. In: 2017 IEEE 41st Annual Computer Software and Applications Conference (COMPSAC), vol. 2, pp. 754–759.

Hiselius, L.W., Rosqvist, L.S., 2016. Mobility Management campaigns as part of the transition towards changing social norms on sustainable travel behavior. J. Clean. Prod. 123, 34–41.

INDC - submissions. https://www4.unfccc.int/sites/submissions/INDC/Submission%20Pages/submissions.aspx.

Jacobson, M.Z., et al., 2019. Impacts of green new deal energy plans on grid stability, costs, jobs, health, and climate in 143 countries. One Earth 1, 449–463.

Javaid, A., Creutzig, F., Bamberg, S., 2020. Determinants of low-carbon transport mode adoption: systematic review of reviews. Environ. Res. Lett. 15, 103002.

Jetten, J., Mols, F., Selvanathan, H.P., 2020. How economic inequality fuels the rise and persistence of the Yellow vest movement. Int. Rev. Soc. Psychol. 33, 2.

Keiner, D., et al., 2022. Powering an island energy system by offshore floating technologies towards 100% renewables: a case for the Maldives. Appl. Energy 308, 118360.

Khan, Urwah, Gonzalez, Juan, 2021. Urban transportation systems in selected small developing island states: a comparative analysis. In: Frontiers in High-Speed Rail Developmen. Asian Development Bank Institute.

Klinsky, S., Mavrogianni, A., 2020. Climate justice and the built environment. Build. Cities 1, 412–428.

Kougias, I., Nikitas, A., Thiel, C., Szabó, S., 2020. Clean energy and transport pathways for islands: a stakeholder analysis using Q method. Transport. Res. Part Transp. Environ. 78, 102180.

Lah, O., Fulton, L., Arioli, M., 2019. Chapter 3 - decarbonization scenarios for transport and the role of urban mobility. In: Lah, O. (Ed.), Sustainable Urban Mobility Pathways. Elsevier, pp. 65–80. https://doi.org/10.1016/B978-0-12-814897-6.00003-X.

Laizāns, A., Graurs, I., Rubenis, A., Utehin, G., 2016. Economic viability of electric public busses: regional perspective. Procedia Eng. 134, 316–321.

Lamb, W.F., et al., 2020. What are the social outcomes of climate policies? A systematic map and review of the ex-post literature. Environ. Res. Lett. 15, 113006.

Lammers, K., Bertheau, P., Blechinger, P., 2020. Exploring requirements for sustainable energy supply planning with regard to climate resilience of Southeast Asian islands. Energy Pol. 146, 111770.

Le Quéré, C., et al., 2020. Temporary reduction in daily global CO 2 emissions during the COVID-19 forced confinement. Nat. Clim. Change 10, 647–653.

Liao, Y., Gil, J., Pereira, R.H.M., Yeh, S., Verendel, V., 2020. Disparities in travel times between car and transit: spatiotemporal patterns in cities. Sci. Rep. 10, 1–12.

Long-term strategies in SIDS: blueprints for decarbonised and resilient 1.5°C compatible economies. https://climateanalytics.org/publications/2021/long-term-strategies-in-sids-blueprints-for-decarbonised-and-resilient-15c-compatible-economies/.

Lovelace, R., 2021. Open source tools for geographic analysis in transport planning. J. Geogr. Syst. https://doi.org/10.1007/s10109-020-00342-2.

Lukuyu, J., Muhebwa, A., Taneja, J., 2020. Fish and chips: converting fishing boats for electric mobility to serve as minigrid anchor loads. In: *Proceedings of the Eleventh ACM International Conference on Future Energy Systems* 208–219. Association for Computing Machinery. https://doi.org/10.1145/3396851.3397687.

Medina Warmburg, B., 2006. Sustainable energy for islands: opportunities versus constraints of a 100%Renewable electricity systems. El Hierro (Canary Islands) and Flores (Azores) case studies.

Milan, B.F., Creutzig, F., 2017. Lifting peripheral fortunes: upgrading transit improves spatial, income and gender equity in Medellin. Cities 70, 122–134.

Modelling Transport, fourth ed. | Wiley. Wiley.com https://www.wiley.com/en-us/Modelling+Transport%2C+4th+Edition-p-9780470760390..

Monioudi, I.N., et al., 2018. Climate change impacts on critical international transportation assets of Caribbean Small Island Developing States (SIDS): the case of Jamaica and Saint Lucia. Reg. Environ. Change 18, 2211–2225.

Mugion, R.G., Toni, M., Raharjo, H., Di Pietro, L., Sebathu, S.P., 2018. Does the service quality of urban public transport enhance sustainable mobility? J. Clean. Prod. 174, 1566–1587.

Niles, K., 2013. Energy Aid in Caribbean and Pacific Small Island Developing States (SIDS). University of Otago.

Niles, K., Lloyd, B., 2013. Small island developing states (SIDS) & energy aid: impacts on the energy sector in the caribbean and pacific. Energy Sustain. Dev. 17, 521–530.

Ourbak, T., Magnan, A.K., 2018. The Paris Agreement and climate change negotiations: small Islands, big players. Reg. Environ. Change 18, 2209–2209.

Prasad, R.D., Bansal, R.C., Raturi, A., 2017. A review of Fiji's energy situation: challenges and strategies as a small island developing state. Renew. Sustain. Energy Rev. 75, 278–292.

Raghoo, P., Jeetah, P., Surroop, D., 2017. Lifelong learning (LLL) for energy practitioners in small island developing states (SIDS): the pivotal role of education in energy efficiency and demand side management. In: Leal Filho, W. (Ed.), Climate Change Adaptation in Pacific Countries: Fostering Resilience and Improving the Quality of Life. Springer International Publishing, pp. 353–368. https://doi.org/10.1007/978-3-319-50094-2_22.

Raghoo, P., et al., 2018. Dimensions of energy security in small island developing states. Util. Pol. 53, 94–101.

Ram, M., et al., 2018. A comparative analysis of electricity generation costs from renewable, fossil fuel and nuclear sources in G20 countries for the period 2015-2030. J. Clean. Prod. 199, 687–704.

Republic of Mauritius- the public transport system needs to be modernised, says mr bodha. http://www.govmu.org/English/News/Pages/The-Public-Transport-System-needs-to-be-modernised,-says-Mr-Bodha.aspx.

Republic of Mauritius- renewable energy roadmap 2030 for the electricity sector launched. http://www.govmu.org/English/News/Pages/Renewable-Energy-Roadmap-2030-for-the-electricity-sector-launched.aspx.

Romano, A.A., Scandurra, G., Carfora, A., Pansini, R.V., 2016. Assessing the determinants of SIDS' pattern toward sustainability: a statistical analysis. Energy Pol. 98, 688–699.

Ronan, I.T.F., 2021. Transport outlook 2021. ITF. https://www.itf-oecd.org/itf-transport-outlook-2021.

Shah, K. U., Awojobi, M. & Soomauroo, Z. Electric vehicle adoption in small island economies: review from a technology transition perspective. WIREs Energy Environ.. n/a, e00432..

Segurado, R., Costa, M., Duić, N., Carvalho, M.G., 2015. Integrated analysis of energy and water supply in islands. Case study of S. Vicente, Cape Verde. Energy 92, 639–648.

Shah, K.U., et al., 2016. Editorial: special issue on energy policy for the future of small island developing states (SIDS). Energy Pol. 98, 650–652.

Soomauroo, Z., Blechinger, P., Creutzig, F., 2020. Unique Opportunities of Island States to Transition to a Low-Carbon Mobility System, p. 18.

Statistics Office, Government of Mauritius, 2019. Energy and water statistics. https://statsmauritius.govmu.org/Pages/Statistics/ESI/Energy_Water/Energy_Water_Yr19.aspx.

Statistics Office, Government of Mauritius, 2020. Energy and water statistics. https://statsmauritius.govmu.org/Pages/Statistics/ESI/Energy_Water/Energy_Water_Yr20.aspx.

Surroop, D., Raghoo, P., Wolf, F., Shah, K.U., Jeetah, P., 2018. Energy access in small island developing states: status, barriers and policy measures. Environ. Dev. 27, 58–69.

Teske, S., Nagrath, K., Morris, T., Dooley, K., 2019. Renewable energy resource assessment. In: Teske, S. (Ed.), Achieving the Paris Climate Agreement Goals: Global and Regional 100% Renewable Energy Scenarios with Non-energy GHG Pathways for +1.5°C and +2°C. Springer International Publishing, pp. 161–173. https://doi.org/10.1007/978-3-030-05843-2_7.

Thomas, A., Lindo, S., 2019. Disappearing Islands: Small Island Developing States and Climate Change.

Transport — IPCC. https://www.ipcc.ch/report/ar5/wg3/transport/.

Tyedmers, E., et al., 2020. Sustainable development opportunities in small island nations: a case study of the Cook Islands. J. Clean. Prod. 277, 123045.

Ueckerdt, F., et al., 2021. Potential and risks of hydrogen-based e-fuels in climate change mitigation. Nat. Clim. Change 11, 384–393.

UNFCCC, S., 2005. Climate Change, Small Island Developing States. Climate Change Secretariat Bonn.

Urbanization and Climate Change in Small Island Developing States | UN-Habitat. https://unhabitat.org/urbanization-and-climate-change-in-small-island-developing-states ..

van Vuuren, D.P., et al., 2017. Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. Global Environ. Change 42, 237–250.

Vencataya, L., Pudaruth, S., Dirpal, G., Narain, V., 2018. Assessing the causes & impacts of traffic congestion on the society, economy and individual: a case of Mauritius as an emerging economy. Stud. Bus. Econ. 13, 230–242.

Wolf, F., Surroop, D., Singh, A., Leal, W., 2016. Energy access and security strategies in small island developing states. Energy Pol. 98, 663–673.

Wong, P.P., 2011. Small island developing states. WIREs Clim. Change 2, 1–6.