European Transport \ Trasporti Europei (2023) Issue 95, Paper n° 1, ISSN 1825-3997

https://doi.org/10.48295/ET.2023.95.1

Preliminary Assessment for a Sustainable and Integrated Solar-Powered Transport System in Asmara – Eritrea

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Abstract

As a result of the new political stability achieved among Eritrea and Ethiopia, even though not completely consolidated after one year from the peace signed on 8 July 2018, the role of Asmara, the Eritrean capital, is under investigation to understand its potential impact on the economic and technological development of the Horn of Africa. In a region such as the Sub-Saharan one, the main challenge in energy is to guarantee a reliable electric grid based on Renewable Energy Sources (RESs). This paper proposes the development of an integrated urban mobility plan in Asmara, monitored by a performance analysis, and then it was simulated to power the service exclusively by a microgrid provided by photovoltaic panels using the software Homer pro, to sustain the demographic and economic growth of the city. From the analysis carried out, the implementation of the service required 52 e-buses, 2 e-minibuses, 7 e-taxis and 50 e-bikes. Furthermore, to economically and environmentally maintain the Project, a PV (Photovoltaic) plant with a surface area of 94,972 m2, equipped with a rated capacity of 4,966 kW. Furthermore, energy will be available at 0.1547 $/kWh. The aim of this work is to propose a future scenario of electric mobility enhancement for developing countries, evaluating their evolution over time to offer an efficient and suitable service throughout the city of Asmara.

Keywords: Sustainable Mobility; e-Mobility; Smart mobility; Transportation Planning; e-Vehicles; Microgrid; Asmara; Rural Transport; Photovoltaic panels.

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1. Introduction

Transport systems for people and goods are considered essential for the economic growth and welfare of a country and for the quality of life in urban areas; in this perspective, transportation and mobility systems are part of social cohesion and demographic development.

From a spatial and quantitative point of view, urban areas can be considered the "engine" of an area's employment and economic growth. In many cities, due to the extensive economic activities in urban areas, issues related to or caused by transport such as congestion, air pollution, safety and noise pollution are addressed and managed. For example, it is estimated that about 73% of European citizens lived in urban areas in the year 2010; by 2050 this percentage is expected to increase to more than 80%. Urban transport can on the one hand have direct impacts on traffic and on the other influence social development, social exclusion, and accessibility for people with reduced mobility. Adopting sustainable transportation systems today has become a global goal that can no longer be postponed (European Commission, 2017).

From a quantitative point of view, CO_2 emissions from road, air, sea, rail and other modes are estimated to account for 71.7%, 13.9%, 13.4%, 0.5% and 0.5% of emissions, respectively.

Different decarbonization policies for the transport and mobility sector implemented at different levels enable climate and environmental protection on the one hand and economic and social balance on the other (Carnevale & Sachs, 2019; European Environment Agency, 2019).

On the regulatory side, the European Council has approved an ambitious target affecting the countries of the European Union: the idea is to become climate neutral by 2050 and especially to reduce greenhouse gas emissions by at least 55 percent by the year 2030. (Directive 2014/94/Eu Of The European Parliament And Of The Council - of 22 October 2014 - on the Deployment of Alternative Fuels Infrastructure -, 2014; European Commission, 2017a, 2017b, 2018).

As anticipated in the previous paragraphs, the ability to easily access different types of services, such as public transportation or efficient telecommunication networks, can bring certain benefits to the community including accessibility to markets, increased connectivity of regions or, more generally, of an area and thus promote its economic development. Thus, over the past decade, community policies have increased national and local efforts to reduce air pollution; this has led to the establishment and adoption of regulatory policies in the areas of transportation and mobility, energy, and economic development (EASO – European Asylum Support Office, 2016; *OECD Regions and Cities at a Glance 2022*, 2022).

More broadly, the area of mobility can be seen as a key factor in our economic and social life; these factors include, for example, daily commuting to work, meeting family and friends, promoting tourism, to the management and operation of supply chains for goods that need to reach stores and for our industrial production. (European Commission, 2021)

Transport systems and people and goods mobility are therefore strongly interconnected concepts, just as the concept of smart mobility is often associated with the concept of smart cities. Smart mobility is a relatively young concept in the context of mobility systems that, over the past decade, has covered policies of both public and private organizations. Today it is difficult to provide a common definition of smart mobility because the topic of smart mobility is interdisciplinary and can involve several elements: smart mobility is about i) vehicle technology, ii) Intelligent Transport Systems (ITS), iii) data, iv) mobility services (Docherty et al., 2018; Jeekel, 2017; Wockatz & Schartau, 2015).

In this perspective, smart mobility outlines scenarios where mobility will be framed as a personalized service available on demand - MaaS (Mobility as a Service) where people will have access to a clean, green, efficient, and flexible transportation system to meet all their needs (Centre for the Fourth Industrial Revolution Japan, n.d.; Utriainen & Pöllänen, 2018).

A further issue relates to rural mobility; over the years rural mobility has received much less attention from policy makers than urban mobility: in many cases there is a lack of conventional transport on the one hand, and on the other the various shared mobility solutions that are spreading in urban areas. In most cases rural areas are served by few buses and in a few cases rail services are used; the most common mode of transport is the car (Campisi et al., 2021; Zheng et al., 2019a; Zhou et al., 2015; Ventura et al. 2022).

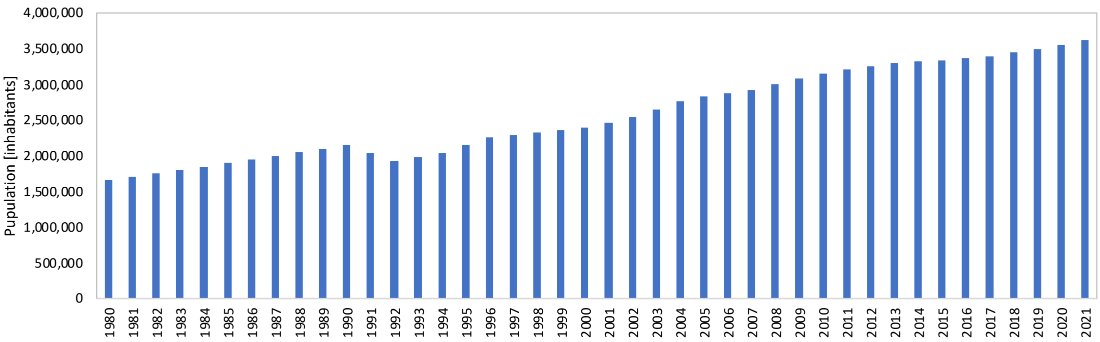
This situation forces people to spend more on travel and use private transport at the expense of more sustainable alternatives. In rural areas, public transport represents a lifeline for certain categories of users including the elderly, young people, tourists, and those who are economically marginalized. (Šipuš & Abramović, 2017; Velaga et al., 2012) The low population density in rural regions often translates into fewer economic and social opportunities, which are found in urban areas: it follows that transportation plays an essential role for the community. In this sense, low population density in rural areas presents important challenges for the economic sustainability of collective transport for the mobility of people and goods.

African cities are growing faster than in any other region in the world (Figure 1a). By 2050, 60% of people in Africa will lives in urban areas and nowadays infrastructures, city services and transit aren't able to keep the pace with this growth. To highlight this infrastructural problem, Figure 1b shows the rate of electrification, which has not yet reached values above 60%. The hugest investments in transportation are related to road construction, even though the large part of Africans does not own cars, instead people must rely on inconsistent, informal, and often dangerous modes of public transport. Different countries began to launch different new sustainable mobility projects since 1998, when IDTP (Institute for Transportation and Development Policy) introduces Afribike, a program in South Africa to distribute bikes to poor communities and healthcare workers. This paved the way for the Access Africa program, which has assisted thousands of people with opportunities for work, education, and improved access to essential services such as to health clinics. Over the years, IDTP Africa has worked with cities in designing and implementing high quality Bus Rapid Transit (BRT) systems, bike networks and pedestrian projects.

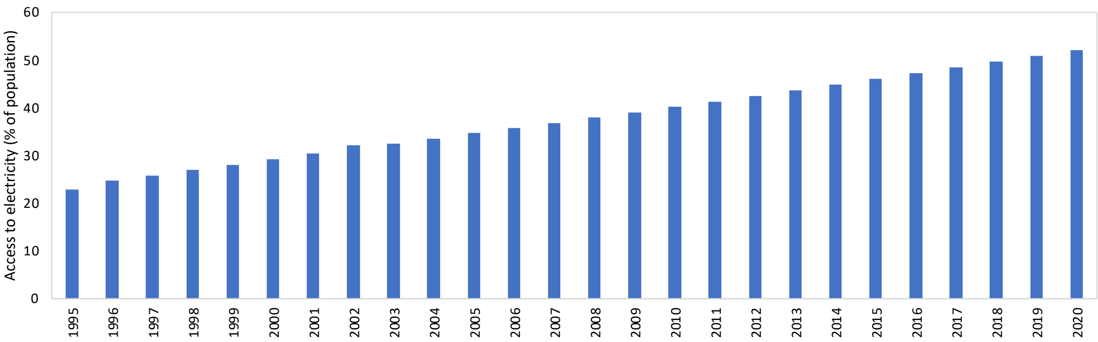
Several countries have promoted and implemented new sustainable mobility projects since the year 1998; in fact, in this year the IDTP (Institute for Transportation and Development Policy) introduced Afribike, which effectively represents a program of South Africa to distribute bicycles to poor communities and health workers. Afribike enabled the planning and implementation of the Access Africa program with the goal of providing thousands of people with employment opportunities, education, and better access to essential services such as health facilities. Over the years, IDTP Africa has worked synergistically with several cities to design and implement high-quality bus rapid transit (BRT) systems, bicycle and pedestrian networks.

After these partnerships, many governments started to interparent a non-motorized policy, helping the diffusion of means of transport without any motor and unable to pollute on the whole Africa. Similarly, to reduce CO_2 emissions, and invert the negative trend shown in Figure 1c, a lot of African countries are starting to develop electrical last mile vehicles (bike, motorbike, and tricycles); in urban areas to reduce traffic issues and in rural areas to overcome distances between major cities, thereby also boosting the economy and increasing the quality of life. In the same way, this project, focusing on Asmara, wants to help the development of Eritrea, following the trends marked by the other countries in the region.

The current mobility situation in Asmara, the capital of Eritrea, is based on taxi and minibus for tourists, while the locals use mainly public buses or private means of transport like cars or bikes. The use of outdated vehicles, with a high pollution rate, can lead this city to a bad air quality, in fact following the World Health Organization data, the Air Quality Index (AQI) of Asmara reaches values over 100 AQI, a significant value meaning an unhealthy air quality for sensitive groups (The world bank-data, 2017).



(a)



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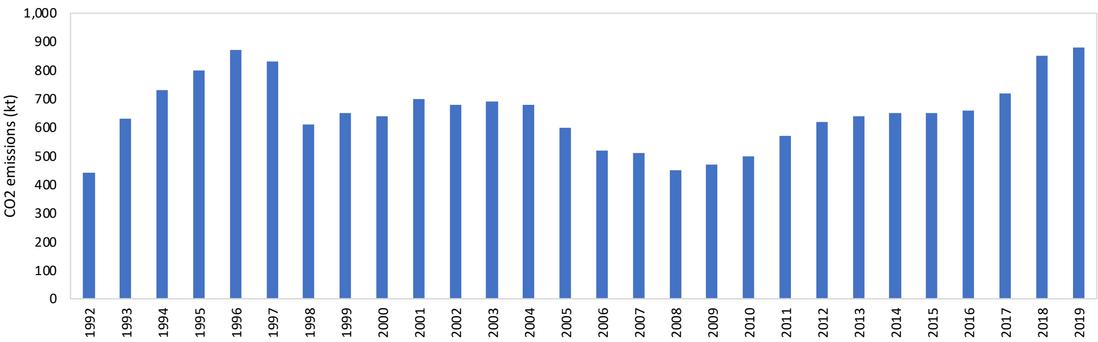

(c)

Figure 1: Some information about a) Population, b) Access to electricity, c) CO_2 emissions of Eritrea.

Source: a) Population, b) Access to electricity, c) CO_2 emissions, Eritrea, Sub-Saharan Africa, World Bank Group Archives, Washington, D.C., United States.

The main goal of this study is to support the development of a sustainable mobility model in Eritrea (Sub-Saharan Africa-SSA). This need arises, analyzing the current situation in the country, from the increase in population and its shift towards the main urban areas, generating new socio-economic scenarios in the territory. To achieve the goal described above, it is considered important to increase the rate of electrification both in terms of the electrical grid and transport systems as shown in Figure 2. To date, in fact, in Sub-Saharan Africa, approximately 47.9% of the population has access to electricity, and Eritrea is in this situation. Focusing on Asmara, the present work is organized as follow:

- *Section II* in which sustainable mobility in rural countries is analyzed.
- *Section III* describes the current transport system in Eritrea with a focus in Asmara.
- *Section IV* proposes a new transportation system considering features and performance's evaluation.
- *Section V* refers to an implementation of new different mobility scenarios.
- *Section VI* studies a possible sustainable energy production (solar systems) to supply the new scenarios identified in the Section V.
- *Section VII*, Conclusions and Future developments of the work are presented in the end of the work.

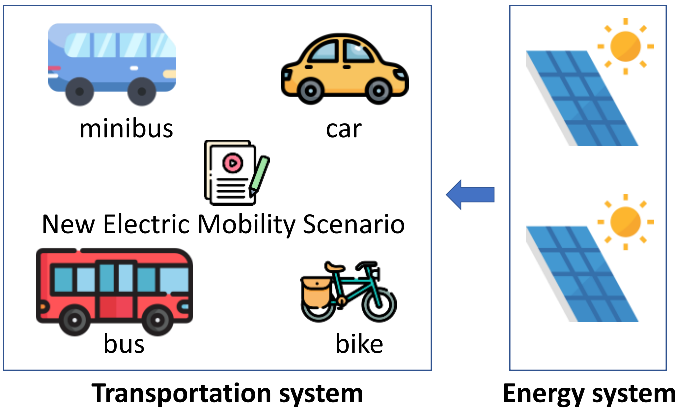

Figure 2: Overview of the work.

2. Background

This section discusses the topic of transportation planning and mobility systems on the one hand and the more specific topic of transportation planning in rural areas on the other.

The implementation of a new transportation system for people and/or goods necessarily involves a planning activity. As anticipated in previous section, a transportation system can be defined as a set of elements and their interactions that generate (Natasha Smithson, 2018):

- the transport demand (need for mobility) within a territory
- the transportation infrastructure and services to satisfy this demand (need).

The notions of transport and mobility also evoke the concept of territory: transportation and territory are strongly connected and above all interdependent; from a logical point of view, the territory influences the transport system and vice versa.

As mentioned above a transport system can therefore be composed of two elements: transport demand and transport supply. Demand for transportation is related to the mobility needs of a group of people in an area (e.g., a neighborhood, a city, a region, etc.); transportation supply, on the other hand, consists of infrastructure (e.g., roads, rail lines, trolley buses, car parks, ports, airports, etc.) and services (Allam, 2020; Kane & Del Mistro, 2003).

The territory is typically represented by the activity system, which can be defined as the set of individual, social, and economic behaviors, actions, and interactions that give rise to transportation demand (reason for journey) (Cascetta, 2009).

From a theoretical point of view, the planning of a transport system can be seen as a process articulated in different phases in which several subjects are involved and play a key role in various ways: technical subjects, political subjects, public and/or private bodies and institutions as illustrated in Figure 3. Following this approach, it is possible to identify several solutions and alternatives, also in relation to the costs and benefits expected over time for the community. In addition, it is possible to define priorities for intervention taking into account available resources and impacts.

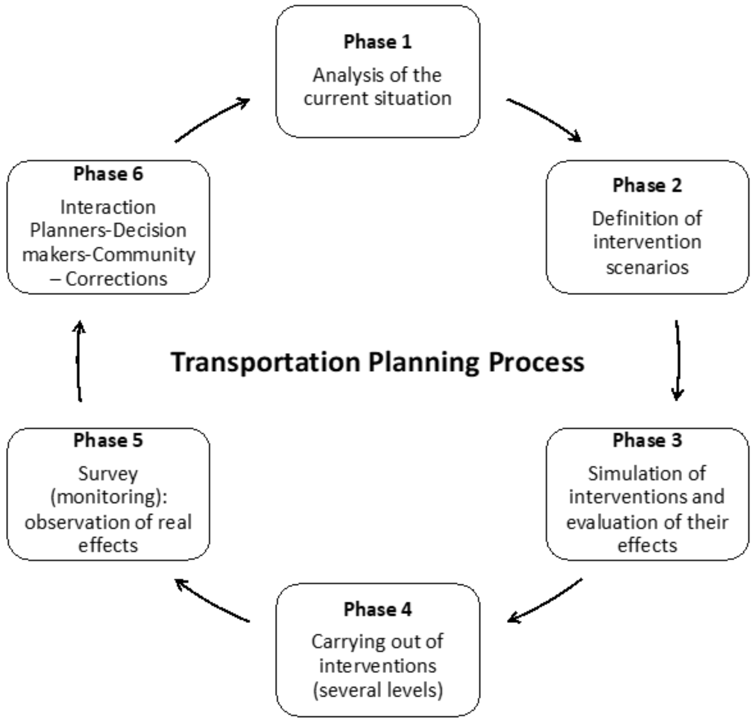

Figure 3: Representation of the six phases in the transportation planning process.

Focusing on rural transportation, it is believed that the poverty of the rural population in most developing countries is caused by an inadequate transportation system. From a numerical point of view, it is estimated that more than 900 million people in the world do not have access to a road during all seasons and about 300 million people do not have access to motorized vehicles.

In much of rural Africa, the choice of motorized and non-motorized means of transportation (including, for instance, camels, donkeys, bicycles, and carts) is often very limited; in those areas where motorized transport services do exist, there are often situations in which these services are not frequent, expensive, unreliable, crowded, and unsafe (Hine, 2014). With reference to the topic of transport planning described previously, the main elements of Rural Transport Planning are shown in Figure 4.

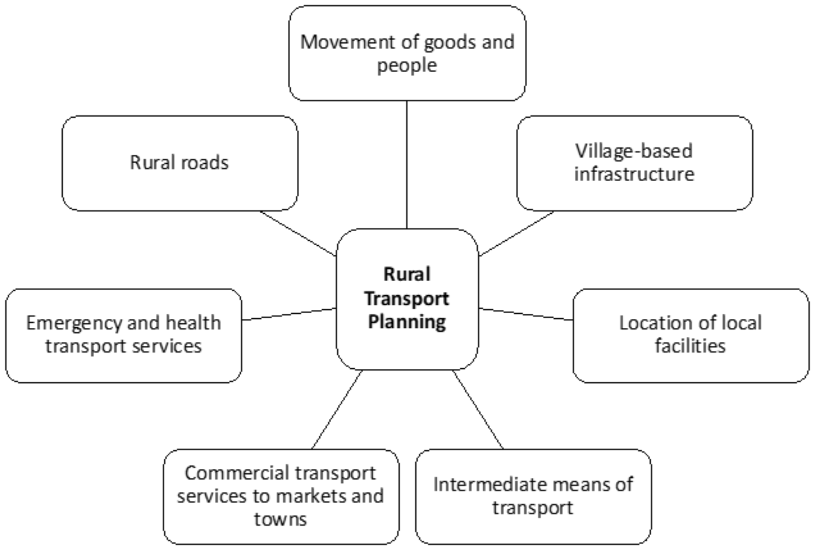

Figure 4: Elements of Rural Transport Planning.

To address this issue, a new simplified and low-cost method for public transportation planning in small and medium-sized cities in developing countries is proposed in the work (Saunders et al., 2020). The method aims to improve the operational efficiency of the public transport network by reducing the total operational kilometers of the network while serving the same number of passengers.

After having addressed the issue of transportation planning, the following are some studies on mobility in rural areas, especially in Africa.

In the study by (Dytckov et al., 2022), the issue of mobility in rural areas with low demand is addressed; DRT (Demand Responsive Transport) is a possible alternative to traditional public transport bus lines that are expensive to operate in such conditions. The work concerns an application of a DRT service in the municipality of Lolland in Denmark. The results confirm that DRT could be a more sustainable mode of public transport in low-demand areas, reducing on the one hand CO_2 emissions and on the other hand the operating costs of the service (Dytckov et al., 2022).

Another work considers the low profitability of transportation services in sub-Saharan Africa due to the high operating costs of conventional vehicles working at relatively low speeds on rural roads. In the paper, the potential of motorcycles and three-wheeled vehicles with small trailers that can carry relatively high loads (1 ton) at low speeds is analyzed. This can reduce operating costs by about half compared to conventional vehicles (Dennis & Pullen, 2017).

A further issue relates to the relationship between rural transportation and climate change in South Africa; in (Chakwizira, 2019) study, it emerges that the impacts of climate change on transportation can be addressed not only through solutions related to transportation systems, but also through solutions involving new planning and locations of schools, hospitals, buildings, etc.

Finally, the work of (Szabó et al., 2021) addresses the issue of analyzing and mapping affordability for photovoltaic-based electricity generation in sub-Saharan Africa, East Asia, and South Asia. In the study, it is found that compared to electricity generation with diesel systems, solar photovoltaic systems are more affordable to no less than 36% of non-electrified populations.

With reference to the analysis of the technical-scientific literature, this work aims to analyze the relationship between sustainable mobility system planning and energy design for the operation of such systems in rural areas.

3. Current transport system in Eritrea: Focus in Asmara

In sub-Saharan Africa (SSA), an estimated 60 % of people live in rural villages (Olinto P et al., 2013) and grow subsistence crops on small plots of land. In fact, the survival of these people depends largely on the sale of surpluses at different markets; this situation is the main driver of rural development, linked to the growing demand for food resulting from increasing urbanization. However, this transport and sale activity is severely limited by (i) long distances to markets, (ii) lack of roads, and (iii) lack of accessible transportation. People's poverty does not allow them to own a vehicle: this condition results in a need for accessible and affordable transportation services to ensure people's access to (i) markets, (ii) health care, and (iii) other essential services.

Asmara is the capital, the most populated city, and the main industrial, economic, and cultural center of Eritrea, as well as the capital of the Central Region. It rises on a plateau over 2.300 m above sea level. and enjoys a particularly mild and healthy climate (the average annual temperature is about 17 °C).

The main Eritrean streets (Asmara-Keren-Berentu, Massawa-Foro, Adi Kuala e Senafe) are in usable conditions. Private transports are quite unusual, mainly for the high cost of diesel. Public transports are more cheapy and link the major cities, especially using public buses, but usually they are crowded. Today Asmara has 10 bus lines in the downtown, developed by Mercedes, and visible sign, written both Latin characters and Arabic ones, signal the bus stops. The buses work with a minimum clocking of 15 minutes and a maximum clocking of 30 minutes during the day, but there is not a public timetable because of the traffic during the peak hours, and they go out of service at 7:00 p.m. The line 1 links the airport and Asmara, crossing the zoo, situated in Biet Gheorghis. The lines having 2 as the first number (i.e., 21, 22 etc.) cross the centre of Asmara arriving to the village in the downtown, but there are not many of these buses during the day, therefor if a travel of this type is scheduled is better to ask to the locals. Long haul buses are not particularly crowded, because is not allowed to stand in the aisle for the passengers (Air Pollution in World: Real-time Air Quality Index Visual Map, 2021; Asmera.nl, 2017).

Alternatively, minibuses and taxis are transport used to move through the city, mostly by tourists. It is possible reach the city of Asmara from the airport by taxi paying 400 Nakfa, otherwise using public buses, which work from 6:00 a.m. to 9:00 p.m. and the prices are different depending on the route. Even the type of bus can influence the price: the oldest ones are terribly slow, but the minibus “Fast” developed by Toyota can be expensive, until the 250% of the average price. The minibuses cross scheduled routes but without any stop or signs, usually using at the bus stops, but the customer still must hail them, just like a cab. Before boarding, the passenger asks them where they are headed, unless the ticket-seller does not beat him to it by announcing it loudly, then the passenger let them know when he wants to get off. Finally, there are the yellow taxis, which are not so different from the minibus: the taxis follow a scheduled path and probably you will share the path with other people. Differently, there are some taxis that do not follow a scheduled route; they are called “kuntrat”. The price of the route must be negotiated before the service. Usually these cabs wait outside: the airport when a plane is coming in, the city’s main hotels (Asmara Palace Hotel, Nyala, Ambassador etc.), the road to the right of the main cathedral and so on. Renting a car is insanely expensive due to the fuel price, which is higher than in Europe. It must be noticed that the air quality in Eritrea is dangerous for the inhabitants. For this reason, it is necessary to study a possible solution using smart and green mobility.

4. Proposal of new transportation systems: features and performance's evaluation

Basing on the actual mobility plan, the vehicles selected for this work are: a) e-buses Solaris Urbino 12 (Solaris, 2019); b) Nissan Leaf e-car (EV Specification, 2019) acting like taxi; c) minibuses based on Maxus EV80 model (LDV, 2019) and d) bikes based on Olympia EX900 model (Olympia, 2019) as illustrated in Figure 5.

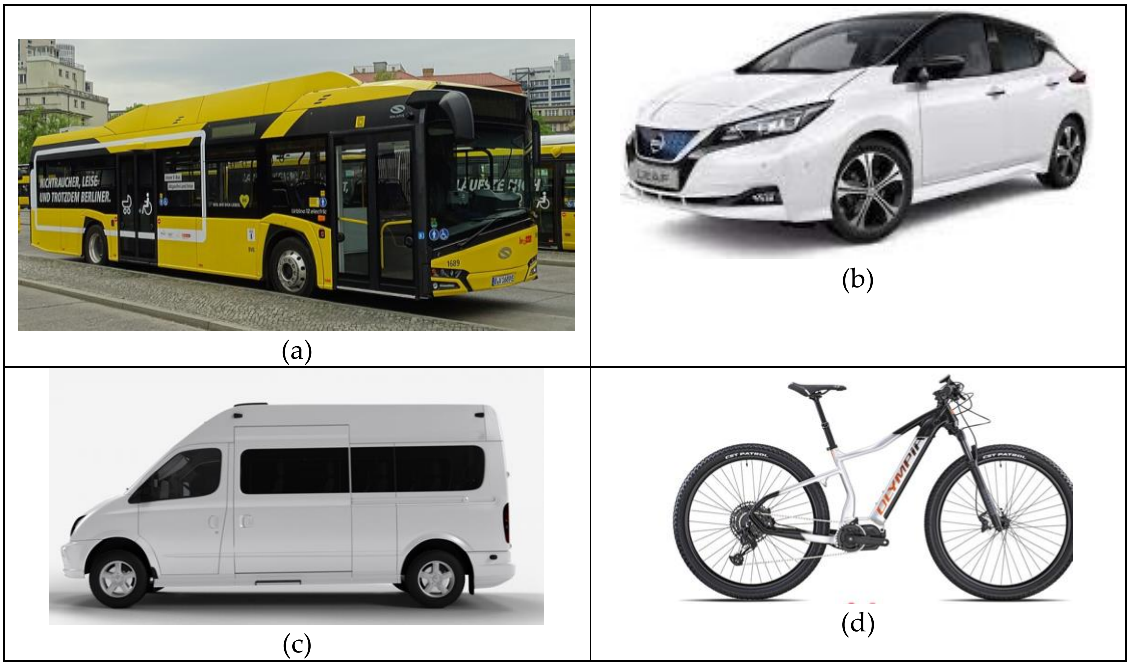

Figure 5: Different vehicles selected in the study: (a) e-bus (b) e-car (c) minibus and (d) bikes.

Table 1 shows the main technical features of the proposed vehicles adopted in this research.

Table 1. Main characteristics of the vehicles.

Data	*Solaris Urbino 12 (a)*	*Nissan LEAF (b)*	*Maxus EV 80 (c)*	*Olympia EX 900 (d)*
Length [m]	12.00	4.49	6.01	1.45
Width [m]	2.55	1.79	1.99	0.20
Height [m]	3.30	1.54	2.35	0.93
Capacity [people]	80	5	15	1
Mass [ton]	19.00	1.64	3.50	<0.01
Motor [kW]	Asynchronous motor, 240	Synchronous PM motor, 110	Synchronous PM motor, 100	Brushless, 0.25
Max Torque [Nm]	1100	320	320	100
Battery [kWh]	240	40	60	0.9
Max Speed [km/h]	80	144	100	25

The choice of the vehicles for the mobility service described in Table 1 represents a reliable standard, in fact:

- Solaris Urbino 12 start to be largely used to decarbonize fleet of buses, and it proves the effectiveness of LiFePO (Lithium-Iron-Phosphate) batteries applied in transport sector (Solaris, 2019).
- In a similar way, Nissan Leaf is selected since is the most sold e-car in 2019, but this choice is also made looking at the future: Nissan Leaf is the first EV able to perform V2G (Vehicle to Grid), and it is still largely use for the service simulations (EV Specification, 2019).
- Maxus EV80, is selected since it is a good compromise for the simulation of a minibus, considering the capacity and the weight (LDV, 2019).
- Finally, Olympia model is selected since are performant e-bikes very helpful in in steeply sloping areas such as the capital of Eritrea (Olympia, 2019).

4.1 Performance's evaluation method.

To evaluate the performances of the vehicles described in Section 4, it is necessary to start from the choice of the routes crossed by them. For minibuses and taxis, the path selected will be the like the one existing yet, since are mainly used by tourists to move from the airport to the city. Bikes will compose a bike sharing hub, therefore a path is not evaluable. Finally, five bus lines are selected in relation to the proximity of utilities, facilities and point of interest.

Using the parameters reported in Table 1, the performances for each vehicle are evaluated considering:

- Speed diagram [m/s] evaluable by the following equation (1):

$$v_{n+1} = a_n \cdot (t_{n+1} - t_n) + v_n \quad (1)$$

where:

- v_{n+1} is the speed of the vehicle at the time instant $n+1$, subsequent to n;
- v_n is the speed of the vehicle at the time instant n;
- a_n is the acceleration of the vehicle at the time instant n;
- t_{n+1} is the value of the time in second at the instant $n+1$, subsequent to n;
- t_n is the value of the time in second at the instant n;

Adhesion Force [kN] is evaluated using (2), where f_{ad} , the adhesion coefficient, is evaluated through the Lamm and Herring Formula:

$$F_{ad} = f_{ad} \cdot m \cdot 9.81 \cdot N_{motweehls}/N_{totwheels} \quad (2)$$

where:

- F_{ad} is the adhesion force in kN;
- f_{ad} is the adhesion cohefficient evaluated through the Lamm and Herring Formula;
- m is the mass of the vehicle in tons;
- $N_{motweehls}$ is the number of motorized wheels;
- $N_{totwheels}$ is the number of total wheels.

Power diagram in phase of traction calculated by (3):

$$P_{Tr} = ((F_T \cdot v_n)/\eta_T) + P_{AUX}, [kW] \quad (3)$$

where:

- P_{Tr} is the electric power in phase of traction in kW;
- F_T is the tractive effort in kN;
- v_n is the speed of the vehicle at the time instant n;
- η_T is the efficiency in phase of traction;
- $P_{AUX}$is the power required to supply the auxiliaries.

Power diagram in phase of braking using (4):

$$P_{Br} = (F_T \cdot v_n \cdot \eta_B) \cdot e_{br} + P_{AUX}, [kW] \quad (4)$$

where:

- P_{Br} is the electric power in phase of braking in kW;
- F_T is the tractive effort in kN;
- v_n is the speed of the vehicle at the time instant n;
- η_B is the efficiency in phase of braking;
- e_{br} is the regenerative percentage of recovery braking;
- P_{AUX} is the power required to supply the auxiliaries.

Energy diagram, which let monitor the discharge of the battery during the journey via (5):

$$E_n = P_n/3600 \cdot (t_n - t_{n-1}) + E_{n-1}, [kWh] \quad (5)$$

where:

- E_n is the amount of energy consumed at the time instant n;
- P_n is the electric power required at the time instant n;
- E_{n-1} is the amount of energy consumed at the time instant $n-1$ before n;
- t_{n-1} is the value of the time in second at the instant $n-1$, before n;
- t_n is the value of the time in second at the instant n;

Thus, the whole fleet can be defined considering the overall time of travel T, the length of the line L, the commercial speed V_c, the transport demand P_d and the clocking between two vehicles h. While the length of the line is easily evaluable from the route, to calculate the overall time of travel (6) it is required to know not only the time necessary to cover the path T_0, but even the time of stop at each terminal t_t.

$$T = 2(T_0 + t_t) \quad (6)$$

where:

- T is the overall time of travel;
- T_0 is the time necessary to cover the path;
- t_t is the time of stop at each terminal;

Therefore, knowing the load factor α, that highlight the utilization of the capacity of the vehicle, the transport demand, and the capacity of a vehicle C_v, using the frequency f (7), to evaluate the clocking h is evaluated using (8).

$$f = P_d/\alpha \cdot n \cdot C_v \quad (7)$$

$$h = 60/f = 60\alpha \cdot n \cdot C_v/P_d \quad (8)$$

where:

- f is the frequency of the service;
- P_d is the potential demand to size the service;
- α is the load factor of the vehicle, that highlight the utilization of the capacity of the vehicle;
- n is the number of articulated;
- C_v is the vehicle capacity;
- h is the clocking between two vehicle;

Then, knowing all these parameters, the commercial speed V_c of the vehicle, using (9) is calculated, and finally, with using (10), the number of unit traction N_{UdT} necessary to provide the service is estimated:

$$V_c \text{ [km/h]} = 120L/T = 120L/(h \cdot N_{UdT}) \quad (9)$$

$$N_{UdT} = 120L/(h \cdot V_c), \quad (10)$$

where:

- V_c is the commercial speed;
- L is the line length;
- T is the overall time of travel;
- h is the clocking between two vehicle;
- N_{UdT} is the number of unit traction necessary for the service;

Finally, all the consumptions and the charging times are evaluated. The goal of the scheduling phase is the creation of an efficient timetable, and this is possible by monitoring the State of Charge (SoC) of the battery even during charging phases.

It is evaluated that the vehicles complete the maximum number of journeys until the battery reach the 20% of SoC. To recharge them it is considered an infrastructure, which power depends on the vehicle characteristics, therefore the times are obtainable.

5. Implementation of new mobility scenarios in Asmara

Using the setup with the main characteristics of the vehicles (Table 1) and the formulas for the driving controls Eqs. (1-5) the performance of the different vehicles is assessed. Then, the fleet dimensioning, i.e., defining the number of buses, is evaluated using Eqs. (6-10). Therefore, knowing the fleet and the driving control of the vehicles an efficient timetable can be evaluated.

5.1 Minibus, Taxi and bike.

The choice of minibus and taxis is made to provide an alternative service to taxis to facilitate the travel between the Asmara airport and the city centre. The vehicle selected to provide the service is an LDV like the Maxus EV80, for the minibus and a Nissan Leaf, for taxi. The route connection between Asmara airport and the city centre (Afabet Street is considered) is 7.230 km long and requires about 15 minutes to cover it. The path described is represented in Figure 6.

Figure 6. Taxi and minibus route (Asmara airport - Afabet street).

It must be noted that Asmara is located on the plateau region; therefore, the conformation of the territory presents significant variation in the slope profile, as visible in Figure 7.

Figure 7. Slope profile taxi and minibus route (Asmara airport-Afabet street).

This leads to a significant increment of power required for the motion, thus the amount of energy required by the vehicles increases. Therefore, an approximative evaluation of the consumption could be very risky, so a detailed performance evaluation is necessary, which takes into account the slope profile shown in Figure 7.

Knowing the route and the vehicles, through Eqs. (1-5) it is possible to evaluate the performances of the vehicles. Both the vehicles run until their batteries reach the 20% of the State of Charge (SoC). This means use the cycle of charge/discharge of the battery at its maximum, therefore the lifetime of the battery will be maximized. After that, the vehicles need to be recharged: minibus uses a charging infrastructure which power is 28 kW, while the taxi uses a charging infrastructure which power is 50 kW. To reach a SoC above the 80% the minibus spends 63 minutes at the station, while the taxi 28 minutes. This process is described in Figure 8.

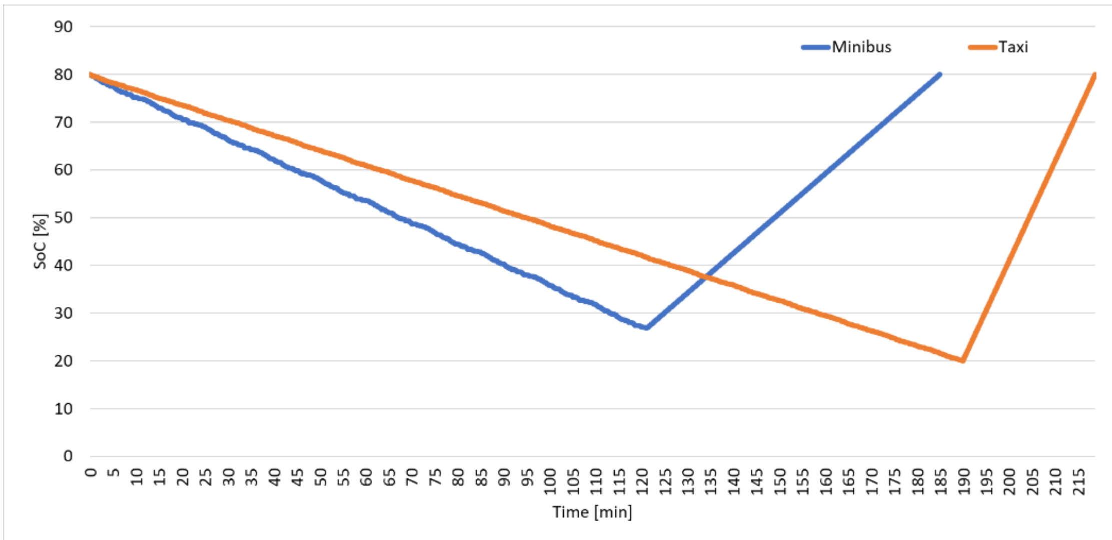

Figure 8. Minibus and taxi SoC trends.

After the simulation performed in Figure 8, it can be noted that minibus service is performed for 2 hours, but then it requires 63 minutes to recharge the battery up to the 80%, therefore only one minibus won't be enough to satisfy the demand. Similarly, taxis are largely used to connect the airport with the city centre, but they are also used to move passengers across the city. Therefore, considering the time for the service and the time to charge the vehicles, 2 minibuses and 7 taxis are supposed for the study.

Another smart mobility solution for the city could be the implementation of a e-bike sharing hub. Considering the size of the city and the proximity of the facilities and utilities, the use of bikes could be a good compromise both for inhabitants and tourists. In this case, it is difficult to select a specific path for the bikes and even understand how the energy demand to the grid to recharge them is distributed. The amount of energy available per bike is 0.9 kWh, considering the bikes shown in Table 1, which have a large battery size, but is useful to model the load prudently. Despite these considerations, the energy available is not the total in the storage system in order to avoid the reduction of the life of the battery, the effective consumption goes from the 90% of SoC to the 20%, so the effective available energy will be 0.63 kWh per bike. The bike Hub will count 50 bikes therefore, to restore all the bikes from the 20% of SoC to the 90% the total energy required will be 31.5 kWh per day.

5.2 Bus Lines

Public buses are largely the most used transportation method in Asmara, but the service is still chaotic and not well scheduled. Therefore, basing on a potential demand five bus lines are selected considering the proximity of utilities, facilities and point of interest for the locals and potential tourists. The structure of the bus service is reported in Figure 9.

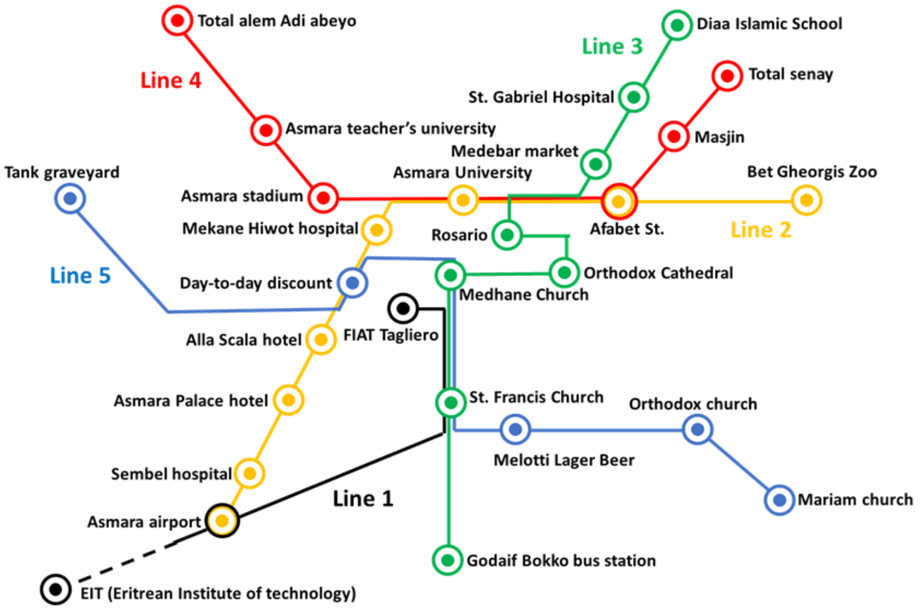

Figure 9. Map of the five bus lines selected for the analysis.

Using Eqs (6-10), the different bus lines are simulated. The main parameters of the service during the peak hour, where the demand is higher, are grouped in Table 2.

Table 2. Bus lines service parameters, evaluated for the peak hours.

Line	*Line 1*	*Line 2*	*Line 3*	*Line 4*	*Line 5*
Length of the line [km]	23	9.6	12.39	8.1	11.75
Exercise time for direction [min]	29.10	19.4	26.49	20.15	23.30
Transport Demand [pax/h]	500	800	760	400	500
Clocking [min]	10.56	6.6	6.56	13.12	10.56
Ring time [min]	78.21	58.48	73.39	60.18	67
Number of unit traction [UTD]	7.42	8.9	10.60	4.56	6.34
Commercial speed [km/h]	35.22	19.59	20.18	16.11	21.04

To study the bus fleet and to schedule an efficient timetable, it is important a continuous check of the consumption along the line, being careful to protect the batteries of the bus. Therefore, the peaks of the power should not be too long in times, and it would be better if they do not overcome the maximum power given by the data (Solaris Urbino 12).

As commonly accepted, the batteries for the vehicles should not discharge completely, but it would be better that the SoC remains over the 20% during the traction, while in phase of charge it is useless to recharge them over the 80%. This means that in the case of Solaris Urbino 12, where the battery has a capacity of 240 kWh, the maximum useful charge will be about 192 kWh, while the minimum will be 48 kWh. The required energy for each path in one direction is evaluable and following the hypothesis of a state of charge that should never be under the 20%, are estimated: the likely journeys, the energy required and the energy remained after the service are provided in Table 3. Finally, the Depth of Discharge (DoD) for each line are reported and the charging time, in minutes, to go from the minimum SoC up to the 80% of SoC, through the infrastructure aforementioned.

Table 3. Number of journeys, energy required, energy remained and DoD and charging time for each line.

Line	*Journeys*	*Energy required [kWh]*	*Energy remained [kWh]*	*DoD [%]*	*Charging Time [min]*
Line 1	2	102.71	89.28	42.80	51.21
Line 2	6	139.28	52.72	58.04	69.38
Line 3	3	113.69	78.31	47.38	56.5
Line 4	5	130.98	61.01	54.58	65.3
Line 5	4	136.37	55.63	56.82	68.1

In Figure 10 the SoCs during the path of the buses are presented, and when they reach near the 20% of SoC, the buses start the phase of charge, using an infrastructure which power is 120 kW.

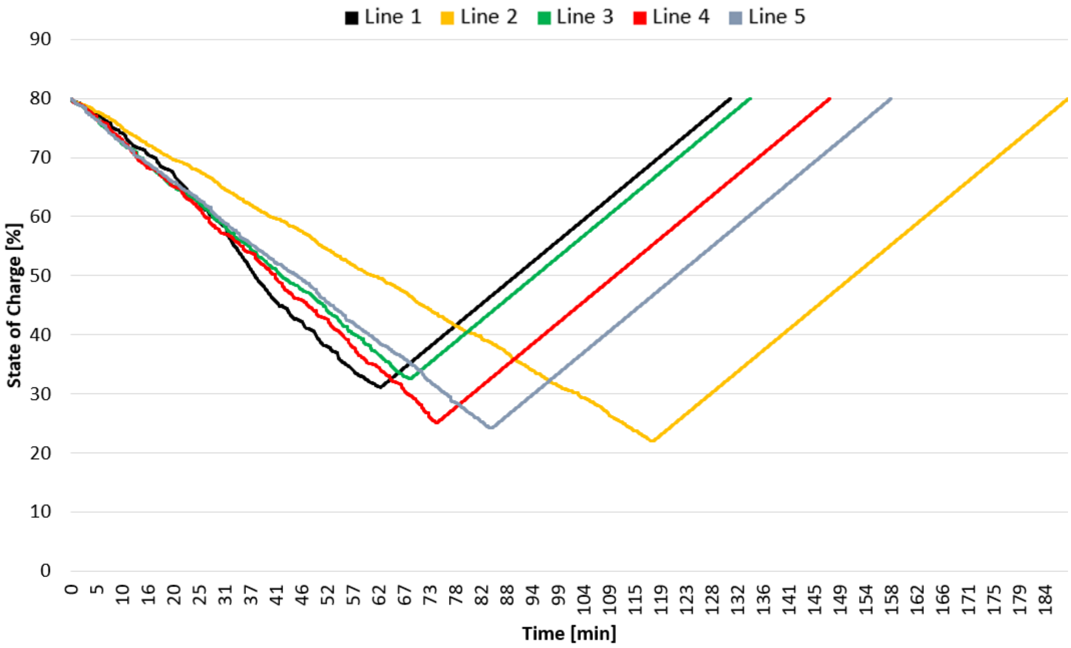

Figure 10. Bus lines SoC.

5.3 Results and discussion

After the performance analysis and the fleet sizing, using an approximation by excess on the number of unit traction per line, the following has been established:

- The number of operating unit traction required is 40;
- The number of spare vehicles is evaluated as the 20% of the operating unit traction, therefore the required number is 8;
- The number of vehicles in maintenance is evaluated as the 10% of the operating unit traction, therefore the required number is 4.
- To sum up, basing on the considerations made here and in the previous section, the whole mobility system considers: 52 e-buses, 2 e-minibuses, 7 e-taxis and 50 e-bikes.

Finally, it is necessary to place in Asmara the charging infrastructures, which are supposed of different types due to the vehicle to provide. The infrastructures used to power the minibus provide 28 kW and are located at the airport since the path begins there. The infrastructures to power taxis provides 50 kW and are located at the airport too. Finally, the buses' infrastructures are located at each terminal and have a power of 120 kW. This solution gives the possibility to charge the battery even in particular cases where the timetable is not respected for any reason. The map which sums up the overall bus service with the charge infrastructure positions marked at the terminals is presented in Figure 11.

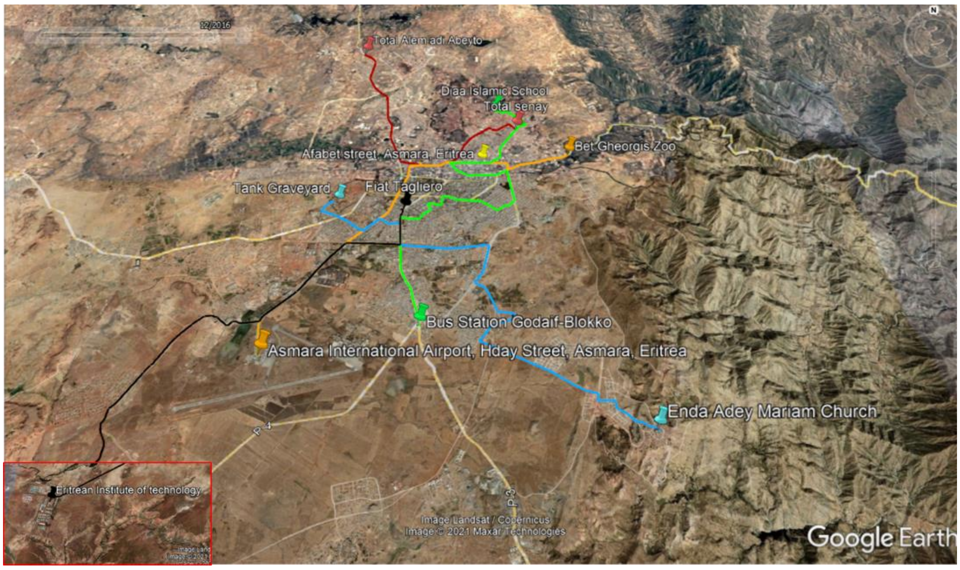

Figure 11: Configuration of the bus services.

Thanks to the evaluation of the demand provided in Table 2, the analysis of the bus performances and the creation of an efficient timetable, the new public service will be able to satisfy the requirements of Asmara, improving the life quality of the citizens, through the implementation of a service based on the customer and the reduction of the pollution caused by the outdated vehicles. Finally, however, it should be specified that the work done does not take into consideration the potential behavioral changes and preferences of users when presented with the option of adopting a sustainable transport system. Therefore, modifying the pre-existing transport service could alter the real service demand due to the influence on users (Axsen et al., 2019).

6. Sustainable energy to supply the new mobility scenarios

After analyzing and evaluating the new sustainable mobility scenarios in Asmara, considering the increase in population and new needs related to the journeys, it is also necessary to study the electricity production. This study is necessary because the current electric grid would not be able to support the new loads to power the vehicles adopted in the different scenarios.

Knowing the timetables of each service the daily load profile and size of a PV power plant for different cases using the software Homer pro are evaluated (UL.com, 2009). Homer pro is a software largely used to simulate the implementation of electrical grids powered by different sources. The use of this software helps to evaluate the performance of an electrical grid, both in case it is the principal one or a microgrid, which can be connected or not to the main one, basing on the electrical load. Usually, in developing country, this software is used to simulate microgrids, since the possibility to enlarge them easily using renewables and helping the evaluation of further interventions (Mehta et al., 2018; Panchenko, 2019, 2020).

To setup the simulation the energy sources are required. In this case PV panels due to the high daily radiation (5.97 kWh/m2/day) and the good clearness index (0.618) are obtainable from the “Renewable energy lab” (UL.com, 2009) as shown in Figure 12.

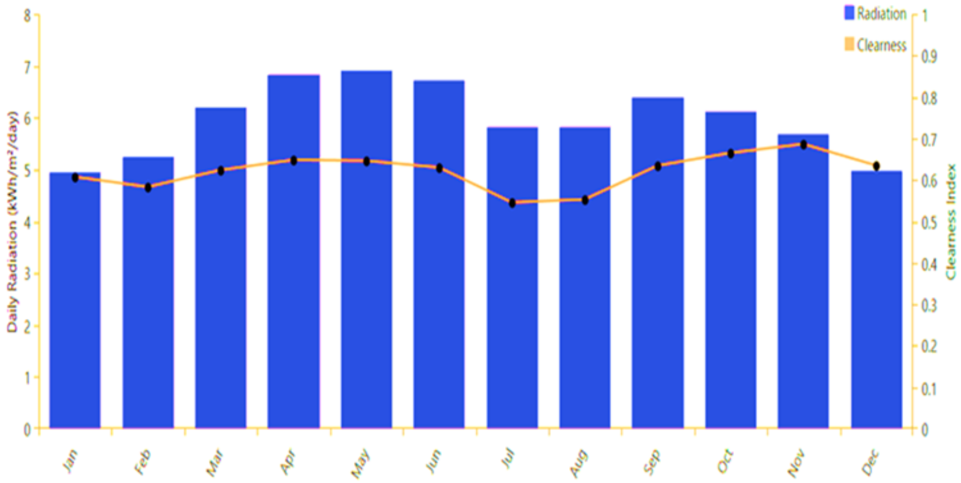

Figure 12. Monthly average daily radiation in Asmara.

The chosen structure used in this simulation is a generic flat plate PV, given by the software and the data are provided in Table 4.

Table 4. Generic flat plate PV data provided by Homer pro.

Quantity	*Value [Unit]*
Panel Type	Flat plate
Rated Capacity	1 [kWh]
Derating Factor	80 [%]
Electrical Bus	DC
Temperature Coefficient	-0.5
Operating Temperature	47[°C]
Efficiency	13 [%]
Capital	2,500.00 [$]
Replacement	2,500.00 [$]
O&M (Operation & Maintenance)	10.00 [$/year]
Lifetime	25 [years]

To avoid instabilities and to store energy whenever the source is not available, a battery storage system is used. Considering the DC bus voltage (600 V) and the necessity of a fast charge and discharge cycle, the storage bank chosen is composed by Zinc-Bromide flow batteries and the main characteristics are given in Table 5. The main advantages of this storage technology are the low energy density, the complete depth of discharge, the long lifetime and the low cost of storage (Wen et al., 2019). Zinc Bromide flow storage solutions can have the lowest cost compared to other electrochemical storage technologies (Yuan et al., 2017).

Table 5. Zinc-Bromide 1kWh flow batteries data provided by Homer pro.

Quantity	*Value [Unit]*
Nominal voltage	600 [V]
Nominal capacity	1000 [kWh]
Nominal capacity	1670 [Ah]
Roundtrip efficiency	90 [%]
Maximum charge current	1670[A]
Maximum discharge current	5000 [A]
Initial SoC	80 [%]
Minimum SoC	20 [%]
Capital	400 [$]
Replacement	400 [$]
O&M (Operation & Maintenance)	10 [$/year]
Lifetime	5/8 [years] - 2000 [cycles]

Then the converter, the controller and the economic parameters must be settled, and in this case the default ones are used within Homer Pro, and the lifetime of the project established is 25 years.

The scenario emerged from the simulations has a high impact from an energetical point of view, therefore the load must be sized accurately basing on the timetable and schedule of exercise. The grouping of such several means of transport leads to the need to know the hourly load profile accurately. For minibuses and buses, knowing the schedule of exercise, it is possible to easily track the daily load profile can be evaluated. On the contrary, for e-bikes and taxis, because of the high flexibility of service and the absence of a fixed timetable, it is required to do some assumptions, considering their load constant during the 24 hours of the day. The daily load profile with a variability of 10%, where the average load is 19224,66 kWh/day for weekdays and 14571,11 kWh/day during the weekend and the holidays can be calculated. From Figure 13 it can be seen the daily load profile of the case study. The load factor, which represents a dimensionless number equal to the average load divided by the peak load is 0.39, linked to a very high value of peak, which corresponds to 1488.66 kW.

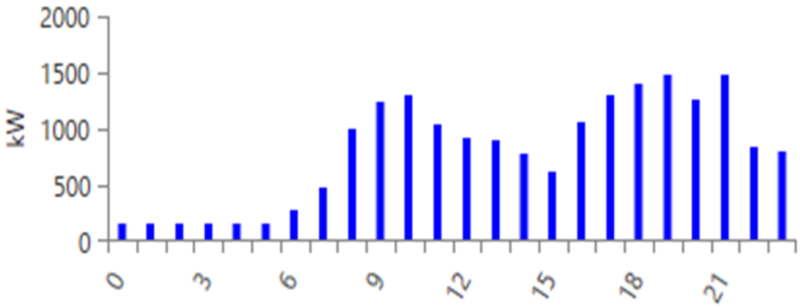

Figure 13. Daily load profile.

Electrical output parameters are given in Table 6 and the parameters of electricity lost are satisfying.

Table 6. Electrical parameters.

Quantity	*Value [kWh/yr]*	*Value [%]*
AC primary load consumption	7,010,984	86.60
Excess electricity	303,914	3.76
Unmet electric load	6,141	0.088
Capacity shortage	7,015	0.010

Generic flat plate PV are selected with the characteristics outlined in Table 4. After the simulations the most valuable values are outlined in Table 7.

Table 7. Flat plate PV plant parameters.

Quantity	*Unit*	*Value*
Rated capacity	kW	4,966
Mean output	kW	923
Daily mean output	kWh/d	22,156
Capacity factor	%	18.6
Total yearly production	kWh/yr	8,086,970
Minimum output	kW	0
Maximum output	kW	4,774
Hours of operation	hrs/yr	4,380

The size of the plant is established starting by its rated power capacity. Considering each single 0.33 kW panel, with a simulated rated capacity of 4,966 kW, then 15,049 panels are needed. Considering the rated capacity, the dimension of a flat plate PV of 0.33 kW (1956×992×40mm) and the distance between the panels, it is recommended that the best place for the plant would be located next to the airport. The perimeter and the surface are evaluated using the tools provided by Google Earth and are respectively 1,413 m and 94,972 m^2. Therefore, the area shown in Figure 14 can be used for huge size plant.

Figure 14. Available zone for a PV plant in Asmara.

The simulation using Homer Pro provided a sized energy storage bank of 90 batteries, the largest one. Table 8 outlines the most important parameters for the batteries.

Table 8. Energy storage bank characteristics.

Quantity	*Unit*	*Value*
Batteries number	-	90
String size	-	1
Strings in parallel	-	90
Bus voltage	V	600
Autonomy	Hrs	89.9
Nominal capacity	kWh	90,000
Usable nominal capacity	kWh	72,000
Energy in	kWh/yr	4,236,873
Energy out	kWh/yr	3,833,800
Losses	kWh/yr	424,802
Annual throughput	kWh/yr	4,041,180

The SoC of the battery pack of the plant is monitored (Figure 15) and is satisfying, considering that in the worst case the risk of an unmet load happens twice a year, in the months of August and September, where the SoC is lower as mentioned before.

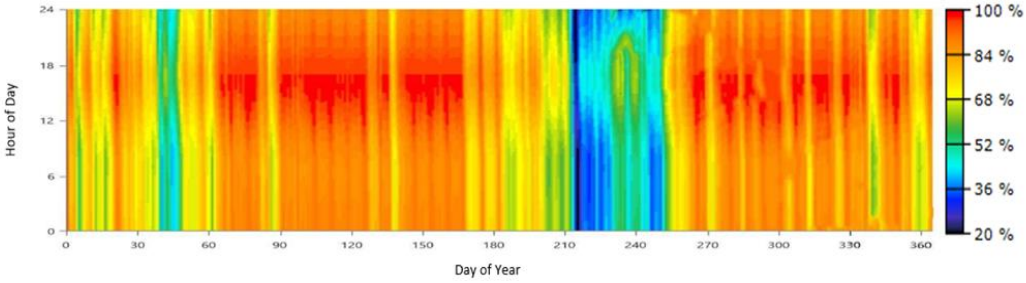

Figure 15. D-Map of annual SoC of the battery.

Finally, in Table 9 are reported the main economical outputs from the creation of the power plant.

Table 9. Economical outputs of the grid simulations.

Quantity	*Value*
Total Net Present Cost (NPC)	14,023,690 $
Operating Costs	69,229.08 $/yr
Levelized Cost of Energy (CoE)	0.1547 $/kWh

Even if the project is evaluated on a period of 25 years, from Table 9 it is possible to establish that NPC of the operation, evaluated as the sum of the costs, can represent a significative economic effort for a developing country. Therefore, a possible solution in addition to incentives can be the division of the costs through a gradual development of the entire systems, transportation, and generation (Chukwu & Mahajan, 2014a; Rezk et al., 2019; Ueckerdt et al., 2015; Zheng et al., 2019b). Splitting the investments for the implementation of the plant can also help to reduce the operating costs, considering that in the future more performant PV plants and storage systems will be developed (Chukwu & Mahajan, 2014b; Laajimi & Go, 2019; Suresh et al., 2020).

As final considerations, the replacement of vehicles through a decarbonization process does not represent the end point of the decarbonization process that many countries are carrying out. The decarbonisation process will bring with it the need to study the sustainable positioning of infrastructures within cities and the revaluation of mobility in a general sense, involving all citizens (Carra et al., 2022; Carra et al., 2020).

4. Conclusions

Considering the African megatrends, it is outlined the importance of setting up an integrated sustainable mobility model capable to promote the development of a country's well-being. The development of an electric sustainable mobility could be a relevant factor both demographically and technologically in the perspective of an expanding city. In this context, the possibility to improve the air quality by the emission reduction generated by outdated vehicles and increment the rate of green electrification over polluting power plant represent a critical point. In Sub Saharan Africa (SSA), the population with the access to electricity is located only in the big cities, where the rate of pollution is high, due to old vehicles and power plants that still use exclusively fossil fuels.

This study, focused on Asmara, aims to propose a model for the future, to promote the development of a fast-growing city like the capital of Eritrea, after the recent political stability achieved in 2018. Therefore, a scenario to gradually develop the city is studied, starting with the connection between the airport and the center of Asmara. In addition, the introduction of a hub composed of 50 bicycles is evaluated. Next, the analysis focused on the electrification of the current five bus lines by improving the service provided in terms of schedules, reliability, safety, and comfort. these evaluations are also carried out considering the charging phase of the vehicles' batteries and the operating time of the vehicles for each line.

The proposed solutions were found to be feasible, but they generate a large load increase on the power grid that is not suitable for the proposed scenario. For rural countries to adopt smart and innovative mobility solutions studied in this work, a microgrid needs to be created to satisfy the energy demand for different solutions (cabs, minibuses, e-buses and bicycles).

To allow the operation of the solutions proposed above, it was necessary to adopt photovoltaic systems capable of producing energy in a sustainable way. this choice stems from considering the high natural availability of daily radiation (6 kWh/m2/day).

The design and sizing of the photovoltaic park follows a modular and expandable approach, taking into consideration a possible increase in electrical load associated with an increase in population. The latter condition also foresees a growth in transport demand and therefore in the number of vehicles on the road.

A new electricity demand for Asmara city therefore regards solar energy as a valid alternative to fossil fuels, not only because of the reduction of environmental impact, but also because of the flexibility of this solution.

Considering the duration of the project (25 years), it can be observed that the progressive development of the mobility and energy system represents a good compromise also considering the economic aspects. A possible development of the project concerns the integration of Vehicle to Grid (V2G): this could provide the necessary electrical load to the grid during peak demand at certain times of the day by taking advantage of e-buses stopped at depots or terminals. Finally, it would be useful, as a possible development of the work, to track transport demand flows in order to assess whether the mobility solutions identified and proposed are correct; if not, it would be appropriate to update the entire planning process.

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