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Adaptive Sustainable Mobility Solutions by Using Vehicle-Integrated Photovoltaic in Kigali City

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ABSTRACT: In a fast-paced urbanized culture, sustainable transportation remains a significant challenge. Quick and smooth mobility of people and goods with the possibility of regulating traffic congestion and preventing climate change is essential for every public transportation user. Urban population in developing nations like Rwanda is expected to double by the year 2050, and balancing the supply and demand of the urban transport system will be a significant issue. Information technology enables elements within the transportation system, including vehicles, roads, traffic lights, and message signs, to become intelligent by embedding them with sensors, processors, algorithms, and actuators, thus empowering them to communicate through various technologies. These technologies improve transportation system performance by reducing congestion, increasing safety and traveler convenience, and protecting the climate against some greenhouse gases. Different mobility solutions are stated in this document. The use of electric vehicles, Passenger Information Systems, Car-sharing and ride-sharing services, electronic payment, Bus Signal Priority, and Vehicle-Integrated Photovoltaics. Using photovoltaics in Rwanda is adequate because of the electricity problem. This is the best solution for fighting against climate change due to fuel from motorized traffic.

KEYWORDS: Information technology, Traffic congestion, Vehicle Integrated Photovoltaics

1. INTRODUCTION

Rwanda has made substantial progress in economic, environmental, human, and social development after the devastation of the 1994 genocide. Government policy has focused on building institutional capacity, good governance, and supporting economic growth, resulting in an annual growth rate of eight percent between 2000 and 2013, a 170 percent increase in real GDP, making the country among the ten fastest-growing economies in the world. Rwanda is one of the densest countries in Africa and one of the least urbanized, with approximately 17 percent of its 12 million people living in urban areas (World Bank,2016). The city is simultaneously administrative, industrial, educational, health centers, and commercial. With an increased shortage of electricity pollution, the City of Kigali cannot introduce faster electric vehicles and other mobility solutions. This phenomenon directly results from the refusal by the population to use electric vehicles and electric motor vehicles because of a lack of charging stops.
The theory of sustainable mobility comes from the more significant concept of "sustainable development," defined as the "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Oxford, 1987). Promoting sustainable mobility is one of the most widespread objectives in transport policy at all territorial levels, whatever the "political color" of the decision-maker. Nowadays, no plan, project, or policy direction concerning the transport sector does not (at least) mention the concept of sustainable mobility (Klecha & Gianni, 2018). The effects of technology on promoting the shift in behavior towards sustainable transportation modes are investigated. The international community has made several commitments over the last decade related to transport, setting the bar high on what is needed to transform the sector and to ensure that the future is sustainable. For example, the 2030 Agenda for Sustainable Development identified many characteristics that define a sustainable world. The UN Secretary General's high-level advisory group on sustainable transport identified the attributes that mobility must embody to ensure a sustainable future, including safety, affordability, accessibility, efficiency, resilience, and carbon impacts. Sustainable mobility includes various measures to reduce CO_2 emissions, such as car sharing and expanding public transport, as the principle of having short distances (Rupprecht Consult, 2019).

Also, the digital automation and networking of vehicles are central. Developing alternative driving systems such as battery and fuel cells is significant. Although the market share of electric and hybrid vehicles rose from 1.8 % to 2.6 % by mid-2019, the limited range, high acquisition costs, and regional gaps in the charging infrastructure require further technical innovations and new scientific approaches (Rupprecht Consult, 2019). At Fraunhofer ISE, transdisciplinary research is conducted on modern technologies for the sustainable mobility of tomorrow, taking all drive systems into account. According to (https://www.ise.fraunhofer.de/en/sustainable-mobility.html), 23 % of CO2 emissions are from the transport sector, primarily due to motorized individual traffic. While the need for mobility is forecast to increase by around 30 % by 2030, implementing the climate protection plan for transport has reached a standstill. Instead of saving 40 % of greenhouse gas emissions, CO2 emissions in this sector – unlike in other areas – have not fallen since 1990. Ecological, economic, and social aspects play a more significant role in mobility than in hardly any other sector. Therefore, the essential prerequisite for a successful transition to sustainable mobility is social acceptance and close cooperation between industry, science, and politics (Rupprecht Consult, 2019).

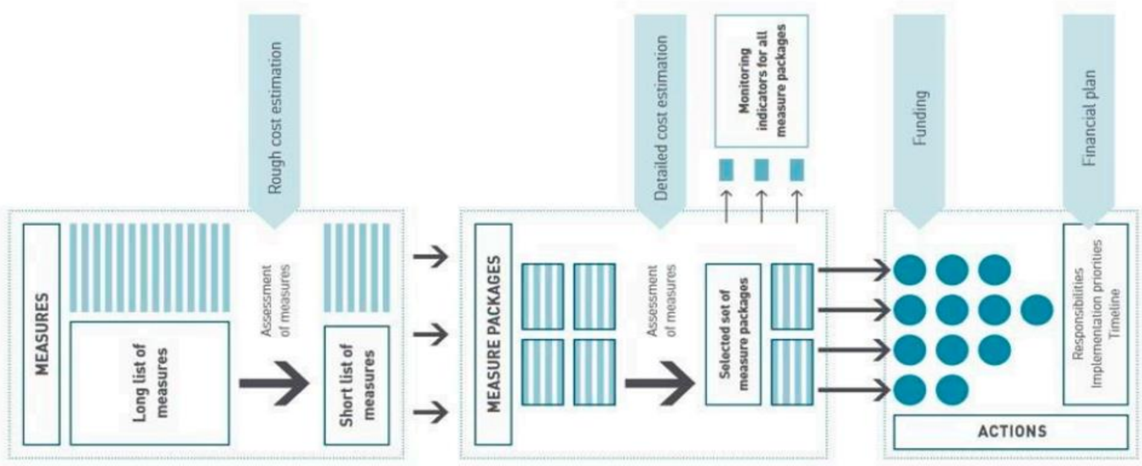

Figure 2. 1. Mobility measures selection process (Rupprecht Consult, 2019)

2. SUSTAINABLE MOBILITY SOLUTIONS

2.1. Electric Vehicles (EVs)

The overall transportation sector is responsible for 30% of all fossil fuel emissions in the EU (European union, 2007). With the increasing cost of energy and climate change constraints leading to pressure to mitigate GHG emissions, the automotive industry is one of the sectors that shows significant investments in R&D to reduce emissions and the dependence on fossil fuels. Powertrain electrification has been advocated for decades as an alternative for ICEVs due to zero tailpipe emissions and higher efficiency by using an electric motor instead of an Internal Combustion Engine (ICE). Typical ICE efficiency is 28–30%, while electric motors achieve 85–95% (Larminie & Lowry, 2003). The main obstacle to the mass adoption of EVs has been the battery, due to the low energy density capability, limiting the vehicle range. Advances in battery technology over the last decades, namely Lithium–ion technology, have led to the viability of mass manufacturing of EVs.

Figure 3 1. Charging infrastructure

2.2. Passenger Information Systems

One of the most relevant issues in cities is mobility. The current traffic congestion situation in cities leads to several health problems derived from pollution, noise, and, obviously, the tremendous stress on drivers who spend several hours in traffic to reach their destination(Allen et. al,.2018). Several developed cities have created innovative mobility systems as new Solutions to solve this problem. The implementation of systems of this kind involves the development of software and hardware infrastructure in the city.

These developed countries have created passenger information systems for bus users that indicate the real-time bus location, and they have also developed several apps that provide this information directly to the smartphones of the bus users. A smart city is an urban development that securely integrates Information and Communication Technologies and the Internet of Things (IoT) technology to manage a city's assets. A smart city can be defined as using information and communication technologies to improve the city's critical infrastructure and make public services for citizens more efficient (Avatefipour & Sadry, 2018). A Smart City uses technology to improve the quality of life and the accessibility of its inhabitants. Additionally, it ensures sustainable economic, social, and environmental development. An intelligent city allows citizens to interact with it in a multidisciplinary way and permits the city to adapt to their needs in real time (Yankevich, 2019). The concept of a Smart City requires the implementation of mechanisms to know the real-time context of the services provided to the citizens. For example, in the case of an intelligent mobility system, such as the one proposed in this research, the users need to know the location of buses in real time to improve the times used to reach a destination.

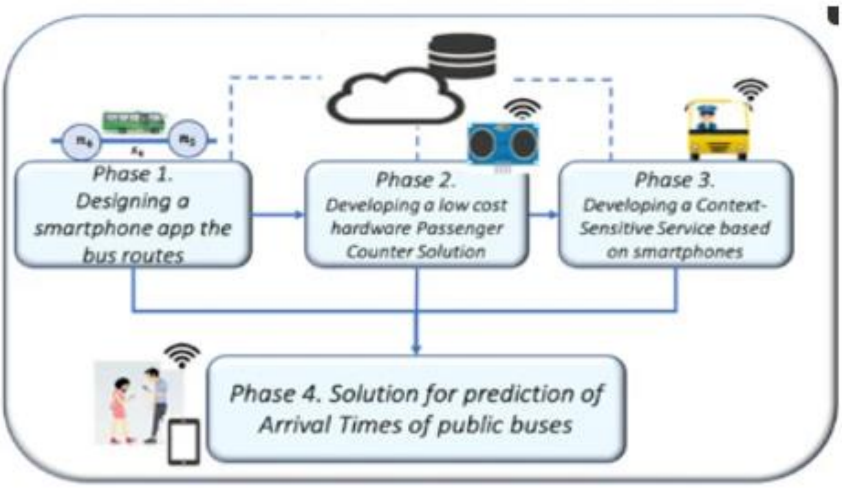

Figure 3. 2. Overview of the proposed solutions

2.3. Car-Sharing and Ride-Sharing Services

Increasing concerns about traffic congestion, road safety, greenhouse gas emissions, and energy consumption have resulted in people making different transportation choices, which in turn are affecting future mobility patterns. As "sustainable mobility" has become increasingly popular, recent transportation research focuses on identifying and building a sustainable transport future. Car sharing faces significant obstacles from primary sources: potential users, transportation infrastructure, governments, and businesses (Zeng, 2015). Although these four are common in cities worldwide, car sharing faces unique challenges in emerging markets, such as poor or insufficient public transport, private car restrictions, severe traffic congestion, and competition with semiformal transport modes. Further, as car sharing is not the only product offered by new mobility services, as technology advances and lifestyles change, customers will use the products and services that best meet their ever-changing travel needs.

2.4. Electronic Payment

Our mobility is undergoing a digital transformation. Innovative apps and digital companies offer mobility solutions where the customer is relieved of payment administration. Physical card payments or manual transfers are history. As a European market leader, Twikey helps to make the right financial choices in the complexity of different bank and online payment methods. We relieve the mobility player from customer identification to the collection agency. Full automation is the only solution to process high volumes without debtor administration. Nowadays, Mobility as a service (MaaS) integrates any discussion, analysis, or forecast on future mobility systems. As discussed (Spickermann et al.,2014), the mobility ecosystem is becoming more fragmented with the introduction of transport solutions, new business models, and new companies, all aligned with the same common objective: providing affordable, convenient, and sustainable mobility solutions. One example of a MaaS solution is Ustra, a mobility shop that provides a channel for selling physical tickets for transport operators. All services are based on a mobility app, essential for providing a pay-as-you-ride or a pay-as-you-go solution, often complemented by additional web-based services.

	Transport mode	Operator	Mode for payment and utilization	App / system used
Traditional transport services	Ferries	TTSL	Digital payment & physical ticket	viva
	Bus	carris	Digital payment & physical ticket	viva
	Light rail	carris	Digital payment & physical ticket	viva
	Rail	CP, fertagus	Digital payment & physical ticket (CP) Fully digital (Fertagus)	viva, Via Verde
	Metro		Digital payment & physical ticket	viva
	Taxi	TAXI	Fully digital	
	Parking	emel, empark	Fully digital	epark, Via Verde
New transport services	Car-sharing	emel, eo	Fully digital	epark, Via Verde
	Ride hailing	Uber, CABIFY, taxify	Fully digital	Uber, CABIFY, taxify
	Bike sharing	GIRA	Fully digital	epark
	Electric scooters	Lime, voi., hive	Fully digital	Lime, voi., hive

Figure 3. 3. Transport operators in Lisbon

2.5. Bus Signal Priority

Bus signal priority (BSP) is an operational strategy that facilitates the movement of public buses through traffic signal-controlled intersections by reducing the time they spend at intersection queues (Smith HR & Hemily , 2005). Thus, it helps improve bus service reliability by reducing schedule deviation, bus travel times, and delays. Another advantage is that it is a relatively less expensive way to make public transit more competitive than automobiles. BSP can be viewed as both demand and supply-side traffic management measures. It helps to make public transit more attractive, making people shift from private modes to public transport, thus reducing road vehicular demand. BSP also improves the signal timing for maximizing the throughput, making it a supply management measure. Despite these benefits, their potential negative impacts on the competent modes raise concerns about their deployment and urge a thorough validation before implementation.

2.6. Vehicle-Integrated Photovoltaics

The automotive sector has been developed and prospered thanks to abundant, cheap, and energy-efficient oil. For more than a century, its domination was unchallenged. Likewise, for decades, the rise in vehicle power was made without considering the environmental dimension (Minak et.al.,2019). EV charging stations present several problems. Indeed, they amplify the electric load. Consequently, it potentially intensifies the peak load or produces other peaks. Moreover, EV charging stations can boost load side uncertainties overload distribution grid devices, which reduce their lifetime, augment power loss, and induce significant voltage deviations compared to their nominal value(Dominguez-Navarro et al.,2019). Integrating PV panels in the vehicle will allow the charging battery to operate autonomously. This means no longer needing charging stations or reducing their use as much as possible.

Schematic of a lightweight module for trucks.

Electric-powered truck and mini truck, both with integrated photovoltaic modules.

Figure 3. 4. Photo with photovoltaics

3. SUSTAINABLE MOBILITY SOLUTIONS IMPLEMENTATION CHALLENGES

The stakeholders identified a lack of commitment behind these policy goals as the most critical barrier. If no goals and targets deriving from transport politics are formulated, there will be no solid political will to reform the system(s). Decisions are often based on political reasons but lack a long-term strategy. Additionally, conflicting policy objectives (e.g., passenger vs. freight) complicate the situation. According to the group, lacking communication between the policy and public administration levels in European multilevel governance may lead to contradictory policy strategies (European Commission, 2011). Another barrier concerns the general interest of industrial players to gain proprietary solutions. Transport operators often have a data monopoly and are not eager to share. It is a common business strategy to create market entry barriers by excluding new entrants from data and information access. In addition, shared data access would expose operators' shortcomings like operation delays and disruptions to public scrutiny. A primary barrier for the private sector is finding profitable business models and investment strategies for traveler information systems and services. Although there are corresponding user needs and wants for quality and reliable information, acceptance of extra charges is limited, especially when sufficient information is already available free of charge. Furthermore, the stakeholders mentioned that real user needs and wants are often not well understood and reflected in decisions being made (European Commission, 2011). A specific gap in knowledge exists concerning the barriers faced by local authorities across the different levels of policy implementation (HILL & HUPE P, 2003). Stakeholders' engagement is lacking, but at the same time, they have contributions considered to be the most significant, thus posing the most severe barriers in terms of the involvement of stakeholders in delivery (A.D, MA, & MRTPI, 2005).

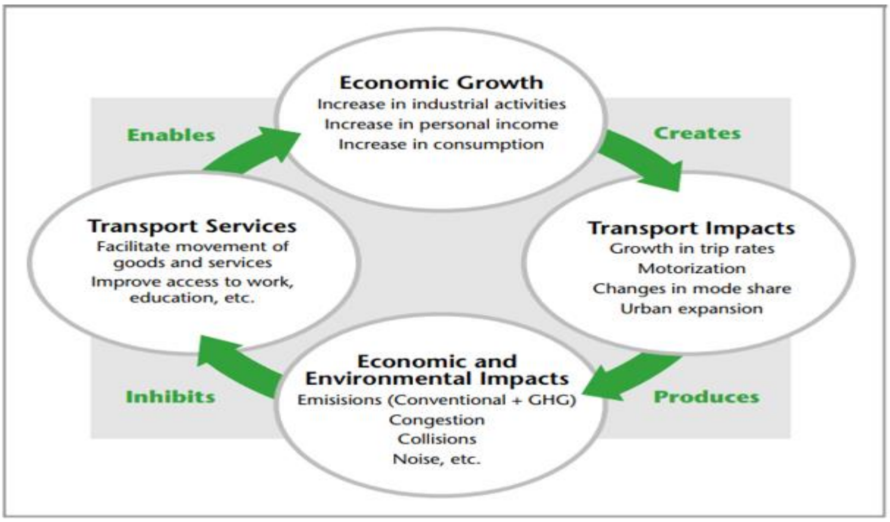

Figure 5. 1. The challenges of making mobility sustainable (Molina,2002)

4. PROPOSED SUSTAINABLE MOBILITY SOLUTION – VEHICLE INTEGRATED PHOTOVOLTAIC (VIPV)

The City of Kigali is the capital of Rwanda and is located at Rwanda's geographical heart. Occupying an area of 730km2, the city is located at latitude 10o58' S and a longitude 30o07' E. The average annual precipitation rate is approximately, with an annual average high temperature of 27°C and annual average low temperature of 16°C (kigali, 2023). We proposed vehicle intergrated photovolataic (VIPV) because it is the cleanest way of sustainable mobility solution in Transportation.

4.1. Integrated Photovoltaic (VIPV)

The idea of a solar-powered vehicle or vehicle-integrated photovoltaics (VIPV) is nothing new. It dates to the 31st of August in 1955 when William G. Cobb, a GM engineer, revealed the world's first VIPV prototype at the General Motors Powerama auto show held in Chicago, Illinois. "Sunmobile" was the name of his 15-inch-long tiny automobile, which included 12 photovoltaic cells made of selenium (a nonmetal substance with conducting properties) to power up a tiny motor that was connected to its rear axle by a pulley (solaredition, 2020). However, the fundamental idea behind that was not creating something clean and green that could help mitigate the environmental effects of diesel cars, as it was not considered a threat then. He wanted to show us the feasibility of running cars with solar energy. Currently, there are several companies like Sono motor (Sion), Lightyear (Lightyear One), Hyundai (Sonata), and Tesla (Cyber Truck), that are trying to use this approach to either extend their range or to be able to charge your vehicle thoroughly. Photovoltaics can be achieved in several ways: by solar-powered charging stations or photovoltaic modules built into a car's body parts (VIPV). The interest in VIPVs is due to the increase in the efficiency of solar modules, the decrease in the prices of solar modules, and the booming market of hybrid or electric vehicles. If all of the electric vehicles by the year 2030 were equipped with a solar roof and assuming those vehicles had an average roof area of 2/m² and a solar module with the capacity of 200 W/m², they would have a potential market of 18GW per year (solaredition, 2020).

4.2. VIPV Benefits

VIPV is still a relatively new technology, but it has the potential to improve the efficiency and sustainability of vehicles significantly. The following are the benefits of VIPV.

i. Increased range for EVs: VIPV can extend the range of EVs by up to 30%. This can make EVs more practical for long-distance travel.
ii. Reduced fuel consumption for gasoline and diesel vehicles: VIPV can reduce fuel consumption by up to 10%. This can save money and reduce emissions.
iii. Lower greenhouse gas emissions: VIPV can help to reduce greenhouse gas emissions from vehicles by up to 30%.
iv. Reduced dependence on fossil fuels: VIPV can help to reduce our dependence on fossil fuels by generating electricity from a clean and renewable source.
v. Enhanced vehicle aesthetics: VIPV can seamlessly integrate into the vehicle's design, adding a sleek and futuristic look.
vi. Potential for additional revenue streams: VIPV can provide opportunities for additional revenue streams through vehicle-to-grid (V2G) technology, where excess solar energy generated by the vehicle can be sold back to the grid.
vii. Reduced reliance on charging infrastructure: VIPV can help to reduce reliance on charging infrastructure, as vehicles can generate their electricity.
viii. Extended battery life: VIPV can help to extend the life of the vehicle's battery by reducing the need for deep discharges.
ix. Reduced maintenance costs: VIPV requires minimal maintenance, making it a cost-effective solution.
x. Improved sustainability profile: VIPV can significantly enhance the sustainability profile of vehicles, making them more environmentally friendly.

4.3. VIPV Challenges

Vehicle-integrated photovoltaics (VIPV) is a promising technology with the potential to significantly improve the efficiency and sustainability of vehicles. However, there are also several challenges that need to be addressed before VIPV can become widely adopted.

i. Cost: The cost of VIPV systems is currently relatively high. This is due to the high cost of the PV modules and the cost of integrating them into the vehicle. As the technology matures, the cost of VIPV systems is expected to come down.
ii. Efficiency: The efficiency of VIPV systems is currently lower than the efficiency of traditional PV panels. This is due to the fact that the PV modules must be integrated into the vehicle's body, which can reduce their exposure to sunlight. As the technology develops, the efficiency of VIPV systems is expected to improve.
iii. Durability: VIPV systems must be able to withstand the rigors of everyday driving, including exposure to the elements, vibration, and impact. As the technology matures, the durability of VIPV systems is expected to improve.
iv. Weight: VIPV systems can add weight to a vehicle, reducing fuel economy. As the technology develops, lighter and more efficient VIPV systems are expected to be developed.
v. Aesthetics: VIPV systems must be aesthetically pleasing in order to be accepted by consumers. More aesthetically pleasing VIPV systems are expected to be developed as the technology matures.
vi. Integration: VIPV systems must be integrated into the vehicle's design in a way that does not compromise the vehicle's safety or performance. As the technology matures, better methods for integrating VIPV systems into vehicles are expected to be developed.
vii. Standards and regulations: There are currently no standards or regulations governing using VIPV systems in vehicles. This could create challenges for automakers and consumers. As the technology develops, standards and regulations for VIPV systems are expected to be developed.
viii. Consumer acceptance: Consumers may be hesitant to adopt VIPV technology due to the higher cost and the perceived risks. As technology matures and the benefits become more apparent, consumer acceptance is expected to increase.

Despite these challenges, VIPV can be a transformative technology for the automotive industry. As the technology continues to develop, VIPV systems are expected to become widely adopted in the years to come.

4.4. Feasibility study

The feasibility of a fully solar-powered vehicle that is able to traverse great distances is very low. It is possible to use a fully solar-powered vehicle for short distances and there are some options on that front as well, like Sion from Sono motors which according to them can add up to 245 km (112 km on average) of driving range per week through solar energy to the car's battery.Also, the body of a vehicle has limited space to accommodate solar panels, and until their efficiency is not increased, they are not suitable for traversing long distances without any other source of energy, and for it to work with high efficiency, certain weather and climate conditions should be met as well. Right now, one of the feasible ways to use vehicle-integrated photovoltaics is to use them as a secondary source of power so they can be charged with electricity from the grid or charging station and solar energy. This, in turn, will also benefit the driving range of the vehicle (solaredition, 2020).

5. CONCLUSION

As of now, there aren't many VIPVs out there, but because of advancements in solar technology regarding efficiency and lowering of module prices, there is scope for further development and growth. This market also has great potential, reaching about 18 GW annually. So much so that by 2030, 10% of electric vehicles could be represented with VIPVs. Especially in sunny conditions, it is possible to drive for weeks without charging. Due to where it has been implemented as an example in the Netherlands, it is expected to have about 25% fewer times charging annually, and in summer, you may even drive for three months without recharging the vehicle a single time. In sunny places like Spain and Italy, the charging time might reach 40% with the current technology annually. Also, with three-to-four-year payback time, there is a reasonable benefit to be considered (solaredition, 2020) ,but when it comes to Kigali,Rwanda this will be more effective and efficient because it is located on a sunny day where it varies an average of between 16 degrees to 27 degrees and most of the times go higher, and also there is a problem of enough electricity which tackled the increase of electricity chargeable vehicles so implementing VIPV in Kigali will be effective and reliable.

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