Research Article

Integration of Microgrids and Electric Vehicle Technologies in the National Grid as the Key Enabler to the Sustainable Development for Rwanda

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Rwanda is an East African Community (EAC) nation with rapid and remarkable past development in different sectors and still with the ambitious targets and plans to be achieved in the coming years ahead. The government plans universal electricity access by 2024 with 52% grid connection and 48% off-grid connections. In the transport sector, the concept of electric vehicles has been initiated and started in order to contribute to the UN Paris agreement and decrease the reliance of the transport sector on gaseous fuels which are one source of air pollutants leading to climate change, premature deaths, and morbidity associated with poor air quality. With higher electricity demand than the generation of the Rwandan power grid, different energy strategies are being developed with the overall objective to achieve the targeted universal energy access. In order to overcome the aforementioned issue, this paper proposes an integration of solar PV microgrids for the satisfaction of electric vehicle (EV) technology in Rwanda. Using HOMER Grid software, a managed EV charging station is simulated to a grid connected solar PV microgrid with storage in order to assess the economic impact. The results show that the proposed technology can lower the levelized cost (LCOE) of electricity by 139.7%. This study can contribute to further research developments in either different perspectives related to the integration of distributed energy resources (DERs) with electric vehicles or studies related to affordable and environment-energy systems.

1. Introduction

Current electricity access all over the world is about 89.589% of the population according to the statistics of the World Bank using the database of Sustainable Energy for All (SE4ALL) [1]. Ten years of continuous improvement enabled the global electrification rate to reach 89.6%, with 153 million people gaining electricity access every year. Moreover, the greatest threat lies with over 573 million people remaining in the dark, especially those living in sub-Saharan Africa and in the remotest parts of the globe. Therefore, solar lighting, solar home systems, and more mini grids would be important at reaching the poor and the remotest of households. Universally, about 34 million people accessed basic electricity services using off-grid technologies in 2017 [2].

To date, access to electricity in Rwanda is estimated at 51% and those not grid connected are about 14% [3]. Rwanda has many distributed energy resources (DERs) like solar, biomass, hydro, methane gas in Lake Kivu, geothermal [4], and availability of feasible microgrids with different distributed energy resources like photovoltaics, battery storage, diesel generator, and electric vehicles are possible and implementable [4, 5].

Sustainable development is among key and crucial pillars for Rwanda and challenges for future community. By December 2015, around 195 countries ratified the Paris agreement to reduce greenhouse gas (GHG) emissions as entrenched in the United Nations Framework Convention on Climate Change (UNFCCC) [6]. Rwanda's mitigation effort comprises reducing the GHG emissions to 63.0% of the baseline over the period 2015-2030. This translates to 37.0% GHGs emission reduction and 4.6 million tonnes (CO₂) in 2030 [6, 7].

From energy generation viewpoint, the government of Rwanda decided to increase the use of renewables through different technologies such as microgrids and electric vehicle technologies (which is still in its initial stages) in order to meet increasing energy demand and tackle gas emissions [8]. Additionally, electric vehicles and vehicle fuel economy implementation guidelines are significant assumptions over the coming decade for new vehicles entering the fleet, development of charging infrastructure, and electricity grid decarbonization rate. The main aim of the paper is to analyze and enhance the contribution of microgrids and electric vehicles as key enablers for sustainable development. A firm EV station is analyzed by simulation considering that it is to be connected to a national power grid or a grid connected microgrid having storage, to assess the system contribution for affordable electricity tariff. The paper is organized into Introduction, Literature Review of Microgrids and Electric Vehicle Technologies, Methodology, Simulation Results, and Conclusion.

2. Literature Review of Microgrids and Electric Vehicle Technologies

Microgrids are small networks composed of different distributed energy resources, frequently linked to an integrated national grid that is able to operate in grid connected or islanded mode, and can be controlled by different control techniques such as traditional droop controller, modified droop controllers, and PQ controllers [9, 10].

2.1. Vehicle-to-Grid (V2G) Technology. Vehicle-to-Grid (V2G) technology discharges energy back to the grid to improve grid utilization, level demand, and improve reliability for utilities of the future. It can be used to support the utility grid services with stability increase and reliability of the network [11, 12]. The control of active power (P), and reactive power (Q) between electric vehicles (EVs), and microgrids through bidirectional energy flows make them to be considered distributed energy storage (DES) units [13]. The owner of electric vehicle is able to control the charging and discharging times and, thus, can be used as sources of income because they can sell excess energy to the utility grid operators. V2G enables energy to be pushed back to the utility grid while Grid-to-Vehicle (G2V) is the process in which electric vehicles are charged via the power grid. Therefore, it is very easy to control and monitor power flow in Vehicle-to-Home (V2H or V2B), and its implementation is not difficult compared to Vehicle-to-Grid because the reverse power interface is not required, but islanding detection capability and other power quality delivery detection interfaces. Different models of charging are considered depending upon the software package. Meanwhile, in energy planning, the four models considered include a dumb battery charger, flexible demand, smart charger, and V2G charging that contains EVs charging control based on different electricity tariff models [14]. Table 1 describes the power levels for the alternating and direct current for charging systems [15].

As the United Nations set guidelines for climate change and greenhouse gas emission limitations, many industries and researchers are still carrying out research on the development of different electric vehicles based on emissions and consumption [16].

2.2. Air Quality Standards in Rwanda. For climate change mitigations, every country should have an air quality standard based on the World Health Organization (WHO) guidelines, and air quality standards, set by Rwanda Environment Management Authority (REMA), are summarized in Table 2:

Table 3 describes the comparison of electric vehicles based on their driving component, energy sources, pros, and cons [16, 20–22]. Rajashekara discovered a new type of electric vehicles, which is slightly different from others and called plug-in fuel cell vehicle (PFCV) with a large battery and small fuel cell storage capacity that makes it a battery dominant car [19].

2.3. Grid-to-Vehicle (G2V) Technology. Grid-to-vehicle technology (G2V) is used in the design of suitable charging algorithm to control charging, battery balance, and condition of charge estimation that enhance the battery life [23]. The vehicle-to-grid (V2G) technology is deployed by the plug-in electric vehicle (PHEV) to release energy to the grid to enhance grid utilization, balance demand, and improve reliability. Furthermore, it is an effective distributed energy resource (DER) [23, 24].

2.4. Smart Charging (V1G) Technology. Different researchers revealed that the utility grid must be innovative and upgraded and with Supervisory Control and Data

TABLE 1: Alternating current (AC) and direct current (DC) power levels [15].

AC charging levels	DC charging levels
AC level 1: 120.0 volt alternating current (VAC). Single-phase (maximum) 16.0 amps (A); maximum 1.9 kilowatts (kW)	DC level 1: 200.0 to 450.0 volt direct current (VDC), maximum 80.0 A and maximum power is 19.2 kW
AC level 2: 240.0VAC, single phase, maximum 80.0 A, maximum 19.2 kW	DC level 2: 200.0 to 450VDC, maximum 200.0 A, maximum 90.0 kW
AC level 3: to be determined, can include AC three phases	DC level 3: to be determined and may cover from 200.0 up to 600.0 VDC, maximum 400.0 A, and maximum 240.0 kW

TABLE 2: Rwanda air quality standards versus WHO air quality guidelines [17–19].

Type of pollutant	Averaging period (hours)	Rwanda standards ($\mu\text{g}/\text{m}^3$)	World Health Organization (WHO) standards ($\mu\text{g}/\text{m}^3$)
Carbon monoxide (CO)	1.0	30,000.0	30,000.0
	8.0	10,000.0	10,000.0
Sulphur dioxide (SO ₂)	10.0 minutes	500.0	500.0
	24.0 hours	125.0	125.0
Ozone (O ₃)	1.0 hour	200.0	200.0
	8.0 hours daily maximum	120.0	120.0
Nitrogen dioxide (NO ₂)	1.0 hour	200.0	200.0
	Annual	40.0	40.0
Particulate matter (PM _{2.5})	24.0 hours	75.0	75.0
	Annual	35.0	35.0
Particulate matter (PM ₁₀)	24.0 hours	100.0	100.0
	Annual	50.0	50.0

TABLE 3: Comparison of electric vehicles (EVs) [20–22].

Type of electric vehicles	Type of driving component	Energy source	Pros	Cons
Solar electric vehicles (SEV)	Electric motor	Battery ultra-capacitor	(i) No expenses (ii) Environment friendly (iii) Zero net emissions (iv) Low maintenance (v) Able to utilize full power at all speeds	(i) Prices depend on the quality (ii) Dependence on the solar radiation
Fuel cell electric vehicles (FCEV)	Electric motor	Fuel cell	(i) Zero net emissions (ii) High efficiency compared to others slightly not expensive (iii) Available in market abundantly for some countries (iv) Energy recovery from regenerative braking	(i) Production of fuel (ii) Fueling facilities and storage security concern (iii) Standard development in process (iv) Scalable for mass manufacturing
Battery electric vehicle (BEV)	Electric motor	(i) Ultra capacitor battery	(i) Zero emissions (ii) Charging and discharging at convenient time and controlled (iii) No dependence on oil (iv) Income generation (v) Prosumer option (vi) Without gas and oil changes (vii) Capacity to conveniently charge at home (viii) Rapid and steady acceleration	(i) Battery life (ii) Battery price and capacity as well (iii) Charging time (iv) Expensive in some country of low and middle income generally (v) Availability of charging stations
Hybrid electric vehicles (HEV)	Internal combustion engines Electric motor	(i) Internal combustion engines (ii) Ultra capacitor (iii) Battery	(i) Composed of electrical and mechanical drive trains (ii) May be powered by both electric supply and other fuels (iii) Long range (iv) Low emissions	(i) Battery and engine capacity optimization (ii) High initial outlay
Plug-in hybrid electric vehicles (PHEV)	Electric motor	(i) Internal combustion engines	(i) Zero net emissions (ii) Little consumption (iii) Optimized performance	(i) Higher initial cost (ii) May be fed by a power from electrical and mechanical sources

FIGURE 1: Diagram of microgrid with different distributed energy resources (DERs). Note: the figure is based on the authors' understanding and analysis of different energy technology exploitations and the desire of EV exploitation for Rwandan market; no source or reference is linked to the figure.

Acquisition (SCADA) software package integration in order to shift from traditional grid to the smart grid, so that it will be able to cooperate with future demand [25]. Smart charging (V1G) is a charging process in which electric vehicles, charging stations, and charging operators exchange data connections. Also, the charging stations can supervise, organize, and regulate EVs for enhanced time, charging power size, direction, and utility applications. V1G is applied in traffic congestion management, frequency control, and charging photovoltaic systems (PV) [25]. V2G can also supply electricity to the home (V2H), building (V2B), load (V2L), and grid (V2G). The major threats to V1G and V2G depend on the uniformity requirements and information exchange protocols between the various systems [26, 27].

2.5. Flywheel Energy Storage System (FESS) Technology. The flywheel energy storage system (FESS) is among the best storage technologies and keeps energy in terms of kinetic energy (KE) through electronics converters [28]. Flywheel is composed of converters (rectifiers and inverters), generator, motor bearings, protection cover, and control systems, built by differ-

ent controllers in charge of controlling and maintaining charging, discharging cycle, and the status of flywheel [29, 30]. Therefore, the speed of flywheel usually varies between 6000.0 and 12000.0 revolutions per minute (r.p.m.). Consequently, energy storages are varying between 2 Mega Joules (MJ) and 500 MJ, and so many types of energy storage devices, namely, batteries, super capacitors, and super conducting magnetic energy storage systems, and every storage device has its own disadvantages and advantages [29, 30].

2.6. Microgrid System with an Electric Vehicle. Contemporary transportation systems using fossil fuels based on conventional vehicles are being capability replaced by electric vehicles which are eco-friendly to the environment [23]. Based on the knowledge that EV technologies are still at their infancy and taking also into consideration that some forms of energy technologies (such as usage of flywheel energy storage systems) have not yet been introduced to the Rwandan energy market, the authors of this paper suggest a new technology which can also be analyzed for energy exploitation and EV technology as it is shown in Figure 1. The concept

FIGURE 2: The lifetime carbon dioxide (CO₂) emission savings from electric vehicles (best case scenario) [33].

FIGURE 3: The lifetime carbon dioxide (CO₂) effluent savings from electric vehicles (worst-case) [33].

FIGURE 4: The carbon dioxide (CO₂) savings in EVs compared to typical diesel and petrol car emissions [33, 34].

TABLE 4: State of the art based on research for electric vehicles and contribution.

Research carried out on	Vehicle to-grid (V2G)	Load shedding scenarios	Multi-objective economic dispatch			Single objective economic dispatch	Algorithms/tools/optimizer	Ref.
			Operating cost (op)	Pollutant treatment cost (PTC)	Carbon dioxide emission (CDE)			
Wind turbine generators (WTG), photovoltaics (PV), cooling heating and power (CHP), battery storage systems (BSS)	Yes	No	Yes	No	No	Yes	CPLEX optimization tool box of MATLAB 2014b	[40]
Wind turbine (WT), photovoltaics (PV), battery storage systems (BSS)	Yes	No	No	No	No	Yes	Hybrid genetic algorithm with interior (pattern search-IP) methods Enhanced bee colony optimization (EBCO), bee colony optimization (BCO), evolutionary programming (EP), genetic algorithms (GA), and Particle Swarm Optimization (PSO)	[39]
Wind turbines, microturbines, photovoltaics, battery storage systems	No	No	No	No	No	Yes		[40]
Wind turbine, Photovoltaics (PV)	No	No	No	No	Yes	No	Composite imperialist competing and gray wolf algorithms (HIC-GWA)	[41]
Electric vehicles	Yes	No	No	No	No	No	Fuzzy logic controllers, traditional droop control and synchronverter	[42]
Photovoltaics (PV), wind turbine (WT), dispersed generation (DG), fuel cell (FC), battery depository system (BES)	No	No	No	No	No	Yes	Artificial bee colony (ABC), fuzzy logic controller (FLC), genetic algorithm (GA), Particle Swarm Optimization (PSO), seeker optimizations approach (SOA)	[43]
Photovoltaics (PV), battery repository system (BSS)	Yes	No	Yes	No	No	Yes	Dynamic programming (DP)	[44]
Microturbines (MT), fuel cell (FC), battery repository system (BSS), wind turbine (WT), Photovoltaics (PV)	No	No	Yes	Yes	No	No	Model Predictive Control (MPC)	[45]
Battery repository system (BSS), wind turbine, Photovoltaics, energy depositories, distributed energy resources (DERs)	Yes	No	No	No	No	No	Multiobjective Particle Swarm Optimizations (MPSO)	[46]
Wind turbine (WT), Photovoltaics (PV), distributed energy resources (DERs), battery depository system (BSS)	Yes	No	Yes	Yes	No	No	Particle Swarm Optimizations (PSO)	[47]

TABLE 4: Continued.

Research carried out on	Vehicle to-grid (V2G)	Load shedding scenarios	Multi-objective economic dispatch			Single objective economic dispatch	Algorithms/tools/optimizer	Ref.
			Operating cost (op)	Pollutant treatment cost (PTC)	Carbon dioxide emission (CDE)			
Electric vehicles (EVs)	Yes	No	No	No	No	Yes	Bi-level optimization (BLP)	[48]
Thermal power plant (TPP), wind turbine (WT), electric vehicles (EVs), battery depositories system (BSS)	Yes	No	Yes	No	Yes	No	Multiobjective Particle Swarm Optimizations (MPSO), fuzzy logic controller (FLC), supervisory control and data acquisition (SCADA)	[49]
Wind turbine, Photovoltaics (PV), microturbines (MT), diesel engine, battery depository system (BSS), electric vehicles,	Yes	No	Yes	Yes	No	No	Adjustable robust optimizations (ARO)	[50]
Wind turbine, Photovoltaics, diesel engine, fuel cell, battery repository system (BSS)	Yes	No	Yes	Yes	Yes	Yes	Particle Swarm Optimization	[51]
Wind turbine, Photovoltaics, diesel engine, fuel cell, battery repository system (BSS)	Yes	Yes	Yes	Yes	Yes	Yes	Particle Swarm Optimization (PSO), artificial bee colony,	[52]
Solar-powered electrical autorickshaw for rural transportation	No	No	No	No	No	No	SPEA as an alternative to conventional autorickshaws	[53]

FIGURE 5: The proposed system (a) and the current system (b).

in Figure 1 can also be mimicked and perfected using the Hybrid Optimization of Multiple Energy Resources (Homer) grid software as it has different distributed energy resources such as PV, flywheel storage, clean diesel generator (CDG), and plug-in hybrid electric vehicles (PHEV). Every microgrid component is connected via a local network communication system based on wired and wireless technologies (WIFI). Figure 1 represents the microgrids composed of different distributed energy resources with electric vehicles. Every component is advantageous to the network, and the different constraints have been analyzed during the design, which is summarized below:

- (i) At the beginning, microgrids and EVs are working in an islanded mode, which means that the PV and flywheel supply the community load while EVs are being charged
- (ii) Whenever the PV system is incapable of supplying the load, at that time, the clean diesel generator will be able to feed the load
- (iii) In case the PV is not able to supply the load and there is no fuel in the diesel generator but the EVs are charged, then the EVs can intervene and supply the community load

FIGURE 6: Average daily profile for the managed EV station.

- (iv) In case PV, diesel generator, EVs, and flywheel are not able to satisfy the demand, the system will be halted, and priority loads will be supplied

FIGURE 7: Annual load profile for the managed EV (average of 1258 kWh/day).

- (v) Microgrids will be responsible for controlling and managing variations of active power, reactive power, voltage, and frequency, which depend upon the type of controllers like traditional droop control and modified droop control
- (vi) During utility grid supply, all parameters will be monitored by the utility grid, especially because the PV, diesel generator, and EVs become incapable of satisfying the demand at that time. The utility grid will intervene depending upon the type of controllers, which are mostly PQ controllers, Virtual Synchronous Machines (VSG) or synchronverter method

2.7. Microgrid Operation. A microgrid operation (MGO) is a distributed class of electricity supply points and loads that typically connect and synchronize with the conventional wide area synchronous grid but could disconnect to an islanded mode through static transfer switch (STS) and function without support. As material or fiscal environments may demand, a ranked order structure could lead to a microgrid main controller (MMC) [31]. The diverse configurations and properties of the electronics in the microturbines, fuel cells, PV panels, wind including twice-fed induction generator technology (DFIG), and wind including permanent magnet synchronous machines (PMSM) technology make microgrids distinct from traditional power systems. Hence, energy repository equipment like flywheels and supercapacitors is interfaced to the grid to provide starting energy balance when the microgrid is islanded. Furthermore, these energy repositories provide active power whenever the microgrid either is islanded or swings in demand and supply occurs [31].

2.8. Technical Problems Based on V2G. The V2G technology, participation, and swift integration of electric vehicles (EVs) in the peak load periods of the network operations [32] provoke instability in the network and generate harmonics with frequencies greater than 50 Hz and 60 Hz, high penetration of EVs in the utility grid which may cause network weakness, electric vehicle smart charging arrangement, and effects of

FIGURE 8: Categorized annual savings.

charging/discharging on EV battery and V2G charger topology.

The bids and purchases of EVs have risen sharply because of the need of carmakers to satisfy the CO₂ emission reduction stipulated by the EU car regulations of 2020 and 2021. Furthermore, within the coming decades, EVs are expected to experience so much mass marketing that the number of EVs on the EU roads would be over thirtyfold by 2030. Based on the statistics, about 3.0% (1.3 million EVs) were sold by the end of 2019 and a total of 44.0 million electric cars are expected to be on the roads by 2030. This translates to over 97.0% EVs which would have been added to the fleet in the coming days and years to 2030. Consequent lifestyle changes would bring with them a collection of lifecycle analyses that measure EV pollutant emissions like carbon dioxide (CO₂), and battery charging/discharging cycles contrasted with traditional fossil fueled cars [33].

Investigators are advised not to use obsolete data in their research because unreliable data can deliberately confuse lifecycle assessments. The obsolete data were used to compare electric vehicles and traditional cars which use either a diesel generator or petrol which needs upgrading [33]. The transport and environment (T&E) company have created detailed and useful analogies of electric, diesel, and petrol engines in distinctive car capacities between 2020 and 2030 as shown in Figure 2. Figure 2 is the lifetime plot of carbon dioxide (CO₂) emission savings from electric vehicles. In the European Union (EU), electric cars emit 80.0% less carbon dioxide (CO₂) than diesel and 81.0% than petrol [33].

Research indicates that the typical EU electric car has about three times superior performance than the traditional equivalence today. It is expected that electric cars will become

FIGURE 9: Monthly utility bills.

over four times cleaner than their traditional equivalents in the EU by 2030 [33].

Typical medium-sized EU electric cars sold in 2020 released about 90.0 gCO₂ e/km, diesel car vented 234.0 gCO₂ e/km, and gasoline car emitted 253.0 gCO₂ e/km over their lifetimes, respectively. Typically, in the EU, the EV releases about 2.7 times less CO₂ than the traditional car in 2020 (2.6 times less than diesel and 2.8 times less than gasoline). A storage battery produced with clean electricity reduces the electric car emission to 86.0 gCO₂ e/km or 2.7–3.0 times less. Electric cars were operated on clean renewable electricity (hydro power); then, the GHG emission reduces to 11.0 tons of CO₂ (47.0 g/km), which is between 5.0 and 5.4 times less than diesel and gasoline equivalents, as shown in Figure 2 [33]. For substantial and leadership classes, the typical EU electric cars are between 2.8 and 3.1 times superior to their traditional equivalents [34].

At the worst, the battery storage is manufactured in China and used in electric vehicles operated on Poland's carbon demanding grids. Therefore, the lifespan effect rises to 41.0 tons of CO₂ (182.0 g/km) and EVs are still 22.0% cleaner than their diesel equivalent and 28.0% cleaner than their gasoline equivalent as shown in Figure 3 [33]. A per European Union (EU) member state testing is possible in the device.

Figure 4 [33, 34] describes the carbon dioxide (CO₂) savings correlated with the typical diesel and petrol emissions. Up to date petrol and diesel cars emit almost 3.0 times more carbon dioxide (CO₂) than the typical European Union electric car [33, 34].

2.9. Levelized Cost Components. EV owners have multiple options for recharging their vehicles, for example, different places such as grocery stores, home, public, shopping malls, workplaces, and private parking area where the charging stations are installed. The vehicle purchase cost, on-fuel operations and maintenance cost, fuel cost, and, occasionally, transportation cost are considered in the overall cost of the EV. The levelized cost is the likely vehicle age current value of the consumer cost per kilometer (km) as depicted in equation (1). Therefore, the vehicle's leftover value is removed from consumer cost analysis. This value may be deducted from the total cost if considered. Some assumptions are made such as ignoring the vehicle residual value mainly because some data are not available conventionally for residual value

TABLE 5: Annual utility bills and savings by category.

	Consumption charge	Total
Base case	\$118,946.00	\$118,946.00
Proposed case	-\$1.61M	-\$1.61M
Annual savings	\$1.73M	\$1.73M

of battery electric vehicles (BEVs) [35–37]. Consequently, the general equation for levelized cost is written as follows:

$$LC_n = \frac{(PC + \sum_{i=1}^n (FC_i + OC_i + AC_i) / ((1 + DR)^{i-1}))}{\sum_{i=1}^n DT_i} \quad (1)$$

AC is the vehicle age substitute transportation cost (only for BEVs) (Rwandan Francs); DR is the 6.0% deduction rate assumed for the analysis, in which a sensitivity analysis addresses the uncertainty; DT is vehicle age (km) distance traveled, OC is vehicle age nonfuel operation and maintenance (O&M) cost (Rwandan Francs); LC_n is the vehicle's levelized cost for *n* years (Rwandan Francs/km); PC is vehicle purchase price (Rwandan Francs); and FC is the vehicle age fuel cost (Rwandan Francs) exclusively for battery electric vehicles (BEVs).

2.10. State of the Art Based on Research for Electric Vehicles and Contributions. Table 4 summarizes the state-of-the-art researches carried out and the gaps associated with electric vehicles (EVs) in [38] wherein the authors detailed the performance analysis and optimization of solar-powered E-rickshaw for environmental sustainability in rural transportation and [39] wherein the authors described different types of fuel cell usually used in microgrids.

3. Methodology

The research in this paper used the HOMER Grid software, a powerful tool for detailed simulation concerning the needs (hourly, daily, monthly, and annual scenarios), capable of optimization (able to optimize for cost effectiveness), and able to carry out sensitivity analysis [53]. Given the fact that EV technology is still at its initial phases in Rwanda (configuration shown in Figure 5(a) where the EV is linked to the power grid), the system used the High E-Tech Smart Grid

FIGURE 10: Utility and the solar PV microgrid electricity production.

FIGURE 11: Daily electricity production over the year from the PV microgrid system.

Laboratory location resources of the African Centre of Excellence in Energy for Sustainable Development (ACE-ESD), University of Rwanda, Kigali, Rwanda, to simulate the grid-connected solar PV microgrid with storage and a managed EV station (as shown in Figure 5(a)), precisely located at KN 3 Avenue, Kigali, Rwanda (1°57.6'S, 30°3.8'E). Rwanda electricity and feed-in tariffs data, NASA climatic weather conditions for solar energy generation, and National Renewable energy laboratory database were adopted as the HOMER resource database. A managed EV station with 100.0 as proportion of the EV population, 150.0 kW maximum charging power per EV (charger output power kW), 40.0 chargers, and 7.0 hours connected mean time were obtained from HOMER software and incorporated into the Rwanda case study in order to study and analyze the impact of integrating solar PV microgrid and EV in the Rwandan network. Note that the managed EVs term used in the concept of this paper is well known as deferrable EV as it allows users to optimize their charging stations, lower their monthly utility bills, and have some flexibility for when the EV load is served [54]. Not only these data, there are also several research documents which were consulted by the authors to make the research work content in this paper more concise and communicative. Note that it was clarified for the whole body of this paper that the term “base case” refers to a system where the EV is connected directly to the national power grid for charging as shown in Figure 5(a), while the “proposed case” refers to the technology where the EV can be connected to the grid-connected solar PV microgrid for charging as shown in Figure 5(b).

TABLE 6: The EV charging load (managed EV).

Annual energy served	459,250.0 MWh
Peak load	300.0 kW
Energy per session	125.0 kWh
Charging sessions per day	10.1
Charging sessions per year	3,674.0
Average missed sessions per day	0
Utilization factor	7.34%
Average session duration	7.00 hr

4. Simulation Results

Electricity generation through solar energy technologies is dependent on climatic weather conditions such as irradiance and clearness index (CI) which is the division output of the sun-oriented radiation that is transmitted through the atmosphere to strike the surface of the Earth; a dimensionless number between 0 and 1 and temperature variation were parameters used for the simulated location in the case study. For the location used in this research paper as the research object location, the average monthly Global Horizontal Irradiance (GHI) (which is the total solar radiation incident on a horizontal surface expressed in kW/m²/day) shows variation throughout the year and within the range between 4.457 and 5.348 kWh/m²/day in which the overall annual average was 4.914 kWh/m²/day for one month. The clearness index falls within the range of between 0.451 and 0.579; and the

FIGURE 12: Energy served (MWh), monthly energy served to the managed EV.

FIGURE 13: Cumulative cash flow over the project lifetime.

temperature is within the range 18.66 and 20.59°C with overall monthly average temperature of 19.583°C throughout the year. Such subjected climatic weather parameters and conditions are the major incentives for high output energy production from solar technologies once well exploited.

Figure 6 describes the average daily load profile for the managed EV stations as simulated in the case study used as the research object of this paper, and Figure 7 shows its variation throughout the year. The managed EV loads usually also referred as deferrable load by HOMER software permits clients and owners to improve EV charging stations and lower their electricity service bill month by month. The managed EV load as simulated in this research has an average of 1258.0 kWh/day. The load consumption structure varies from hour to hour within a day, and it is shown that the minimum consumption was between 7.279 kWh and 8.173 kWh occurring around 00:00 pm (midnight), respectively, for both weekdays and weekends, the maximum consumption was between 84.82 kWh and 92.307 kWh occurring at 12:30 pm and 11:30 am, and the highest consumption of 9.0 kWh occurs within 09:00 am up to 19:00 pm.

Figures 8 and 9 describe the categorized annual savings per year for the proposed system and the monthly electricity bills for both basic and proposed systems. With the proposed system, there will be annual energy savings with the value

equal to US\$1,725,103.00, and it will decrease the cost for operation and maintenance (O&M) which is considered the cost associated with operating and maintaining the proposed project to US\$-11,248.00 and the total annual overall energy value stream was US\$1,173,857.00. As it can be shown in Figure 9, the monthly electricity bill for the proposed system is lower than that for the basic (current) system for the whole year.

Table 5 describes the annual utility bills and savings by category for both the current system and the proposed system, and it can be shown that the consumption charge with the proposed system is around -\$1.6M while for the base case system is estimated at \$118,946 which results in overall annual saving for the consumption charge equals \$1.73M. Note that the base case is the EV connection to the grid, and the proposed case is the EV connection to a grid-connected system with solar PV microgrid with its storage.

Figure 10 describes the monthly electricity production as expressed in MWh for both the utility grid and the PV system, and Figure 11 is the daily electricity production from the PV system over a period of one year with hourly details for one day. The minimum electricity production required from the grid of 10.995 MWh occurred during November, while for the PC system, a minimum production of 823.731

TABLE 7: Cash flow through the project lifetime (25 years).

(a)										
Year	1	2	3	4	5	6	7	8	9	10
PV	(\$11,246.0)	(\$11,246.0)	(\$11,246.0)	(\$11,246.0)	(\$11,246.0)	(\$11,246.0)	(\$11,246.0)	(\$11,246.0)	(\$11,246.0)	(\$11,246.0)
PV bonus depreciation	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00
PV capital incentive	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00
Grid tariff	\$1.61M	\$1.61M	\$1.61M	\$1.61M	\$1.61M	\$1.61M	\$1.61M	\$1.61M	\$1.61M	\$1.61M

(b)										
Year	11	12	13	14	15	16	17	18	19	20
PV	(\$11,246.0)	(\$11,246.0)	(\$11,246.0)	(\$11,246.0)	(\$11,246.0)	(\$11,246.0)	(\$11,246.0)	(\$11,246.0)	(\$11,246.0)	(\$11,246.0)
PV bonus depreciation	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00
PV capital incentive	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00
Grid tariff	\$1.61M	\$1.61M	\$1.61M	\$1.61M	\$1.61M	\$1.61M	\$1.61M	\$1.61M	\$1.61M	\$1.61M

(c)					
Year	21	22	23	24	25
PV	(\$11,246.0)	(\$11,246.0)	(\$11,246.0)	(\$11,246.0)	(\$11,246.0)
PV bonus depreciation	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00
PV capital incentive	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00
Grid tariff	\$1.61M	\$1.61M	\$1.61M	\$1.61M	\$1.61M

TABLE 8: Utility monthly summary for the base case.

Month	Energy purchased (kWh)	Energy sold (kWh)	Net energy purchased (kWh)	Peak load (kW)	Energy charge	Demand charge	Fixed charge	Minimum charge	Taxes	Total
January	41,125.0	0.0	41,125.0	300.0	\$10,651.0	\$0.0	\$0.0	\$0.0	\$0.0	\$10,651.0
February	36,125.0	0.0	36,125.0	300.0	\$9,356.0	\$0.0	\$0.0	\$0.0	\$0.0	\$9,356.0
March	39,750.0	0.0	39,750.0	300.0	\$10,295.0	\$0.0	\$0.0	\$0.0	\$0.0	\$10,295.0
April	34,875.0	0.0	34,875.0	300.0	\$9,033.0	\$0.0	\$0.0	\$0.0	\$0.0	\$9,033.0
May	40,625.0	0.0	40,625.0	300.0	\$10,522.0	\$0.0	\$0.0	\$0.0	\$0.0	\$10,522.0
June	38,200.0	0.0	38,200.0	300.0	\$9,894.0	\$0.0	\$0.0	\$0.0	\$0.0	\$9,894.0
July	38,175.0	0.0	38,175.0	300.0	\$9,887.0	\$0.0	\$0.0	\$0.0	\$0.0	\$9,887.0
August	40,625.0	0.0	40,625.0	300.0	\$10,522.0	\$0.0	\$0.0	\$0.0	\$0.0	\$10,522.0
September	38,000.0	0.0	38,000.0	300.0	\$9,842.0	\$0.0	\$0.0	\$0.0	\$0.0	\$9,842.0
October	37,625.0	0.0	37,625.0	300.0	\$9,745.0	\$0.0	\$0.0	\$0.0	\$0.0	\$9,745.0
November	34,875.0	0.0	34,875.0	300.0	\$9,033.0	\$0.0	\$0.0	\$0.0	\$0.0	\$9,033.0
December	39,250.0	0.0	39,250.0	300.0	\$10,166.0	\$0.0	\$0.0	\$0.0	\$0.0	\$10,166.0

TABLE 9: Utility monthly summary for the proposed system.

Month	Energy purchased (kWh)	Energy sold (kWh)	Net energy purchased (kWh)	Peak load (kW)	Energy charge	Demand charge	Fixed charge	Minimum charge	Taxes	Total
January	14,700.0	826,677.0	-811,977.0	300.0	-\$133,421.0	\$0.0	\$0.0	\$0.0	\$0.0	-\$133,421.0
February	13,149.0	776,038.0	-762,889.0	300.0	-\$125,417.0	\$0.0	\$0.0	\$0.0	\$0.0	-\$125,417.0
March	13,496.0	825,538.0	-812,042.0	300.0	-\$133,544.0	\$0.0	\$0.0	\$0.0	\$0.0	-\$133,544.0
April	12,666.0	765,615.0	-752,949.0	300.0	-\$123,811.0	\$0.0	\$0.0	\$0.0	\$0.0	-\$123,811.0
May	13,684.0	790,264.0	-776,580.0	300.0	-\$127,640.0	\$0.0	\$0.0	\$0.0	\$0.0	-\$127,640.0
June	13,472.0	835,826.0	-822,354.0	300.0	-\$135,258.0	\$0.0	\$0.0	\$0.0	\$0.0	-\$135,258.0
July	14,305.0	914,351.0	-900,046.0	300.0	-\$148,077.0	\$0.0	\$0.0	\$0.0	\$0.0	-\$148,077.0
August	14,004.0	933,383.0	-919,379.0	300.0	-\$151,314.0	\$0.0	\$0.0	\$0.0	\$0.0	-\$151,314.0
September	13,368.0	871,782.0	-858,414.0	300.0	-\$141,253.0	\$0.0	\$0.0	\$0.0	\$0.0	-\$141,253.0
October	12,789.0	852,903.0	-840,114.0	300.0	-\$138,269.0	\$0.0	\$0.0	\$0.0	\$0.0	-\$138,269.0
November	10,695.0	734,075.0	-723,379.0	300.0	-\$119,086.0	\$0.0	\$0.0	\$0.0	\$0.0	-\$119,086.0
December	13,017.0	797,812.0	-784,794.0	300.0	-\$129,065.0	\$0.0	\$0.0	\$0.0	\$0.0	-\$129,065.0
Annual	159,347.0	9,924,264.0	-9,764,917.0	300.0	-\$1.61M	\$0.0	\$0.0	\$0.0	\$0.0	-\$1.61M

MWh occurred in April and the maximum PV production of 1008.212 MWh occurred in July and 14.699 MWh in January, respectively, for the PV system and the utility grid. The PV system has a nominal capacity of 7,497.0 kW. The annual production was 10,762,281.0 kWh/yr; capital cost, \$10.8 million; specific yield, 1436.00 kWh/kW; and maintenance cost, \$11,246.00 per year.

As given by the simulation results and as shown in Table 6, the annual energy consumption of this EV depot is 459,250.0 kWh and the peak load is 300.0 kW. The 10.1 charging sessions per day are supplied through 40.0 chargers, each capable of providing 150.0 kW maximum power output. The average session duration is 7.0 hours. The electric vehicles served by this depot have the following charging characteristics: 100.0% percentage of EV population, 150.0 kW maximum charging power per EV, and the 125.0 kWh as average required energy.

Figure 12 describes the energy served in Megawatts hour for every month to the managed EV load where it kept fluctuating within the year. The highest 41.125 MWh was achieved during January, and the lowest 34.875 MWh occurred during April and November, respectively. Figure 13 represents the cumulative cash flow over the project lifetime, and Table 7 describes in detail the cash flow through the project lifetime over 25 years. It can be seen from Figure 13 that the cost (cash flow) for the base system slightly increases as time goes on while the cost with the proposed system greatly decreases with the project time frame period. Tables 8 and 9 describe the utility monthly summary for both the base system and the proposed system, respectively. It can be shown in Table 9, through peak load shaving of the PV system on the 300.0 kW peak load each month which led to a good system profit through energy sold, energy purchased, net energy purchased (kWh), energy charge, and the overall system total.

5. Conclusion

The geographical location of Rwanda promises a good and fruitful output of solar energy once well and highly exploited. The study in this research proves it through an integrated solar PV microgrid connected to the national power grid with a managed EV charging station. The proposed technology once implemented promises the reduction of NPC from \$1,715,610 to -\$15,480,080 and the LCOE from \$0.259/kWh to -\$0.103/kWh all contributing to affordable and reliable energy system (the negative value of levelized cost of electricity and net total net present cost means that the income obtained from selling electricity to grid is more than the money spent to purchase electricity from the grid; and this indicates that the revenues exceed the costs). The solar energy system (integrating a solar PV system to a grid for the EV charging) as proposed in this research can lead to an efficient increase of national energy resource exploitation in the Rwanda, resulting in reliable, affordable, and sustainable energy access to all the citizens, and is known to be reliable and affordable and to have pillar sustainable development.

Data Availability

The data used in this research are available upon the request from the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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