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Research Article

VIRTUAL POWER PLANT SOLUTION FOR KENYA RURAL ENERGY NEEDS

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Abstract: *A Virtual Power Plant system is an advanced power distributing and trading platform, that acts as a smart grid system unlike the existing conventional methodology of power allocation. The system is known to facilitate the connection of renewable energy sources to the national grid from a specific region, it is made up of Energy Storage System, Distributed Energy Resources, and Control System. Energy sources are classified as Distributed Energy Resources and various assets can be linked to the platform such as small-scale microgrids or community-based power platforms with demand-side management portfolios. A Virtual Power Plant platform has the power-distributing capability and an evolutionary trading platform (Peer to Peer trading). It has also proven to cut down carbon emissions as more renewables find their way to the grid. Additionally, data analytics and forecasting tools on the Virtual Power Plant are used to give information to the end-users on their storage, demand, and expected future generation. The user can interact with the system through a Human Machine Interface with an easy-to-use dashboard. Currently, the VPP systems have been implemented as pilot programs in countries such as Sweden, Norway, Belgium, and the USA. The potential application of the system can be extended as a case study and futuristic smart grid system for Kenya, as the National grid is substantially fed from renewable energy sources, and the vast majority of rural areas can benefit from cheap and affordable energy.*

Keywords*: Virtual Power Plant, Distributed Energy Sources, Rooftop photovoltaic, Renewable Energy Sources, Energy Storage Systems.*

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1. Introduction

Kenya is located on the eastern part of the African continent bordered by Tanzania to the south and Uganda to the West. It has 582,650 sq kilometers and its location astride the equator enables Kenya to receive sunlight almost throughout the year. Average annual irradiation ranges from 4 to 6kWh/m^2-day and average sunshine duration varies from 5 to 7 hours a day depending on the regions. Kenya's installed capacity is 2,545MW as of July 2019, exceeding the demand figure of 2018 of about 1,802MW. However, the supply is not enough to keep up with the demand due to frequent network losses, droughts and renewable energy that varies with weather conditions from region to region. Out of the total installed capacity, the Independent Power Producers account for 991MW of on-grid capacity. In the year 2019, Kenya's energy mix was largely from renewable energy sources with an average of 86.8% of which 45% came from geothermal energy, which reduced thermal power dependence by 11% [1].

The country's energy reserves have diversified for the last decade and include petroleum, natural gas, coal, uranium, geothermal and Renewable Energy Sources including wind, solar and biomass as shown in Table 1.

Table 1. Total Energy Reserves 2019 [2].

Source	Installed capacity (MW)
Hydropower	820
Thermal generators	716
Geothermal	877
Wind	336
Solar PV	54
Thermal (gas turbine)	60
Off-grid and temporary thermal	57
Biomass	30
Total	**2,950**

The government has shown an increasing interest in the development of solar power plants across the country such as 50MW Garissa solar photovoltaic power plant which is a joint venture between the Kenya Rural Electrification (KREA) Authority and the Jiangxi Corporation for International Economic and Technical Co-operation (CJIC). Also, there are plans to step up power generation capacity to about 3,400MW from the existing 2,545MW for the next 5 years. Long term objective is to reach an installed capacity of 6,000MW within a decade. Solar and wind energy are less common energy sources, but through effective government policies investors have been motivated with fast bureaucracy and approval for on-site process. Projects below 3MW of solar power generation are permit free. There are about 150 commercial microgrids in Africa, whereby 65 of them are located in Kenya [3]. The expected number of microgrids in Kenya is estimated to be 2000-3000 in 2021, representing a huge market potential for microgrids. Diverse microgrids can be connected to the VPP platform, which provides a future market support platform for various energy actors especially renewables, and in the coming years renewable energy could replace fossil energy [4] , with implementation of this platform, new energy market systems will allow participation of consumers in trading, though, uncertainty of electricity price [5] could impede the adoption process. Research on mitigation of the uncertainty risk is suggested in [6] with emphasis on adjustment on confidence and robustness coefficients .Additionally, a cooperative optimal scheduling of energy resources has been studied in [7], and subsequent models have been suggested.

This paper focuses on the available energy mix in Kenya given that the country's economic growth has put pressure on electricity supply. Between 2004 and 2013, power demand rose by 18.9% annually. Therefore, VPP power sharing platform is suggested to connect rural areas that experience regular power outages or lack electricity due to distance from the national grid. Three households are modelled and assumed to be apart geographically (DER). Furthermore, the impact analysis of PV systems to the grid is analyzed and future work is suggested. Possible use cases for Kenya both as an emerging flexibility and trading concept are investigated. The model has been developed using MATLAB Simulink and MATLAB library components. Models of energy systems (such as energy storage, PV) and residential loads have been integrated and linked to the point of common coupling, the parameters used are solely for simulation purposes and they might not reflect the actual scenario of the Kenyan Grid network.

2. Previous Work

A VPP can be defined in various ways, it can be an aggregation of different type of distributed resources dispersed in different points of medium voltage distribution network. Additionally, it is a system that has flexible representation of portfolios of distributed generation units that can be contracted in the wholesale market and offer services to the system operator. Lastly, as per the features and functions, it aggregates the sum of many diverse DERs to create a single operating profile from an amalgamation of various parameters characterizing each DERs, by incorporating the impact of the network on aggregate DERs output.

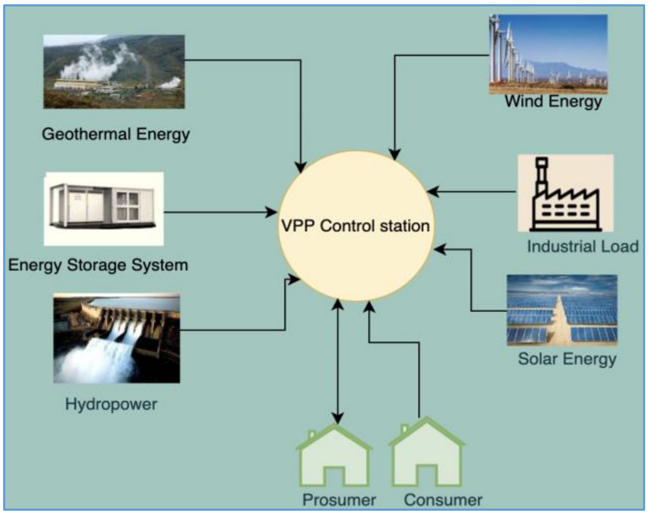

Figure 2. Large Scale VPP System for Diverse Renewable Energy Sources.

The system is composed of distributed energy resources, energy storage systems and a control centre for information management or information and communication Technologies as shown in Figure 2[8].

Distributed Energy Sources can be grouped into various categories depending on primary energy sources, capacity, ownership, and operational nature. In the first category, they can be wind-based generators, photovoltaic power plants, combined heat and power, biogas, and fuel cells (FC). As for capacity, these systems can be small-scale or both medium and large-scale capacity distributed generators. Regarding ownership, mostly the national government owns and operates these energy sources, but governments also encourage ownership by creating effective policies and licensing at the residential, commercial (Independent Power Producers DGs) or industrial level. According to the operational nature, DERs can vary with technologies based on wind, photovoltaic, FCs or micro-turbines [9]. Energy Storage Systems can store energy during off-peak period when the demand is low and give it off when the demand is high or during peak period.

Energy Management system coordinates and executes the commands between the DERs and existing loads, communication is bidirectional involving reception, control and forecasting of information of every component connected. Figure 2 demonstrates DERs in Kenya, more than 39% of electricity is hydro generated and are in most parts of the country. Geothermal energy sources are mostly located in a specific region (Olkaria), and Mega Solar power plant and wind-based energy sources are in Garissa and Turkana on the northern part of Kenya.

Table 2. Energy Demand Side Strategies and Technologies.

DSM Strategies	DSM Technologies
Community involvement	Pre-paid meters
Consumer education and village committees	Advanced metering systems with centralized communication
Price incentives	Conventional meters
Restricting residential use	Distributed Intelligent load controllers
Commercial load scheduling	GridShare
Efficient appliances and lights	Current limiters

Table 2 shows demand-side strategies in residential sectors as per government and other stakeholders' directives, this aims at fostering participation of consumers in the stabilization of the grid, and further lays a roadmap for future implementation of smart grid systems in the country [10]. For the VPP platform to be realized both consumers and prosumers play key roles in trading electricity power, as the latter can consume and generate power also termed as community-based small scale VPPs. In the case of large scale VPP, distributed generators or DERs require intensive capital investment as production capacity is within the range of 500-1000MW, which requires advanced system structures to control power flow by keeping up with the demand and dispatching DG resources on a timely basis, such kind of resources are not entirely switched off but are optimally controlled.

Table 3. Scheduling procedure based on priority [11].

Demand / Priority	Remaining load 1	Remaining load 2	Remaining load 3
1st Priority	DG3(Hydro energy)	DG1(Geothermal energy)	DG2(PV)
2nd Priority	DG2(PV)	DG3(Hydro Power)	DG1(Geothermal energy)
3rd priority	GRID	GRID	GRID

Load scheduling and resource dispatch are given priority through control of active power for large scale VPP according to Table 3. Loads can be modelled as industrial loads attached to the grid network.

$\mathbf{P_{d(1,2,3)}}$: Active power demand signal from load 1, 2 and 3.

$\mathbf{\Delta P_{d(1,2,3)}}$: Remaining active power demand signal from load 1,2 and 3.

$\mathbf{P_{e(1,2,3)}}$: Active power signal from DG 1, 2 and 3.

A limit is set for each load and when consumption is high and one single DG cannot cope with the supply a second DG is scheduled until all the DGs are used. In case the demand is not met by the available DGs, the grid power is scheduled. The process goes on repetitively ensuring steady power flow in the network, this is enabled by a communication and information module that collectively work to determine economical dispatch of DGs. The modules constitute a platform, in which data analytics, cloud computing and artificial intelligence functions are systemically accomplished, subject to low latency and high transmission performance [12].

2.1. Energy Management Algorithm

In this paper a central energy management algorithm is designed and the working of a local or household energy management has similar functionality. The energy algorithm has been designed for future use cases, control of renewables and storage systems for arbitrage energy trading, with focus on optimal dispatch of storage systems. It is assumed combined PV generation of households, energy storage systems and total load consumption are modelled as a unit and later extended into the grid network through the point of common coupling, at this point the exchanged energy between the modelled microgrid and the grid can be monitored.

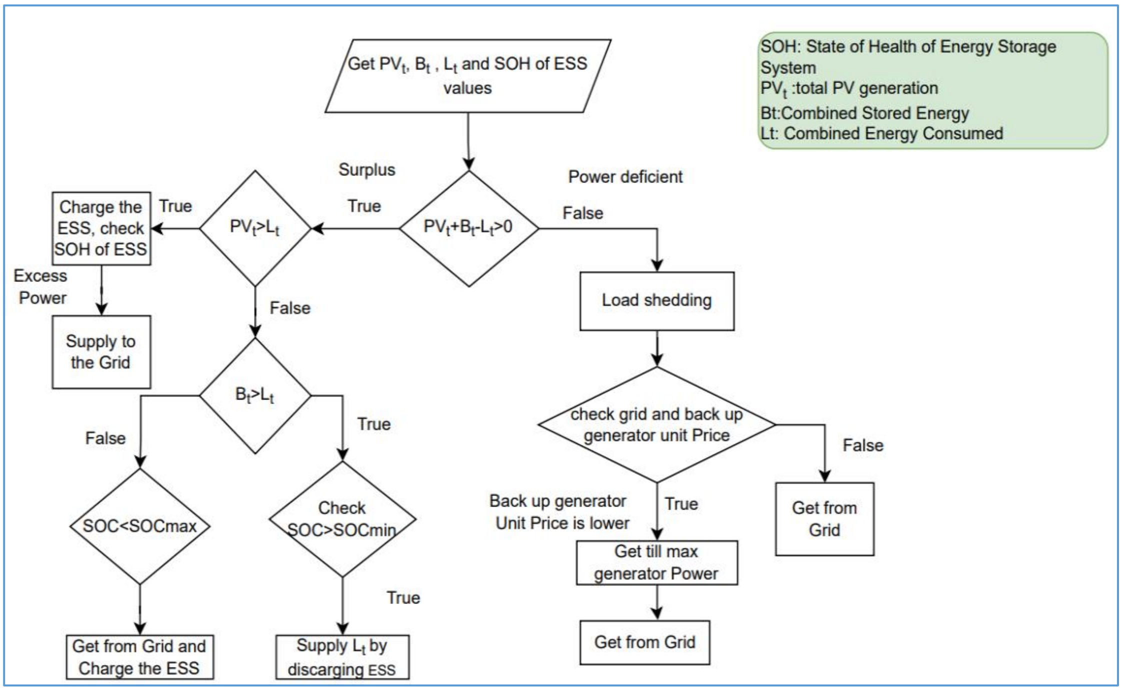

Figure 3. Energy Flowchart Algorithm

Figure 3 shows an energy algorithm flowchart that takes in values such as total Solar PV from the households, combined stored energy and total load consumption from the households under study. Depending on the energy balancing equation, an energy management system evaluates every part of the algorithm, if the output of the balancing equation is negative, then power deficit exists and the user is advised to apply load shedding, which reduces the amount of power consumed by altering non-critical consumption devices, this can either be by switching them off or changing the device settings. Additionally, the algorithm can check the prices of backup generator prices and compare them with the grid prices, and according to the energy needs of the households, the generator can supply maximum power and if power deficiency still exists, the grid can cater for the remaining power deficient.

On the hand if the balancing equation is positive, it implies surplus exists and both the battery and the total Solar PV have to be checked, in case total PV does not meet the households load demand, stored energy is checked and if true, state of charge is compared to the state of charge minimum to avoid over-discharging of energy storage system, if false, and it is found state of charge is less than state of charge maximum, then this ensures the energy storage system in not undercharged when supplied from the grid. In the instant that the Solar PV exceeds the household demand, energy storage system is charged by considering its state of health, after the cycle of charging, excess power is supplied to the grid, and the process continues.

3. Modelling and Simulation

Small-scale VPP is simulated using MATLAB Simulink 2021. Three households are connected to create a microgrid system that in turn forms an interface with the grid transmission system at a Point of Common Coupling (PCC). Each Household has a generation unit (Solar PV), Energy Storage System and a load. Solar panels are typical technology tools and can be acquired and installed easily in many parts of the country.

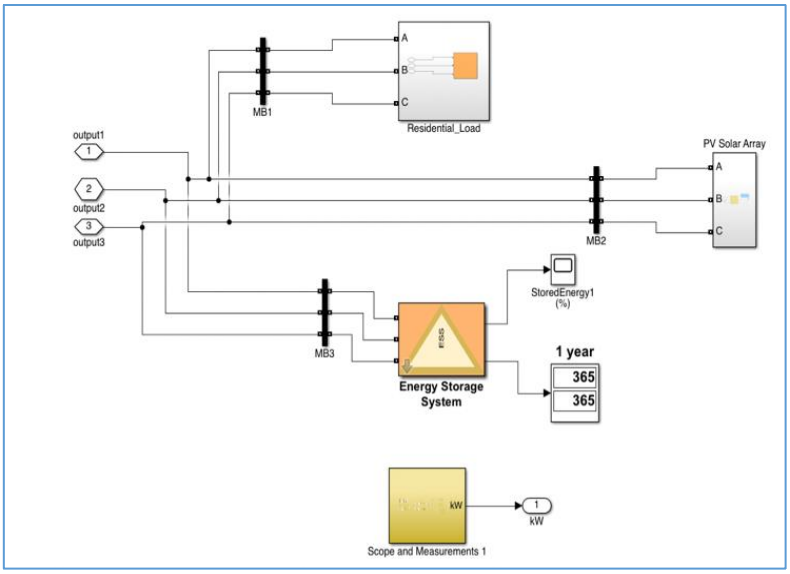

Figure 4. Energy Storage system, PV, and Load Household Simulink model

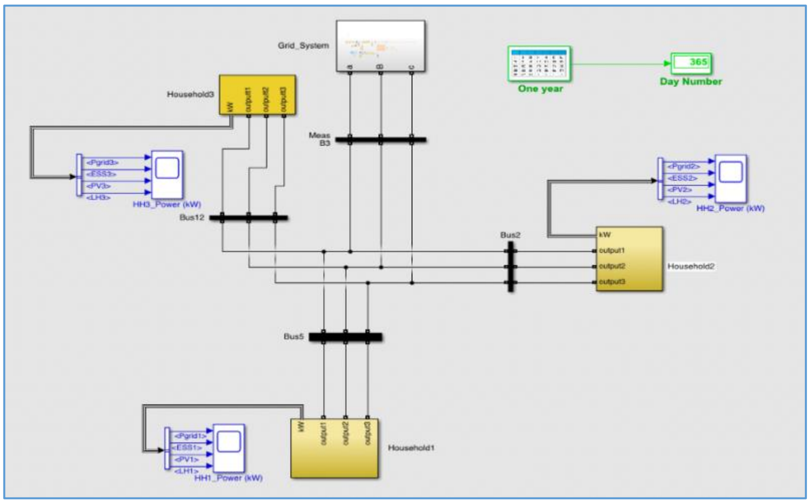

Figure 5. Three Households Grid-connected

Household structural arrangement of generational unit, Storage and load system is given in Figure 4 while MATLAB Simulink Model for VPP containing three households and grid is shown in Figure 5. The PV unit has a 20% efficiency and depends on the solar irradiance and temperature. In this study, Phasor simulation method is used, the simulation time is set to 365 days.

Table 4. Energy system components and capacities.

Energy system components	HH1	HH2	HH3
ESS (kW/kWh)	300/1500	240/1000	240/1000
Nominal LOAD (KVA)	1300	1500	1500
PV (kW)	220	200	1000

The battery has a capacity of 1000kWh for HH2 and HH3 with rated power of 240kW each, and the rated power for HH1 is 300kW with a capacity of 1500kWh. The rated capacity is set at 300kW for HH1 to monitor the impact of energy storage on the grid network. For each household, it is assumed that the load profile for HH2 and HH3 are the same 1500kVA each and for HH1 it is set at 1300kVA, while PV production for each household is also altered and studied as seen in Table 4. The maximum power that can be imported from the grid to the battery is 1000kW, and the grid transmission voltage is set to 120kV and is subsequently stepped down to 600V sufficient for this study.

4. Results and Discussion

Small VPP systems are interconnected as microgrids and then linked to the large scale VPP or the National grid, at the point of common coupling (PCC). The energy at the PCC increases due to the presence of ESS and PV generation systems that simultaneously import and export energy according to the household demand and solar irradiance.

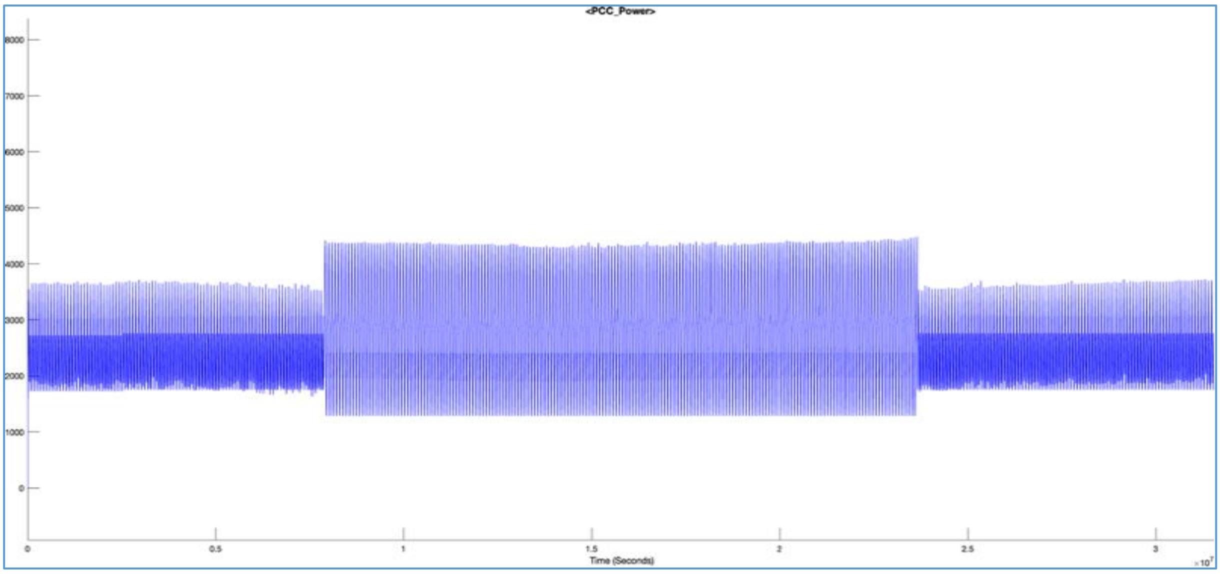

Figure 6. Power at the Main Point of Common Coupling

The resultant power at PCC (kW) is shown in Figure 6, for the first three months there is power variation and households do import energy from the PCC, and therefore maintains a profile of about about 3800kW, which later rises to about 4800kW for the following six months due to high solar irradiance experienced, and the PCC profile continues steadily until Solar PV output decreases as cooler months are approached, which explains the sudden decrease of power at the main PCC, a state that is quantified by more power exchange between the grid and the modelled microgrid that imports grid power to a large extent to cater for the household demand.

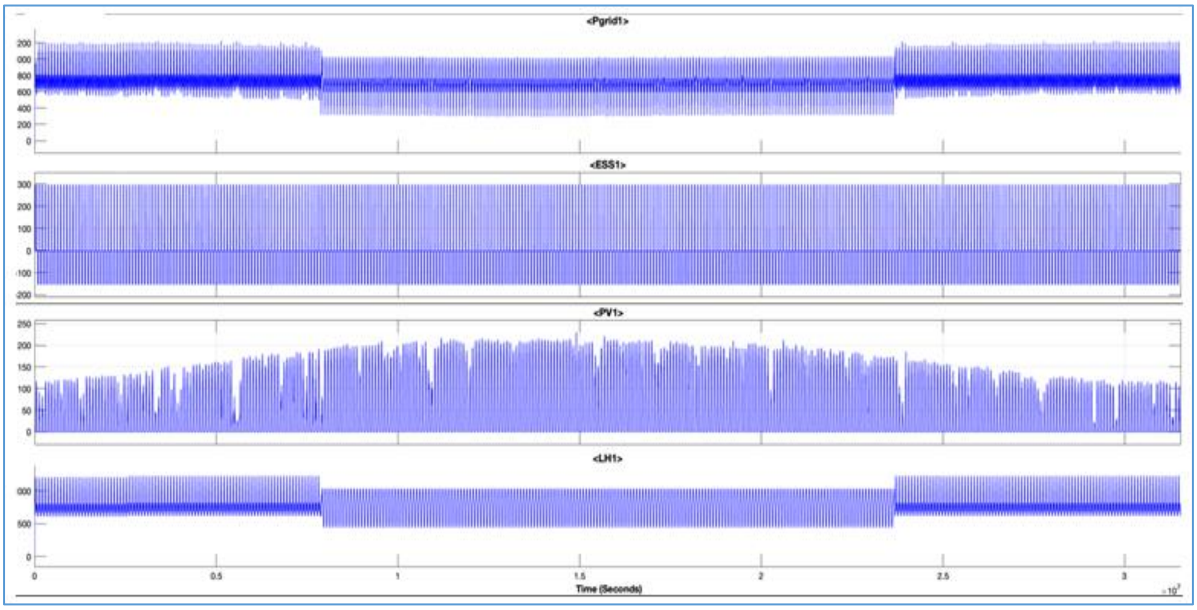

Figure 7. Household1 ESS1, PV1, LH1 Power Profile

Household1 shows that consumption decreases after the first three months, which also has an impact on the grid as more power is imported from the grid, the ESS has constant charging and discharging cycles, impliying maximum use of the ESS, there is surplus power as the load consumption for household 1 decreases slightly below 1000kVA, more power is stored with an approximate charge rate of 300kW, and PV output decreases slightly below 100kW towards the end of summer. Finally the ESS system stabilizes the grid by steadily supplying the load with an almost constant charge rate, Figure 7.

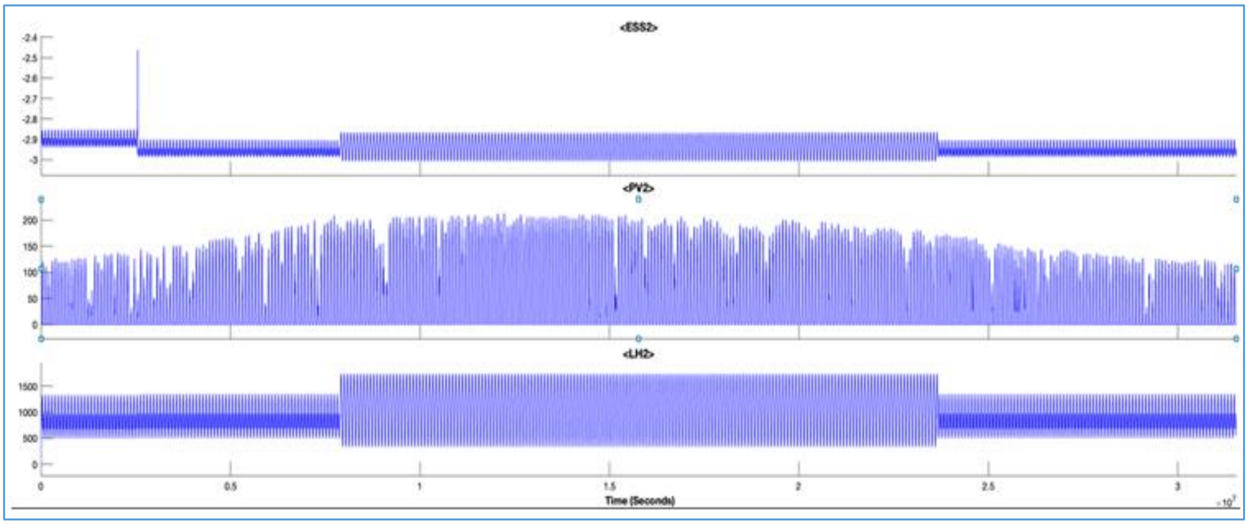

Figure 8. Household2 ESS2, PV2 and Load Power Profile

Figures 8 shows energy dissipated from the ESS, PV, and consumed energy by the load, and represents HH1whose ESS shows a declining energy profile in kWh as most of it is fed to the grid and the rest is consumed by the load. For the PV, Energy increases because of increased irradiance throughout the months, the beginning of the first three months, there is Solar PV output of about 120kW which is the amount of energy consumed by the load and stored, overtime Solar PV hits a record of about 150kW at the same time the ESS is maximumly discharged to an approximate value of 2.85kW, and further discharged to 2.9kW as Solar PV output decreases to about 100kW. In the meantime, the load consumes maximum power of about 1500kVA during maximum Solar PV output, which explains sharp discharge of ESS to extensive negative values, and the consumption of 1400kVA continues irrespective of the status of the ESS, a challenge that is caused by over-discharging of the storage systems, this can be rectified by application of a robust energy management system techniques.

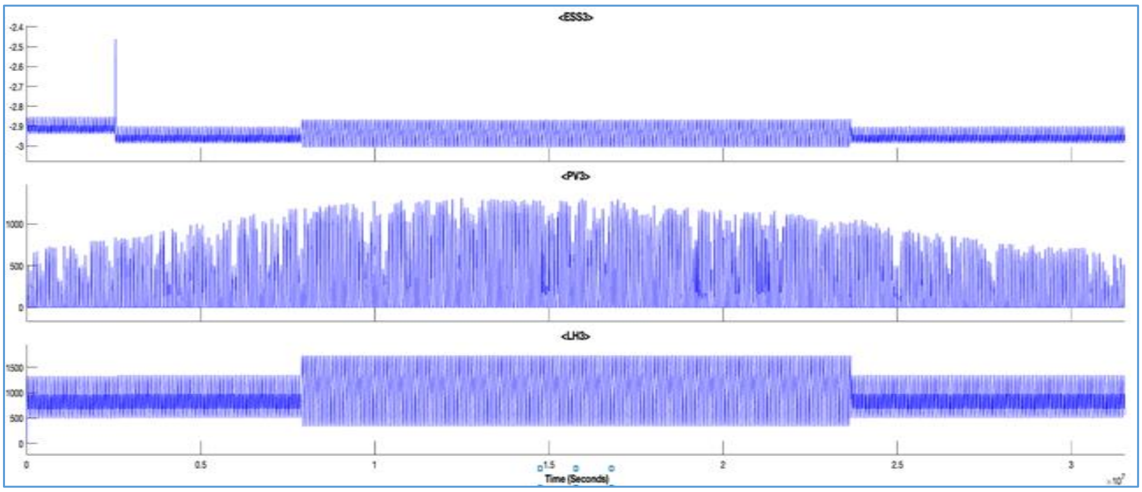

Figure 9. Household 3 ESS3, PV3 and Load3 Power Profile

In the case of Figure 9, Solar PV output is about 500kW for the first three months and later rises to about 1000kW as maximum, the previous households Solar PV output ranges between 100kW-150kW as minimum and maximum obtainable outputs. This implies the charge rate of ESS has to be increased to cater for more energy and both charge and discharge constraints have to be included, so as to avoid quick discharge cycles due to excess power demand from the load and Solar PV output intermittency that causes uncertainity in power output, causing a continuous discharge phenomenon of the ESS to about 2.9kW. The load is maximumly catered for, and in the first three months it consumes 1400kVA and takes a sharp increase to about 1500kVA, uncontrolled nature of the load results in extreme consumption of energy creating a completely unbalanced grid network, and violation of energy balancing equation as shown in Figure 3.

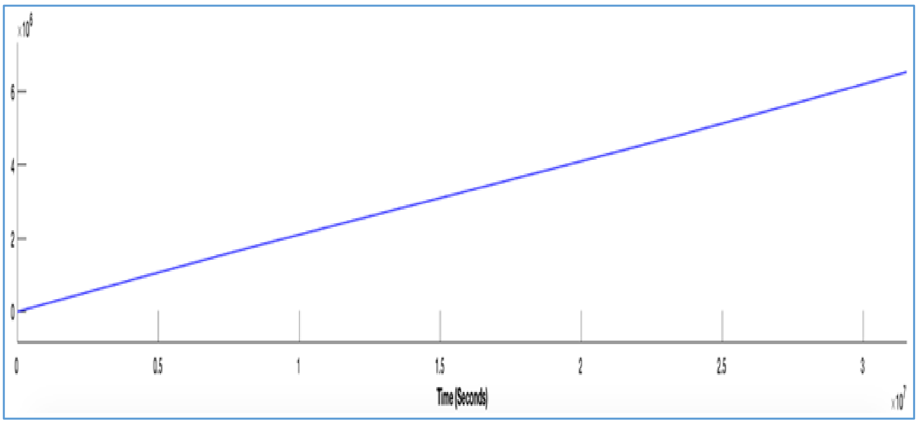

Figure 10. Energy (kWh) at the Point of Common Coupling

The beginning of January is characterized by low irradiance, the PV output is insignificant and most power is supplied by the grid at an average of 200kWh, but towards summer the output of PV increases and the amount of energy drawn from the grid decreases, which shows a typical value of around 600kWh available at PCC, this amount is quite large due to the Solar PV surplus at the household level that can easily cater for the demand and at the same time be stored in respective energy storage systems.

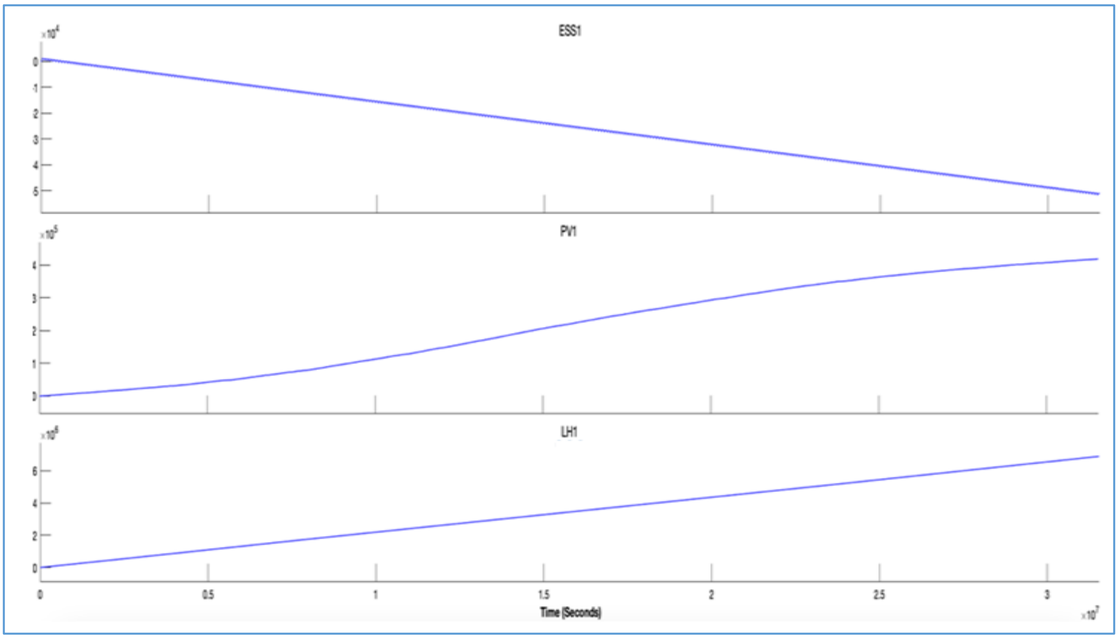

Figure 11. Energy kWh Variation for Household1

Energy (kWh) can be represented by using HH1 for this study. Energy at the PCC steadily increases, and the ESS shows a declining trend to almost -40kWh, meanwhile PV generation shows a positive generation to a maximum of about 300kWh and finally the load indicates consumption is in the upward trend and almost reaches 500kWh in Figure 10 and 11. The upward trend is due to the incoming energy supply from the battery and the Solar PV output, both energy supply systems boost the load consumption profile as evidenced in LH1 of Figure 11.

The discharge circle is quick especially for HH1 which is about 300kW maximum, as the load consumption drops during summer, excess power is stored and discharged to cater for the load consumption at the same time export to the grid, at the beginning of the first three months due to less PV generation the load consumes about 1250kVA partially from the grid power and the ESS power, as Solar PV output increases steadily the load later drops to 1000kVA following the start of April, the PV generation steadily increases but power at Pgrid1as shown in Figure 7 also decreases to about 1000kWh, implying more PV power is stored and consumed rather than be imported from the grid, which explains the bulging nature at the main PCC.

HH2 and HH3 as shown in Figures 8 and 9 have a similar trend in the load consumption pattern, but the difference is exhibited in the Solar PV output which creates power imbalances for the households, HH2 ranges between 100-150kW of PV output, for HH3 the large penetration of Solar PV creates excess intermittent power in the range of 500kW-1000kW with the storage capacity of 1000kWh used for this study. The load consumption is 1400kVA at the beginning of the first three months, and then rises to a maximum of about 1500kVA towards the end of summer, which creates an unbalanced power for the households and later over-discharging of storage system, which can be lethal in real physical systems, i.e., fire break out, reduced storage efficiency or even explosions. Additionally, the loads especially for HH1 shows more energy consumption of about 1000-1250kVA, at the expense of the available storage capacity of 1500kWh (charge rate of 300kW), and the generation of Solar PV that stands at 220kW maximum.

To have a more stable and well-balanced grid system and avoid uncertainty, more robust system controllers must be implemented to manage output of Renewable Energy Sources (RES), and similarly excess energy should be channeled to the storage systems. According to the simulation, addition of more PVs leads to unforeseeable technical challenges and actors such as storage systems should be properly sized to avoid undercharging or over-discharging challenges, hence energy must be managed to ensure the health and safe operation of storage systems and maintain grid stability.

The demand has to meet supply all the time, which physically implies ensuring generation output does not exceed the demand and the ESS can store and export without being over-discharged for optimal performance of the grid network, research that is out of the scope of this paper.

Use Case for Kenya:

The ESS has a storage capacity of 1000kWh. It is to be synched with the generation unit of individual households and 100% charged at rest. ESS couple to VPP system are mostly fitted with charge controllers, amount to be dispatched is pre-determined to guarantee storage for a longer period. Therefore, a prosumer can decide to trade the remnant power after meeting household power demand, through selling the remaining power to utility service provider or the KPLC state-controlled company, to be enabled through usage of smart metering systems that measure, record, send and forecast future electric demand and supply. If generation units meet the demand of the household but fail to store more energy, the consumer is relieved from incurring any extra cost.

If the demand supersedes generation, households must supplement their demand by importing from the grid and incur slightly less charges than the normal tariffs charged by the utility company, and both the storage and PV output will cater for most of the household demand. Kenyan diverse payment platform M-Pesa is the most used platform for sending and receiving money. Therefore, through incorporation of smart meters with M-Pesa till numbers and finally with VPP, automatic transactions can be actualized in real time for users trading power to the grid, and in return they will receive less charges depending on their household demand.

VPP plants in Kenyan energy sector can also be extended to serve rural settlements. The state can easily offset charges for energy poor settlements as monitoring of wide range of microgrids can easily be assessed and controlled through the Information Computer Technology component of the VPP, an initiative that can boost small medium enterprises.

5. Future Work

Following subjects can be considered as future works:

- A study on how to maximize the profit of VPP for rural poverty eradication program.
- Optimization techniques in handling multiple microgrids connected to the VPP platform.
- Developing an energy management tool for the households and determining charge and discharge levels for households.
- Re-modelling the households and power analyzers to adopt Kenyan M-Pesa transaction platform for trading and rural electrification programs.

6. Conclusion

The household model has been developed in MATLAB, and power profiles for the households have been analyzed. The effects of adding renewables to the grid system are apparent as consumption from one household to another changes, and therefore an energy management system is suggested for future work. Additionally, the model can act as a baseline for Kenya to lay the digital blueprint for futuristic VPP trading platform. The Kenyan payment platform M-Pesa can help commercialize VPP systems across the country. Also, a VPP solution for Kenya energy needs especially for people living in rural areas can facilitate rural electrification programs through cheap and affordable electricity.

Finally, adoption of VPP can eliminate the negative economic impact caused by power outages for investors and various manufacturing sectors, and enable consumers to participate in production of power, the presence of energy storage systems will also boost participation in arbitrage trading.

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