IJEEP
INTERNATIONAL JOURNAL OF ENERGY ECONOMICS AND POLICY

International Journal of Energy Economics and Policy

ISSN: 2146-4553

available at http: www.econjournals.com

International Journal of Energy Economics and Policy, 2020, 10(5), 196-207.

Macro Economics of Virtual Power Plant for Rural Areas of Botswana

Sampath Kumar Venkatachary[1*], Jagdish Prasad[2], Ravi Samikannu[3], Annamalai Alagappan[4], Leo John Baptist[4], Raymon Antony Raj[5]

[1]Grant Thornton, Acumen Park, Fair Grounds, Plot 50370, Gaborone, Botswana, [2]Coordinator, Amity School of Applied Sciences, Amity University Rajasthan, Jaipur, Rajasthan, India, [3]Department of Electrical, Computers and Telecommunication Engineering, Botswana International University of Science and Technology, Palaype, Botswana, Botswana, [4]Research Scholar, Amity Institute of Technology, Amity University Rajasthan, Jaipur, Rajasthan, India, (Currently Affiliated to Botho University, Gaborone, Botswana, PO Box 501564, Botho University, Kgale KO, Near Game City, Gaborone, Botswana), [5]Research Scholar, Department of Electrical, Computers and Telecommunications Engineering, Botswana International University of Science and Technology, Palaype, Botswana. *Email: sampathkumaris123@gmail.com

Received: 19 March 2020 **Accepted:** 15 June 2020 **DOI:** https://doi.org/10.32479/ijeep.9602

ABSTRACT

The growth of renewable energy technologies as an alternative source of power is a great boon to the rural masses where energy is predominantly a challenge. This paper focuses on studying the microeconomic benefits of the virtual power plant as a solution to the rural masses who either have no access to energy or has limited access. The model here uses HOMER as a tool for modelling the design. The simulation results discuss the profitability of the virtual power plant as a solution not only to the virtual power plant operator but also to the rural households while ensuring a sustainable income source with the use of solar power PV as a generator.

Keywords: Virtual Power Plant, Levilised cost, Annualised Cost
JEL Classifications: D0, E0, Q4

1. INTRODUCTION

The increasing share of renewable energy has redefined the power sector to a large extent. Thanks to ICT technologies which drive the sector to new heights. The Virtual Power Plant is one such technology-driven entity aimed at solving the technical-economic problems in renewable energy sources (Dotzauer et al., 2015; Houwing et al., 2009; Koraki and Strunz, 2017; Garcia et al., 2013; Heide et al., 2011; Hochloff and Braun, 2013; Petersen et al., 2013; Mashhour and Moghaddas-Tafreshi, 2010; Zamani et al., 2016; Candra et al., 2018). As named, a virtual power plant does not reflect reality like concrete and-turbine. Instead, it utilises the infrastructure foundation to integrate little, divergent energy assets as a single generator. Pretty much any energy resource can be connected and can be a combination of non-renewable and renewable energy resource. In other words, VPP is a virtual cluster of microgrids interconnected system through a centralised management system. Thus, the virtual power plant can be a blend of fossil generators, sustainable power generators (Venkatachary et al., 2018; Venkatachary et al., 2017a). "In the VPP model, the aggregator assembles an arrangement of small generators and works them as a unit together and flexible resource on the energy market or sells their power as a system reserve." (Davis, 2010; Venkatachary et al., 2017b) similarly to cloud infrastructure in cloud computing. This rising energy cloud enables consumers to effectively take an interest in the generation and distribution of power strategically to accomplish plans of action that advantage buyers, producers, and distributors of energy. "Virtual power plants represent an "Internet of Energy," said Navigant senior analyst Peter Asmus in a market report." (Asmus, 2014). VPPs in this way can be named as the appearance of trans-dynamic energy implementing new advances like sun based photovoltaic systems, propelled battery electric vehicles, demand response along these lines changing consumers effectively as members in the services. Since in a DG various members take part in the cluster, it is imperative to provide information on each participating member to one another. Therefore, communication becomes a criticality in the system. As VPP is a network of resources and takes its cue from the IoT model, in essence, there is a multitude of operations take place; in short, it is a manifestation of transactive energy. VPP encapsulates many services, and some of them are demand response, demand-side management, advanced metering infrastructure, automatic control and dispatch, optimisation etc. The Control Centre or the Virtual Power Plant Control Centre forms the core of the business model. The control centre effectively functions to maintain and control operations across all the individual resources. It effectively manages the demand response, demand-side management, VPP auctions, real-time monitoring, optimisations, and so on. Independent distributed generators like EV, Wind Farms, Solar Power generators, are connected to the virtual power plant control centre through the grid network or the community grids. The DER's are participatory entities and contribute to the generations through a commitment binding. An individual generator can generate and provide to the VPP on a fixed basis or a demand basis. The VPP control operator ensures that the demand in the grid is met by ensuring individual participation. As consumer behaviour will impact the operations in a VPP, it is essential to ensure a proper business model is formulated depending on the appropriate sizing of the DER. This will ensure that the operations are not significantly impacted in the event of an unprecedented demand in the grid. The generated energy from the DER's supplies the grid. The VPP forms part of the commercial grid or the traditional grid. As there is disparity due to the inconsistencies in the DER generators, it is essential to ensure a balance between the DERs and the conventional grids (Lombardi et al., 2009; Venkatachary, 2017b; Venkatachary et al., 2018; Asmus, 2014.

VPP Systems rely heavily on software for monitoring, automatic dispatch, optimisation functions in DER. The categorisation of the VPP is mainly based on the technical and commercial aspects based on their operations. As it implies, the technical aspects predominantly address the technical areas, while the commercial aspects include the market operations. (Candra et al., 2018; El Bakari and Kling, 2010; Lombardi et al., 2009; Lukovic et al., 2010). The emergence of AI development in this sector has enormously contributed to the improvement of Critical Infrastructure and this, in turn, has contributed enormously to the field and fuelled the research for progression in VPPs application, (Hyken, 1999), thus aiding in the breakdown of complex structures into simpler and efficient VPP. Many factors need to be considered in the VPP system like grid security, data flow, transmission speed/delays. As the system is networked, it is essential to ensure the system is fast, reliable and provide minimum delay and to accommodate new devices or systems (Lombardi et al., 2009). It is basic that the consolidated generation of electrical energy in a virtual power plant is managed proficiently as for networks are concerned. (Caldon et al., 2004).

The paper is organised as follows. Section two reviews of energy consumption while section three models the collected data for HOMER analysis. Section 4 analyses and discusses results while section 5 concludes the paper.

2. OVERVIEW OF ENERGY CONSUMPTION

A Virtual Power plants key portfolio is to deliver and manage power in the form of demand response, real-time monitoring, coordination, and balancing services while optimally maintaining a dynamic control over the participating entities. To ensure optimal decisions, the costs and the benefits in each of the entities based on demand response must be considered effectively (Kok, 2009). It is most likely that the consumption of electricity in most cases are likely dependent on independent DERS. This, therefore, could lead to a potential fallout in the DERs (Kok, 2009). To understand further, it is essential to study the consumption pattern in the participating DER's.

Consumption is critical to building a load profile which depends simply on the power consumption devices like TVs, stoves, fridges, roof fans, lights, and so forth. The utilisation among rural families in Botswana has expanded considerably and is steadily on the rise. Thanks to growing awareness of sustainable development program initiatives by the Governments and the vision of providing power to all. As the family income rises quickly, the methods for access to purchasing electrical or electronic devices will imply that power utilisation will only increase. Along these lines, understanding power utilisation in the rural residential families and contemplating factors influencing them can be valuable for a reasonable estimation of future demand which will thus help in increasing power generation capacity and meet the need. It is likewise fundamental to remember the costs associated with building non-renewable power plants which have huge social and environmental issues when running these plants.

Residential electricity consumption (REC) can provide more significant insights for a better analysis of the savings which can be obtained from energy efficiency and conservation. For enhancing energy efficiency, it is also essential to gain knowledge on how people buy and use appliances, thereby aiding companies to build energy-efficient products. REC also helps in developing new smart technologies as the consumer is now more conscious of his energy consumption. Additionally, in a distributed energy scenario, these smart technologies aid the consumer with an opportunity to be part of a larger distribution group of producing or generating electricity. This is different from the traditional model of electricity where the consumer is mostly passive. Understanding consumers responses not only help in new business models and technologies but is also crucial for distributors, policymakers, stakeholders to incorporate new policies and adapt changes effectively. (Pachuari and Filippini, 2004) Considering the importance of REC in both countries, it is essential and imperative to collect periodical data for conducting systematic, rigorous research. Figure 1 shows a simple framework used for collecting energy consumption data. As can be seen, the factors that influence consumption is based on the type of appliance, usage hours, so on and so forth.

2.1. Load Profile

Load profiling plays a critical role in understanding power and power markets. The load profiling also provides insights into the load fluctuations, durations over a specified period. Technically, the load profiles will tend to vary in winter and summers. For a place like Botswana, the load profile during summer is likely to be higher than the load consumed during winter (Conkling, 2011).

Power utilisation to a great extent relies upon two significant components, the number of hours utilised at some random purpose of time and the time duration the apparatus is being used in a day. In this way, the hour of the use of the apparatus is significant. For example, on a freezing day, the heaters might be turned on, and on a hot day, the Air coolers or conditioners could be turned on to cool the house. Utilisation additionally relies upon the number of elements, for example, atmosphere, family propensities, salary (as in case of a single earning member), number of appliances etc. Although numerous studies have been carried out in the past to understand energy utilisation, it has been hard to dissect the example. Different investigations directed by prominent researchers and scientists show that individuals will, in general, consume more power with more pay (Pachuari and Filippini, 2004).

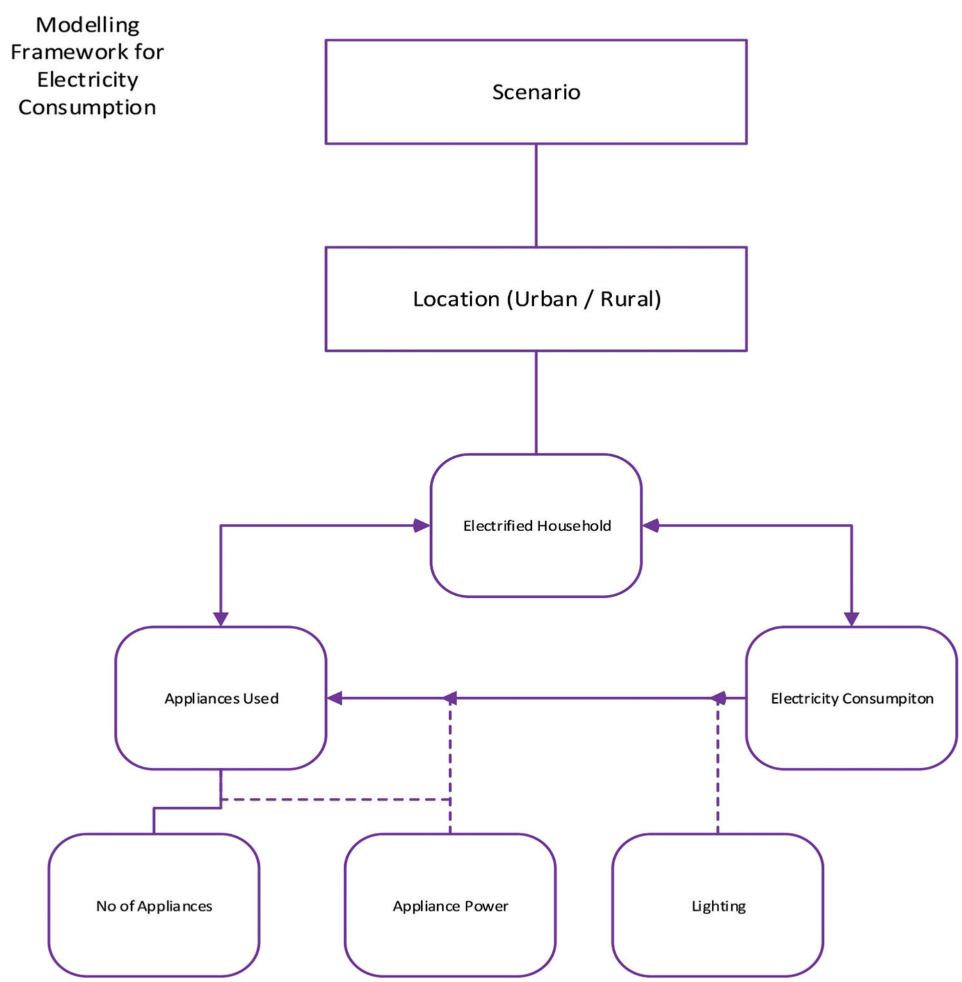
The data used here is based on a social survey (Table 1) in the selected localities to study the electricity consumption based on appliance ownership and the cost involved or spent by the consumer on the electricity. The data or the sample size is small and is not necessarily a proportional representation of both the semi-urban and rural households and the total population. Therefore, the data should be used as an approximation for patterns of usage of appliances and electricity. The data collected from the individual house units were then used as a base model for simulation. The first approach to data collection was through a structured survey questionnaire which included household appliance usage in the rural areas such as basic amenities like a lamp, tube lights and other household appliances.

Demographic Details – Details like housing, Locality, Age group, education etc.

Electricity Usage – Energy Source, Appliance details etc.

Consumption – Monthly bill, usage in kWh. (The consumers were asked to fill in a monthly consumption data for each month for a year).

Figure 1: Electricity Consumption Data Collection Framework



In the second approach, an electricity consumption calculator was designed. The design consisted of two sets of sheets. The primary sheet consisted of the users keying in their data. The secondary sheet, sheet 2, had details of appliances captured. The consumption calculator consisted of various fields like location, cost/kWh, total rating per hour, maximum consumption, appliances, rating, hourly usage, to name a few. The responses gathered were later tabulated in a worksheet to understand the consumption of electricity. A sample data sheet used for collection is shown in Figure 2.

3. MODELLING AND METHODOLOGY

The software used for analysing or simulation is HOMER design software (Homer Energy) which is widely used for the design of microgrids. The HOMER system (Figure 3) consists of two modules, the input and the output. The system input components include load, the solar resource, sensitivity components (which include different constraints) and the optimisation criteria. These basic input components are then simulated into two components as output financial and technical. The financial components include the net present cost, total capital costs, energy costs savings, optimal system category while the technical components include the renewable energy fraction, fuel consumption and excess energy fraction.

The VPP operations are restricted by individual household energy demand and storage capacity. This impacts largely on the power produced due to the consumption by the producer. A proper storage facility enables more flexible trading in the market. Therefore, it is also essential to consider the storage capacity installed by the individual household.

3.1. System Design Components

The LCOE or the levelised costs generally include all fixed, variable and investment costs in the entire lifecycle of the system. Various factors impact the expenses in the generators, and these expenses can be determined at either on the grid or when connecting the end-user, discount rates and are expressed in either kWh or MWh. Since, electrical power generation is from numerous sources like hydro, PV, atomic, and so forth., these expenses should be institutionalised or levelised. In short, levelised cost is the overall measure of power generation costs consistently at the source. To put it plainly, it is the average computed cost of the complete infrastructure, which includes constructing and operating power generation plant. LCOE can be named as the base expense at which power must be sold to end clients to accomplish the break-even cost or the original investment invested over the lifetime of a venture (Wittenstein, 2015).

Levelized cost can be calculated by using the following formula (Homer Energy).

LCOE = Sum of costs/Sum of electrical energy produced (1)

$$LCOE = \sum_{t=1}^{n} \frac{It + Mt + Ft}{(1+r^2)} / \sum_{t=1}^{n} \frac{Et}{(1+r^2)} \tag{2}$$

Thus from equation 1 and 2, *LCOE* can be expressed as the ratio of summation of the expenditure, maintenance costs, fuel costs for a given period to the cost of electricity generation. In other words, It is the expenditure invested during the year, and *Mt* determines the cost incurred on operations and maintenance. *Ft* is the annual fuel expenditure, *Et* the electricity generated, n denotes the life expectancy of the system and r is the rate of discount.

In a virtual power plant, there are multiple inputs and multiple generators connected to the system. The basic costing thus will include the total value, the time taken to payback and the rate of return. Total present value or TPV has defined the difference between the present value and the present cash outflow, and it determines the profit of the project. TPV can be written down using the following.

Figure 2: Sample Questionnaire Format

ENERGY CONSUMPTION CALCULATOR

Location			Maximum consumption per day	7.44	kWh
Cost/kWh		Rs.	Average consumption per day	6.01	kWh
Total Rating/Hour	6,849.00	Watt	Total Consumption per month	180.20	kWh
			Total Monthly Cost	-	Rs.

No	Appliances	Rating (W)	Hourly Usage per Day	# of Units	Consumption per Day	Day Frequency Usage per Week	Consumption per Week	Day Frequency Usage per Month	Consumption per Month	Monthly Cost
1	Television - Samsung	150.00	8.0	1	1.20	7.0	8.40	30.0	36.00	-
2	Air Conditioner - Panasonic	480.00	-	1	-	7.0	-	30.0	-	-
3	Air Conditioner - Panasonic 2	400.00	-		-		-		-	-
4	WiFi Modem	10.00	-		-		-		-	-
5	Cable TV Setup Box	25.00	24.0		0.60		4.20		18.00	-
6	Internet Modem	10.00	-	1	-		-		-	-
7	Mobile Phone Charger - Samsung	3.00	3.0	1	0.01	7.0	0.06		0.27	-
8	Microwave	1,100.00	-	1	-	7.0	-		-	-
9	Refrigerator	105.00	-	1	-	7.0	-		-	-
10	Coffee Maker	600.00	-	1	-	2.0	-	20.0	-	-
11	Toaster	600.00	-	1	-	5.0	-	20.0	-	-
12	Laptop	50.00	-	1	-	7.0	-	20.0	-	-
13	Electric Iron	1,100.00	3.0	1	3.30	7.0	23.10	20.0	66.00	-
14	Washing Machine	1,000.00	1.0	1	1.00	7.0	7.00	20.0	20.00	-
15	LED Light Bulb - 7	7.00	-	4	-	7.0	-		-	-
16	LED Light Bulb - 9	9.00	-	4	-	7.0	-		-	-
17	Tube Light 40	40.00	5.0	6	1.20	7.0	8.40		36.00	-
18	Incandescent Light Bulb - 60	60.00	1.0	2	0.12	7.0	0.84		3.60	-
19	Music System 5.1	1,100.00	0.0	1	0.01	7.0	0.08		0.33	-
20										
21										
22										
23										
24										

How to Use

Type location (optional) and Cost/kWh

Select Appliance Item from dropdown list in Appliances Column

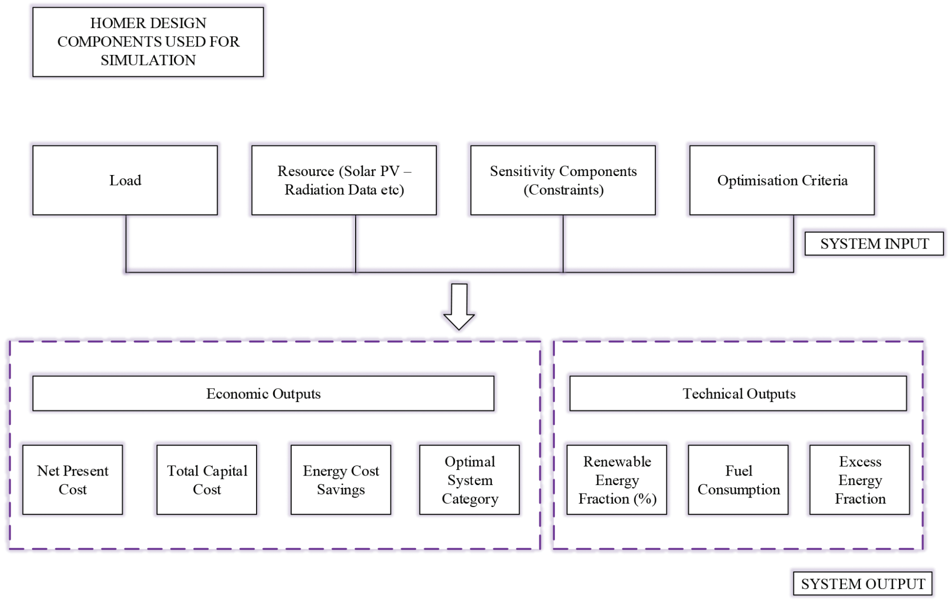
Type Hourly Usage per day for selected appliance

Type number of similar appliance unit (if you leave it empty, consumption per day will take 1 as defaullt number)

Type day frequency usage per week (if you leave it empty, consumption per week will take 7 as default value)

Type day frequency usage per month (if you leave it empty, consumption per month will take 30 as defaullt # of days)

Figure 3: Homer Design Components (Homer Energy)



$$TPV = \sum_{t=1}^{r} \frac{C}{(1+r)^t} - C_t \quad (3)$$

Where *TPV* is the net present value, *t* is the period, *Ct* is the net cash inflow during the period at given instance of time, *r* is the discount rate.

Payback period or (PBP) can be defined as the time taken to get back the invested costs. It is an essential part of the project. The project profitability is determined by the internal rate of return or IRR. In simple terms, IRR defines the project viability in a VPP as it takes into consideration the various discount rate, total present value and the cash flow. In short, the project is deemed to be viable and profitable if the IRR is greater than the discounted rate from the TPV. The IRR can be computed as follows.

$$IRR = \sum_{t=1}^{r} \frac{C}{(1+irr)^t} - C_0 = 0 \quad (4)$$

Where *IRR* is the internal rate of return and is expressed in percentage. *T* is the period, *Ct* is the net cash flow at a given instance of time and r is the discount rate.

The retail electricity costs can be segregated into two segments, commercial and non-commercial or residential Loads. Botswana as a country has special slab rates for both the type of loads. However, in case of commercial load an additional levy in the form of demand charge generally a fixed cost is added to it. For keeping the calculations simple, the average cost is taken up for study. The assumptions for economic calculations are indicated in Table 2 and the electricity costs are indicated in Table 3.

3.1.1. Net present costs (homer energy)

The formula used for the net present value is,

$$NPV = \sum_{t=1}^{r} \frac{C}{(1+r)^t} - C_0 \quad (5)$$

Where NPV is the net present value. *T* is the period for which cash flows are expected *Ct* is the cash flow in year t and r is the discount rate, and C_0 are investment costs. The internal rate of return can be calculated using the formula.

$$IRR = \sum_{t=1}^{r} \frac{C}{(1+irr)^t} - C_0 = 0 \quad (6)$$

The discounted payback period is determined by calculating the number of years it takes to get back the investment made with the discounted cash flows.

The net cash flow can be calculated as stepwise as follows,

Earnings before interest, tax, depreciation and amortisation (EBITDA) has been calculated by REVENUES – COSTS.

Earnings before interest and tax (EBIT); can be calculated as EBITDA – Depreciation.

The net profit can be calculated by subtracting the tax 12% in the case of Botswana from EBIT.

The net cash flow can be calculated by net profit + depreciation – investment.

Depreciation can be calculated as.

$$\text{Annual depreciation expense}(\text{ADE}) = \frac{\text{Cost of Fixed Assets} - \text{Scrap Value}}{\text{Life Span Years}} \quad 7$$

3.2. Assumptions for NPV, IRR and Discounted Payback Period Calculations

Table 4 provides the list of assumptions for computing the net present value, return rate and discounted payback period calculations.

3.2.1. Emissions

Emission costs	Value in (USD)	Remarks
Carbon dioxide ($/t)	1000	
Carbon monoxide ($t)	1000	
Unburned hydrocarbons ($/t)	1000	
Particulate matter ($/t)	990	
Sulphur dioxide ($/t)	990	
Nitrogen oxide ($/t)	990	

Table 1: Survey questionnaire sample

Demography	Personal details (Locality, age group, marital status, education level, income group, employment)
Electricity consumption usage	Facility setup What are sources of energy you use in the facility? Type of house/dwelling where you reside? What type of electrical appliances do you own?
Electricity consumption	What is the approximate total amount of energy/ units consumed approximately for each month (in Watts or kWh)

Table 2: Cost assumptions for economic calculations (based on sellers information)

	Solar power PV (Tata BP module) (USD)	Battery lifetime (USD)	Converter (USD)	Project lifetime
Capital costs	137.00/Wp	556.50	1400	25 years
Average OM costs	10%	10 years	15 years	25 years
Lifetime system	15	10	15	25 years

Table 3: Consumer electricity prices

	2016-2017	2018-2019
	Botswana BWP	
Electricity Price (Household) Per kW	0.1992	0.2533
Commercial per kW	0.161	0.177

3.2.2. Assumptions for optimisation

	Value	Remarks
Maximum simulations	15000	AT 60 min/step at 8760 Steps
System design precision	0.0100	
NPC Precision	0.0100	

3.3. Annualised Costs

HOMER enables calculation of annualised cost component and is calculated as the cost that occurs equally every year during the lifetime of a project. It is given by the equation as follows,

$$C_{ann} = CRF\left(i, R_{proj}\right) - C_{NPC} \tag{8}$$

Where,
C_{NPC}=Net Present Caost ($)
i=Annual Interest Rate (%)
R_{proj}=Project Lifetime (year)
CRF()=Function returninf the capital recovery factor.

3.3.1. Operation and maintenance (O and M) costs

The cost that is associated with the operating and maintenance of the equipment is the O and M costs. HOMER accommodates other maintenance costs that can be used as part of the analysis. The O and M costs are the total sum of O and M Cost, Penalty for the capacity shortage, emission charges.

$$C_{om,others} = C_{om,\,fixed} + C_{cs} + C_{emissions} \tag{9}$$

Where $C_{om.,fixed}$=system fixed O and M codts [$/year]
C_{cs}=penalty capacity shortage [$/year]
$C_{emissions}$=penalty emission [$/year].

3.3.2. Grid costs

Homer calculates the grid as charges based on the following calculations.

Energy charge

The total annual energy charge is calculated using the following equation.

Table 4: Assumptions for NPV, IRR, and discounted payback period

	Value	Remarks
Nominal discount rate	8%	Standard value generally applied as part of the project in homer application
Real discount rate	4.85%	
Inflation rate	3%	
Project lifetime	25	
Annual capacity shortage	10	
Lifetime of PV	15	
System fixed capital cost	132 USD	Per Wp
Constraints		
Maximum annual shortage capacity (%)	10	
Minimum renewable fraction (%)	50	
Operating reserves (As a percentage of load)		
Load in current time step (%)	10	
Operating reserves (As a percentage of renewable output)		
Solar power output %	80	
Wind power output %	50	

$$C_{grid,Energy} = \sum_{i}^{rates}\sum_{j}^{12} E_{gridpurchases,i,j} . C_{power,j} - \sum_{i}^{rates}\sum_{j}^{12} E_{gridsales,i,j} . C_{sellback,i} \tag{10}$$

Where $E_{gridpurchases,i,j}$=The amount of enery purchased from the grid in a month j during time that rate i applies
$C_{power,i}$=Grid power price for rate i expressed in \$/kWh
$E_{gridsales,i,j}$=Amount of energy sild to the grid in month j at rate i expressed in \$/kWh
$E_{sellback,i}$=Sellback rate for rate i expressed in \$/kWh.

In the event of net metering applying monthly in the grid, the generation is calculated monthly using the following equations.

$$C_{grid,Energy} = \sum_{i}^{rates}\sum_{j}^{12} \{E_{gridpurchases,i,j} . C_{power,j} \ if \ E_{netgridpurchase,i,j} \geq 0\} \sum_{i}^{rates}\sum_{j}^{12} \{E_{gridpurchases,i,j} . C_{sellback,i} \ if \ E_{netgridpurchase,i,j} < 0\} \tag{11}$$

Where $E_{netgridpurchases,i,j}$=The net amount of enery purchased from the grid in a month j during the time that rate i applies (grid purchases minus grid sales)
$C_{power,i}$=Grid power price for rate i expressed in \$/kWh
$E_{sellback,i}$=Sellback rate for rate i expressed in \$/kWh.

$$C_{grid,Energy} = \sum_{i}^{rates}\sum_{j}^{12} \{E_{netgridpurchases,i,j} . C_{power,j} \ if \ E_{netgridpurchase,i,j} \geq 0\} \sum_{i}^{rates}\sum_{j}^{12} \{E_{netgridpurchases,i,j} . C_{sellback,i} \ if \ E_{netgridpurchase,i,j} < 0\} \tag{12}$$

Where $E_{netgridpurchases,i,j}$=The net amount of enery purchased from the grid in a annually during the time that rate i applies (grid purchases minus grid sales)
$C_{power,i}$=Grid power price for rate i expressed in \$/kWh
$E_{sellback,i}$=Sellback rate for rate i expressed in \$/kWh.

Demand charge

HOMER calculates the demand charge as follows

$$C_{grid,Energy} = \sum_{i}^{rates}\sum_{j}^{12} \{P_{grid,peak,i,j} . C_{demand,i}\} \tag{13}$$

Where $P_{grid,peak,i,j}$=Peak hourly grid demand in month j during the time that rate i applies in KWh $C_{demand,i}$=Grid demand rate for rate i expressed in \$/kWh.

4. MODEL COMPARISON, ANALYSIS AND RESULTS

Figure 4 shows the cost summary for a homer grid cycle. As can be seen from the figure the operating costs from the grid are negative. This indicates that the system can function as an independent generating unit or generator.

For an investment of \$12k in the solar systems and the operating value of \$42k, or the system costs of \$29k the grid operating costs comes down drastically, that is, the consumer is not buying electricity from the grid.

As seen from the Tables 5 and 6, the net present cost of the system is calculated at 3.0 million dollars, for a project period of 25 years. From the table, it can also be inferred that the annual cost of the complete system amounts to 209 thousand. On comparing the two Tables 5 and 6, it can be assumed that both the annualised cost and the net present value is nominal. Botswana has one of the highest insulation capacity and solar radiation. Figure 5 shows cash flow graphs for the system simulated for Botswana. As can be seen from the figure, the initial capital amount or capital cost is the cost that is invested in the project at the beginning, which means that at the end of the year it is zero. The operating costs occur throughout the year and are indicated over the 25 year period.

4.1. Grid Summary

The simulation details in HOMER enables us to understand the electricity generated in the system and also provides us to understand the Grid profile. The grid simulation provides us with an insight into understanding the feasibility of the project in terms of understanding what amount of energy is produced by the system, what amount of energy is required to meet the requirements and what amount excess energy produced can be sold back to the grid. The grid also provides the resulting costs generated as against the energy produced. The output of the grid has the following components.

Energy Purchased – Total amount of energy purchased from the grid and is in kWh.
Energy Sold – Total amount of energy sold to the grid and is in kWh.
Net energy purchased – The net power purchased from the grid in kWh.
Peak Demand – The actual peak power demand in the system serviced by the grid and is in kWh.

Figure 4: Cash flow summary

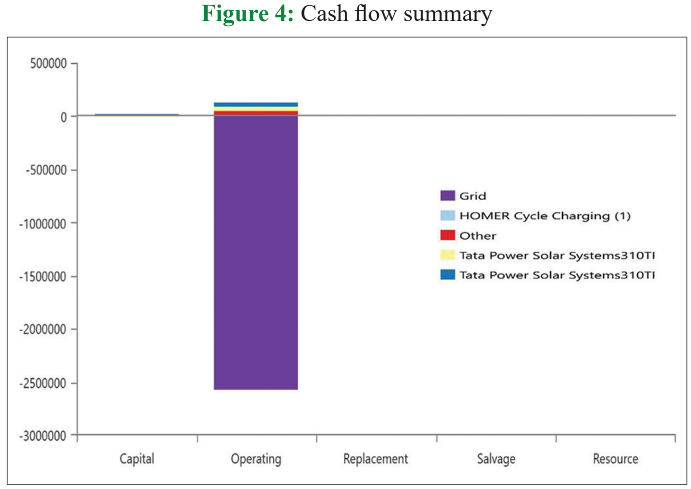


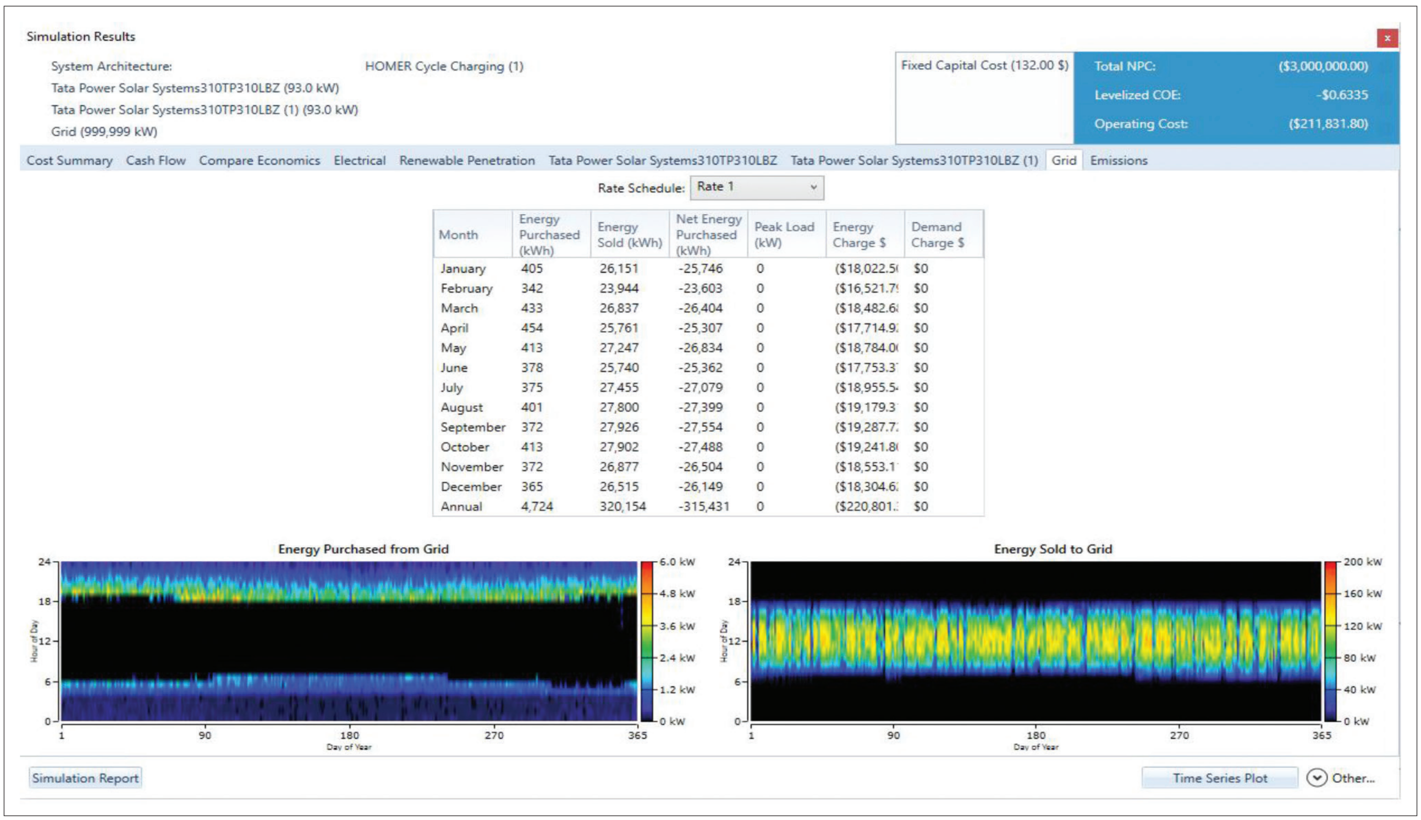
Table 5: Net present cost - 1

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Grid	$0.00	−$3.16M	$0.00	$0.00	$0.00	−$3.16M
HOMER cycle charging (1)	$4,000	$0.00	$0.00	$0.00	$0.00	$4,000
Other	$132.00	$43,157	$0.00	$0.00	$0.00	$43,289
Tata power solar systems310TP310LBZ	$12,741	$42,563	$0.00	$0.00	$0.00	$55,304
Tata power solar systems310TP310LBZ (1)	$12,741	$42,563	$0.00	$0.00	$0.00	$55,304
System	$29,614	−$3.03M	$0.00	$0.00	$0.00	−$3.00M

Table 6: Net present cost - 2

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Grid	$0.00	−$220,801	$0.00	$0.00	$0.00	−$220,801
HOMER cycle charging (1)	$279.68	$0.00	$0.00	$0.00	$0.00	$279.68
Other	$9.23	$3,018	$0.00	$0.00	$0.00	$3,027
Tata power solar systems310TP310LBZ	$890.86	$2,976	$0.00	$0.00	$0.00	$3,867
Tata power solar systems310TP310LBZ (1)	$890.86	$2,976	$0.00	$0.00	$0.00	$3,867
System	$2,071	−$211,832	$0.00	$0.00	$0.00	−$209,761

Figure 5: Simulated Energy Generation and Costs



Energy charge – Total amount of energy paid and is in $.
Demand charge – Total amount of demand paid and is in $.
HOMER allows multiple inputs for calculating the grid costs, and there are several different ways that can be used. Some of the rates that can be provided as inputs are as follows
Simple Rates – simple rates calculated at a constant power price, sell back price and sale capacity, net metering.
Real-time Rates – Allow inputs in real-time on an hourly basis
Scheduled Rates – Allows prices at a different time during the day and month of the year.
Grid Extension – Allows the cost of a grid extension with the cost of each standalone system configuration.
Demand Rates – Allows real-time rates based on demand.
Emissions – Allows for specifying grid emission charges.

4.2. Grid Summary

Table 7 show the grid summary. From the table, it can be seen that the peak demand is indicated for each month in kW. The table shows the amount of energy purchased and sold as per the simple rate adapted. The net energy purchased from the grid is negative, indicating that the PV solution modelled is not only sufficient to meet the load but also enables sell back to the grid at a charge. The over energy charge provides the amount of energy sold during each month back to the grid. The amount of energy purchased and sold back to the grid is indicated in Figures 6 and 7. From the tables and figures, it can be observed that the energy purchased from the grid is marginal, with the highest being 454 kWh during the winter months between April-June when the penetration level is slightly low. It can also be noticed that the generated power sold back to the grid during the year is 320,154 kWh as against the annual purchase of 4724 kWh.

The Table 8 provides the computed economics summary for Botswana. As can be seen, the interest return rate is about 875%, with a discounted payback of 0.12/year and simple payback of 0.11/year. The base case in the table provides a simple analysis of the investment made for the project, which includes the various emission costs as input.

IRR (%): 875

Discounted payback (year): 0.120

Simple payback (year): 0.114.

Table 7: Grid rates

Month	Energy sold (kWh)	Energy purchased (kWh)	Net energy purchased (kWh)	Peak demand (kW)	Energy charge	Demand charge
January	26,151	405	25,746	4.77	$18,023	$0.00
February	23,944	342	23,602	4.32	$16,522	$0.00
March	26,837	433	26,404	5.58	$18,484	$0.00
April	25,761	454	25,307	5.18	$17,716	$0.00
May	27,247	413	26,834	4.2	$18,785	$0.00
June	25,740	378	25,362	3.61	$17,754	$0.00
July	27,455	375	27,080	4.27	$18,957	$0.00
August	27,800	401	27,399	4.12	$19,180	$0.00
September	27,926	372	27,554	4.49	$19,289	$0.00
October	27,902	413	27,489	4.77	$19,243	$0.00
November	26,877	372	26,505	5.35	$18,554	$0.00
December	26,515	365	26,150	4.97	$18,306	$0.00
Annual	320,155	4,723	315,432	55.63	220,812	0

Figure 6: Energy purchased from grid in kWh

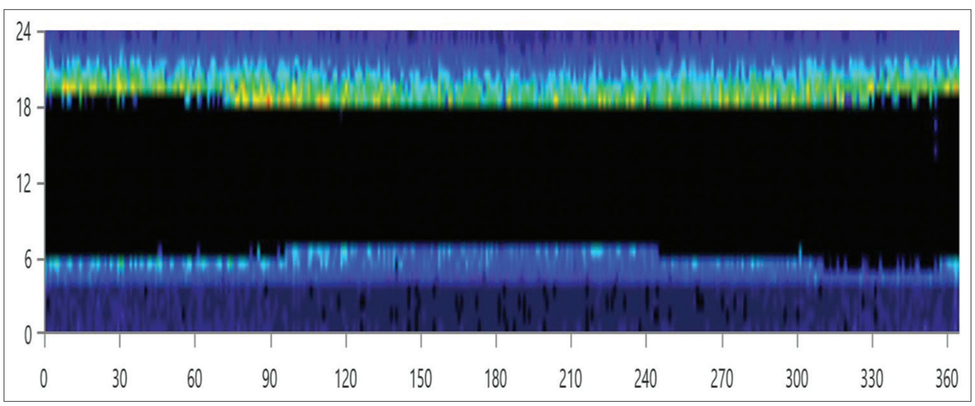


Figure 7: Energy Sold to Grid in kWh

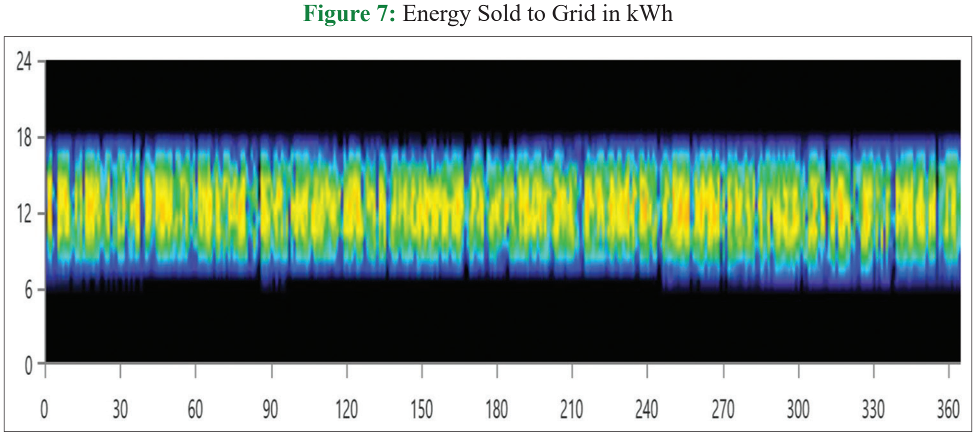
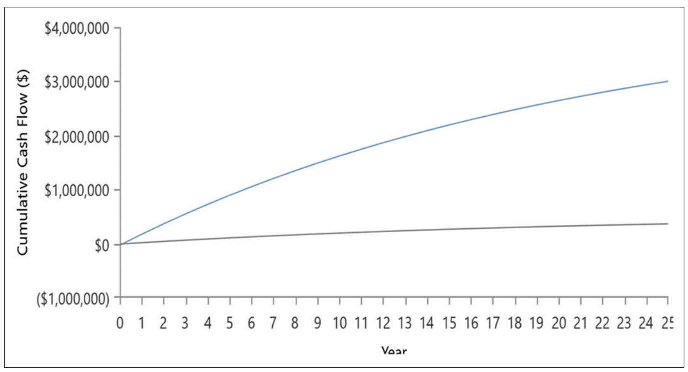


Figure 8 protrays the cashflow generated and Figure 9 describes simulated results for comparing the economics of the proposed system. As can be seen, the net present worth of the system is approximately \$3.0m, with an annual value of \$211,832 with a return on investment at 870%. The optimiser has computed the LCOE at \$0.6335 with a simple payback in about 0.11 years over 25 years. This positive value on the present worth indicates that the system will perform favourably as an investment option with the base case system. The cost also denotes that the system will save money over the project lifetime as compared to the base system. The return on investment also indicates a positive trend which means that the system will provide a good return on the investment made on the project. Table 9 provides the computed value for 30 houses where a generation plant can be adopted. The rate of return over a period of 25 years is estimated by homer to be about 90 million and the discounted rate to be 27 million. The operational expenses in a virtual power plant are limited and translate mostly to include the daily gird operations, grid maintenance, so on and so forth. Assuming the VPP operator costs to be at 20%, the value of operating costs will be roughly 5.4 million.

Table 8: Economics summary

	Base case	Current system
Net present cost	−\$364,801	−\$3.00M
CAPEX	\$8379	\$29,614
OPEX	−\$26,093	−\$211,832
LCOE (per kWh)	−\$0.428	−\$0.633
CO_2 emitted (kg/yr)	3287	2985
Fuel consumption (L/yr)	0	0

Figure 8: Cumulative Cash Flow



From the Table 9, it is observed that the average monthly profit for a virtual power plant operator is roughly about 176 thousand while on the generator is roughly about 27k. This indicates that the model is feasible for rural areas. The availability and the access to clean energy will not only ensure sustainability and the livelihood of the rural suppliers, while also mitigating the shortfall in the generators of conventional generators and thus increase energy security. It is important to note that the VPP operational expenses for each individual component are pegged at 20% with regulatory overhead costs, operational maintenance at 5%. This technically would indicate that the model is profitable to the VPP operator, though, there are many components that need analysis pertaining to VPP, which is not covered a part of the study.

Figure 9: Simulated Results - Comparing Economics

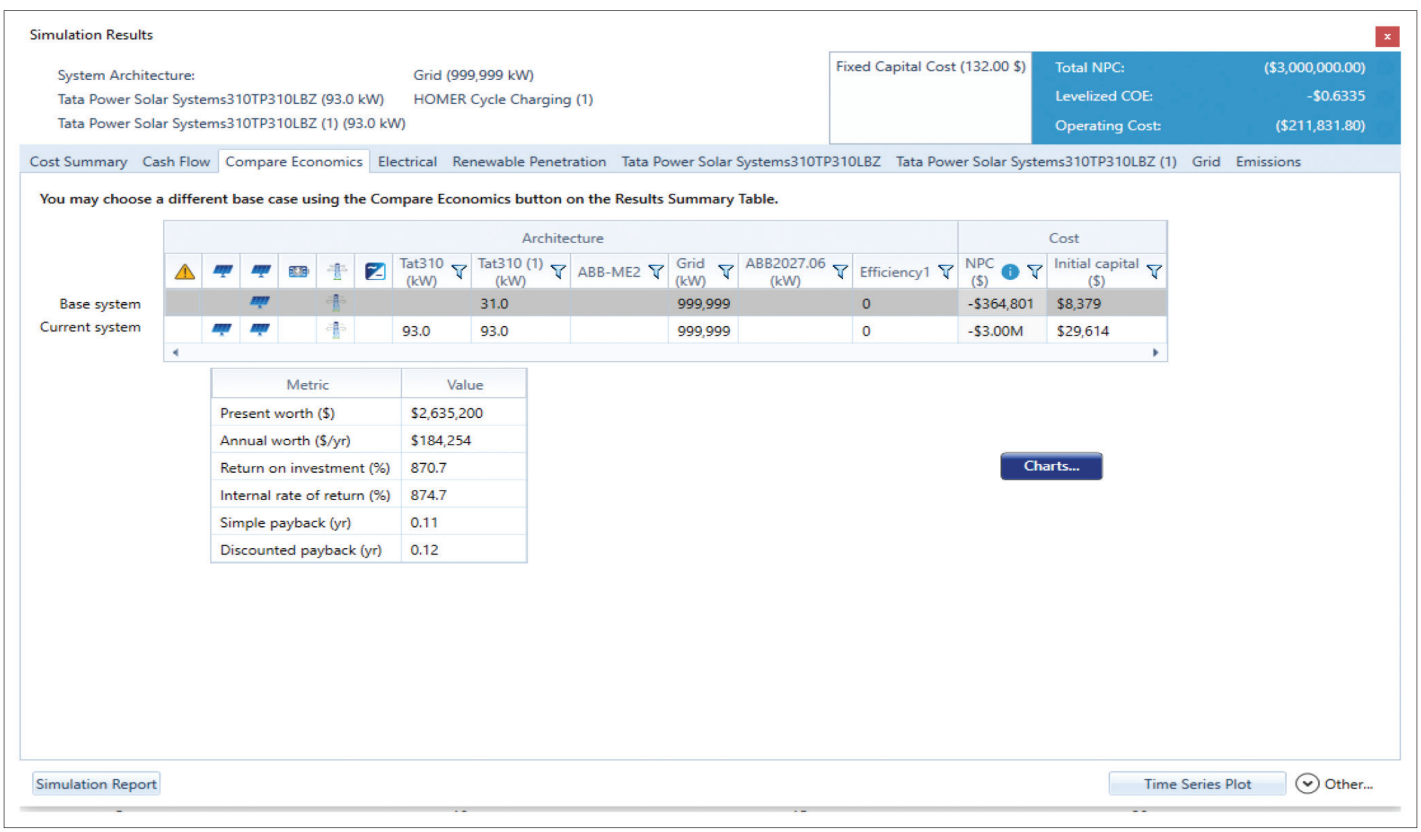


Table 9: Cash flow for a small virtual power plant (30 houses)

Botswana						
Years	Nominal total	Discounted total	Nominal total 30 houses	Discounted total (30 houses)	T and D loss at 30% (nominal)	T and D loss at 30% (discounted)
0	($29,614)	($29,614)	−888,420	−888,420	−266,526	−266,526
1	211,832	202,025	6,354,960	6,060,750	1,906,488	1,818,225
2	211,832	192,672	6,354,960	5,780,160	1,906,488	1,734,048
3	211,832	183,752	6,354,960	5,512,560	1,906,488	1,653,768
4	211,832	175,245	6,354,960	5,257,350	1,906,488	1,577,205
5	211,832	167,132	6,354,960	5,013,960	1,906,488	1,504,188
6	211,832	159,394	6,354,960	4,781,820	1,906,488	1,434,546
7	211,832	152,015	6,354,960	4,560,450	1,906,488	1,368,135
8	211,832	144,977	6,354,960	4,349,310	1,906,488	1,304,793
9	211,832	138,265	6,354,960	4,147,950	1,906,488	1,244,385
10	211,832	131,864	6,354,960	3,955,920	1,906,488	1,186,776
11	211,832	125,759	6,354,960	3,772,770	1,906,488	1,131,831
12	211,832	119,937	6,354,960	3,598,110	1,906,488	1,079,433
13	211,832	114,384	6,354,960	3,431,520	1,906,488	1,029,456
14	211,832	109,089	6,354,960	3,272,670	1,906,488	981,801
15	211,832	104,038	6,354,960	3,121,140	1,906,488	936,342
16	211,832	99,222	6,354,960	2,976,660	1,906,488	892,998
17	211,832	94,628	6,354,960	2,838,840	1,906,488	851,652
18	211,832	90,247	6,354,960	2,707,410	1,906,488	812,223
19	211,832	86,069	6,354,960	2,582,070	1,906,488	774,621
20	211,832	82,084	6,354,960	2,462,520	1,906,488	738,756
21	211,832	78,284	6,354,960	2,348,520	1,906,488	704,556
22	211,832	74,660	6,354,960	2,239,800	1,906,488	671,940
23	211,832	71,203	6,354,960	2,136,090	1,906,488	640,827
24	211,832	67,907	6,354,960	2,037,210	1,906,488	611,163
25	211,832	64,763	6,354,960	1,942,890	1,906,488	582,867
		3,029,615.00		90,000,030.00		27,000,009.00
Running costs of VPP operator/connection*						
Less	Cost towards VPP operational expenses (at 20%)			605,923.00		
	Overhead regulatory costs (at 5%)			151,480.75		
	O and M costs (at 5%)			151,480.75		
				908,884.50		
	Monthly expenditure on VPP			3,029.62		
	Net profit over 25 year period			2,120,730.50		
	Average monthly profit/Connection*			176,727.54		
Overall plant operational expenditure						
Less	VPP operational expenses (at 20%)			5,400,001.80		
	Overhead regulatory costs (at 5%)			1,350,000.45		
	O and M costs (at 5%)			1,350,000.45		
	Overall expenditure			8,100,002.70		
	Monthly profit			27,000.01		

5. CONCLUSIONS AND IMPLICATIONS

The paper highlights the operational aspects of the virtual power plant and a comprehensive summary of how the RE potential can benefit the rural areas of Botswana. The Model considers various factors prior to the simulation process. The Simulation of the model is focussed with the aim of finding the best cost and optimum utilisation of the resources available to the residents in the rural areas of Botswana. While highlighting the operational aspects, the economic feasibility and the nature of how the rural community benefits are highlighted. The simulated model provides an in-depth insight into the operating of a DER for a single household. The model also reflects on various electrical components that are critical to the operation of the system. From the results of the electrical components, it can be inferred that there is no capacity shortage or unmet electrical load in the model. As the system is an "ON-GRID" model, the grid facilitates the sale of the electricity back to the grid. Thus power generated can be sold back to the grid at a price. The economic values on the present net worth clearly indicate that the project is economically feasible and viable as the system is designed to perform favourably over the project lifetime as against the base case system. From the cash-flow analysis, it can be inferred that the cash-flow statements indicate a positive trend on the performance of the model. The return on investment for the rural investors in Botswana also provides excellent returns for the investments made. Analysis reveals that the on an average a single generator largely can lead to a good profit margin to both the virtual power plant operator while ensuring that the prosumer is benefited economically. It can be noted that the VPP provides a great opportunity to the consumer/prosumer when connected to the grid economically. While ensuring economic benefits, the model also reduces the dependency on the grid in the community.

The research takes into consideration the empirical data analysis on energy consumption and costs which forms the basis for virtual power plant deployment. The important implication of the study derives from finding climate profile. Botswana has the highest solar penetration level will enhance the contribution and increase the confidence of the investors planning for solar power PV. With the investment increase, the cost per kW for PV will further reduce, making it more affordable. The increase in production is also likely to increase the jobs in the solar power panel manufacturing sector and the related industries. This will further allow policymakers, investors and governments to look into providing more subsidies to improve and increase renewable energy production, thereby by decreasing or minimising carbon footprint. The concept will also act as a trigger in revising some of the age-old policies to accommodate new technologies favouring the consumers. With more and more investments in the sector, the growing demand will slowly lead to an excess in production for the consumer, which will further facilitate the consumer to sell the energy produced back to the grid thus ensuring the consumer a sustainable income in the form of revenue. With the advancement in technologies, the virtual power plant will also force the grid networks across the countries to be upgraded, thereby, effectively aid in minimising losses. Many others could derive similar implications from the study findings.

REFERENCES

Asmus, P. (2014), Power Plants Go Virtual in the Emerging Cloud. Available from: https://www.navigantresearch.com/blog/virtual-power-plants-harness-the-power-of-the-energy-cloud. [Last accessed on 2016 Nov 27].

Caldon, R., Patria, A.R., Turri, R.R. (2004), Optimal Control of a Distribution System with a Virtual Power Plant. Cortina d'Ampezzo, Italy: Bulk Power System Dynamics and Control.

Candra, D.I., Hartmann, K., Nelles, M. (2018), Economic optimal implementation of virtual power plants in the german power market. Energies, 11(9), 1-24.

Conkling, R.L. (2011), Energy pricing: Economics and principles. In: Energy Systems. Berlin: Springer. p301-324.

Davis, K., editor. (2010), Virtual Power Plants Set to Potentially Change Power Structure. Available from: http://www.elp.com: http://www.elp.com/articles/powergrid_international/print/volume-15/issue-12/feature/virtual-power-plants-set-to-potentially-change-power-structure.html. [Last accessed on 2016 Nov 27].

Dotzauer, M., Naumann, K., Billig, E., Thrän, D. (2015), Demand for the flexible provision of bioenergy carriers: An overview of the different energy sectors in Germany. In: Smart Bioenergy. Heidelberg, Germany: Springer. p11-31.

El Bakari, K., Kling, W.L. (2010), Smart grids combination of virtual power plant concept and smart network design. In: Young Researchers Symposium. Leuven, Belgium: YRS. p1-5.

Garcia, H.E., Mohanty, A., Lin, W.C., Cherry, R.S. (2013), Dynamic analysis of hybrid energy systems under flexible operation and variable renewable generation-Part I: Dynamic performance analysis. Energy, 52, 1-16.

Heide, D., Greiner, M., von Bremen, L., Hoffmann, C. (2011), Reduced storage and balancing needs in a fully renewable european power system with excess wind and solar power generation. Renewable Energy, 36, 2515-2523.

Hochloff, P., Braun, M. (2013), Optimizing biogas plants with excess power unit and storage capacity in electricity and control reserve markets. Biomass Energy, 65, 125-135.

Homer Energy, Homer Components Library (Software). Boulder: Homer Energy.

Houwing, M., Papaefthymiou, G., Heijnen, P.W., Ilic, M.D. (2009), Balancing wind power with virtual power plants of micro-CHPs. In: IEEE Bucharest Power Tech. Bucharest, Romania: IEEE. p1-6.

Hyken, S. (1999), Neural Networks: A Comprehensive Foundation. 2nd ed. Michigan: Prentice Hall.

Kok, K. (2009), Short-term economics of virtual power plants. In: 20th International Conference on Electricity Distribution. Prague: IEEE. p1-4.

Koraki, D., Strunz, K. (2017), Wind and solar power integration in electricity markets and distribution networks through service-centric virtual power plants. IEEE Transactions on Power Systems, 33, 473-485.

Lombardi, P., Powalko, M., Rudion, K. (2009), Optimal Operation of a Virtual Power Plant. Power and Energy Society General Meeting. Calgary, Canada: IEEE Xplore.

Lukovic, S., Kaitovic, I., Mura, M., Bondi, U. (2010), Virtual power plant as a bridge between distributed energy resources and smart grid. In: 43rd Hawaii International Conference on System Sciences. Honolulu, Hawaii, USA: IEEE. p1-8.

Mashhour, E., Moghaddas-Tafreshi, S.M. (2010), Bidding strategy of virtual power plant for participating in energy and spinning reserve markets-Part II: Numerical analysis. IEEE Transactions on Power System, 26, 957-964.

Pachuari, S., Filippini, M. (2004), Elasticities of electricity demand in urban Indian households. Energy Policy, 32(3), 429-436.

Petersen, M.K., Hansen, L.H., Bendtsen, J., Stoustrup, J. (2013), Market integration of virtual power plants. In: Proceedings of the 52nd IEEE Conference on Decision and Control. Florence, Italy: IEEE. p2319-2325.

Venkatachary, S.K., Prasad, J., Samikannu, R. (2017a), Overview, issues and prevention of energy theft in smart grids and virtual power plants in Indian Context. Energy Policy, 110, 365-374.

Venkatachary, S.K., Prasad, J., Samikannu, R. (2017b), Cost optimization of micro grids using homer: A case study in Botswana. International Journal of Energy Economics and Policy, 7(5), 323-339.

Venkatachary, S.K., Prasad, J., Samikannu, R. (2018), Barriers to implementation of smart grids and virtual power plant in sub Saharan region-focus Botswana. Energy Reports, 4, 119-128.

Wittenstein, M. (2015), Projected Costs of Generating Electricity. Organization for Economic Cooperation and Development Projected Costs of Generating Electricity. Paris, France: Nuclear Energy Agency, International Energy Agency. Available from: https://www.oecd-nea.org/ndd/pubs/2015/7057-proj-costs-electricity-2015.pdf. [Last accessed on 2017 Jun 20].

Zamani, A.G., Zakariazadeh, A., Jadid, S. (2016), Day-ahead resource scheduling of a renewable energy based virtual power plant. Applied Energy, 169, 324-340.