Impacts of Electricity Rates on the Economics of Rooftop PV System

Atanda K Raji
Dept. of Electrical Electronic and Computer Engineering
Cape Peninsula University of Technology
Cape Town, South Africa
rajia@cput.ac.za

Abstract— **The huge negative environmental impacts of using fossil fuel-based electricity generation systems is widely visible in terms of air pollutions, greenhouse gas emissions induced climate change, and skyrocketing of electricity prices while the resource is continuously being depleted. Using renewable energy source such as solar energy will surely reduce the negative impacts of conventional fuels used for electricity generation.**

Mitigating the negative impact of the traditional energy sources usage for the production of electricity needs a concerted effort of all inhabitants of the planet Earth. Renewable energy sources such as wind and solar have recently been seen as saviours. While the technical possibility and their readiness are seen as non-barriers to their deployment, one major barrier that recently has been showing up is the economical comparison of their economics with grid electricity where and when it is available. The premium is still acceptable for having a standalone PV system where grid electricity is not reachable. The economics analysis of such standalone system can easily been computed as there are less dynamics involved. The case is a bit complicated where the PV system is grid-tied and bidirectional energy exchange with the grid is allowable. Dynamics such as feed-in tariffs, time of use tariffs, block tariffs et cetera makes the economics analysis of grid-tied energy systems complicated to model, analyse, and optimise. Net present cost as an economic indicator of technical feasible grid-tied energy system is used to assess the economic viability using HOMER software. Different scenarios are evaluated with fixed electricity rate but with different sellback prices.

Index Terms— **Grid-connected, PV cells, HOMER, battery storage device, electricity rates, system design, renewable energy, solar radiation Introduction**

I. INTRODUCTION

The enormous negative environmental impacts of using fossil fuel-based electricity generation systems is widely visible in terms of air pollutions, greenhouse gas emissions induced climate change, skyrocketing of prices of this continuingly decreasing resource [1,2]. The gains of PV learning curves by reducing the price of PV modules are threatened by emerging barriers from utility companies and their subsidiaries by hampering deployment [3]. One instrument that is commonly used by electricity players is the increasing price of cost of grid connection and stay-connected cost as well. Scheme such as feed-in tariff as implemented in many part of the world is being used to deter participation especially in the areas of high penetration of variable generations in one to prevent grid instability, and the other to prevent grid electricity sales and profits erosion [4]. Technical limitations also contributed to this problem in order to maintain the electricity system integrity. Billing instruments such as block tariff, real-time electricity price, off- and low peak load price signals are commonly used to control the system in areas where smart meters or advanced metering infrastructure are available [5]. It must be said that the cost of these meters, maintenance and installation is generally bored by the electricity customers. A partial technical solution to this problem to mitigating the financial strain is studied in this research work, and the technical and economical evaluation thereafter is performed as well.

The design of grid-connected variable generation systems has traditionally followed the method of using the grid as the infinite energy storage system [6]. In such systems, excess energy generated that cannot be utilized on-site is pumped into the grid and the grid is relied upon to supply energy when insufficient energy is generated for on-site energy demand. In some areas, the excess energy supplied to the grid is remunerated for and the drawn energy from the grid during need period is usually charged at a much higher [7].

A simulation-based integrated energy storage grid-connected variable generation system is conducted using HOMER software environment. HOMER is a very versatile software platform that is used for the modeling and simulation of hybrid energy system for identifying optimized, technically, and economically viable system with the capability of being able to evaluate the modeled system for various parameters sensitivities [8, 9, 10]

The rest of the paper is organized as follows. The next session details the operation of solar cells module and the one thereafter evaluates a rooftop PV system that is deployed in an urban area. HOMER is used for the system modeling in the system design methodology employed in this research work. Results and discussions are presented in the penultimate session and the paper concludes in the last part.

IJARE

II. SOLAR CELLS MODULE

Solar cell is essentially a diode with a very large surface area that allows light to fall on in order to initiate direct current electricity generation. The quantum or photon energy contained in the solar radiation is used to liberate electrons and possessed enough energy to escape the atom and wanders in the lattice crystal. These electrons are collected by the negative electrode and propagate through the external circuit to arrive at the positive electrode to complete the electrical circuit connection. Semiconductor material absorbs a particular portion of the solar spectrum. Common semiconductor material in use is silicon. PV cell is commonly modelled using a single diode as shown in figure 1 but a more accurate model can be used if need be to completely represents its operation. Shunt and series resistances are used to represent the leakage current and the inherent losses due to connection needs respectively [11].

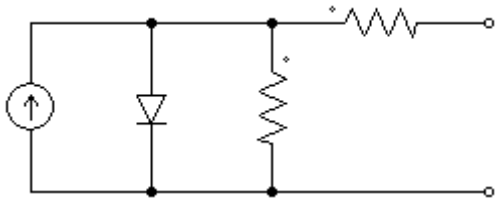


Figure 1 Single diode model of solar cell

The insolation is strongly directly proportional to the solar cell current and the cell operating temperature is inversely proportional to the output voltage across the solar cell. These factors basically limit the maximum power that can be generated by the solar cell [11, 12, 13]

Many solar cells are connected in series to get higher output voltage while parallel connection is performed to increase the output current. These configurations together invariably produce a higher output power solar cell module typically in a range of 100-150W. The variations in the insolation level and cell operating temperature continually shift the operating point on the I-V characteristics curve. Operating the PV module at maximum power point requires an auxiliary power electronics circuit to ensure that the output voltage of the module is adjusted electronically [14, 15]

III. Grid-connected Rooftop PV systems

PV system that is correctly sized to the available local solar radiation and the local electrical load profile will produce cost effective and efficient energy system. This will optimize the system the system design and consequently will lead to increased net present value, higher rate of return on investment while producing environmentally sustainable electricity. Typical system architecture is illustrated in figure 2 wherein the grid is connected to the household through smart meter or advanced metering infrastructure that can measure bidirectional flow of electricity but conceptually illustrated as two independent meters [16, 17, 18, 19].

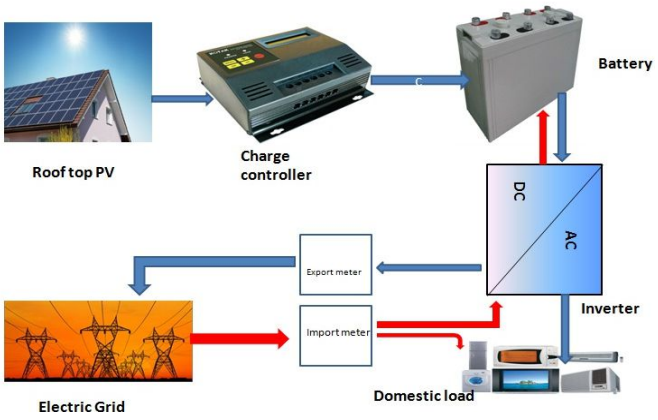


Figure 2 Grid connected rooftop PV system (http://www.firstgreen.co/)

The PV system is connected via an inverter system to convert the produced DC power to AC power for the local load as well as the grid via the metering infrastructure. HOMER is used in this study to size, optimize and perform sensitivity study on different technically feasible and economically viable systems.

IV. HOMER System modelling and simulation

HOMER hybrid optimization model for electricity renewable is used in this work to model a grid connected PV for deployment in an urban area in Cape Town South Africa [22] The components of the system include power inverter, electrochemical energy storage device, electricity grid, representative electricity load profile.

The power inverter sub-system converts the energy stored in the battery to an AC power suitable for local load usage and for grid electricity export whenever onsite power demand is less than PV generated power. The energy storage device stores the energy produced by the PV modules. A hidden electronic device in between the energy storage device and the PV modules is the charge controller that ensures that the battery device is not overcharged or undercharged for longer lifespan and reduced maintenance cost. The charge controller also includes the maximum power point tracking electronic circuit that makes sure that the energy produced by PV modules is maximized under any prevailing atmospheric conditions [20]. The sub-system parameters used in HOMER are tabulated in table 1 below. Prices of all the sub-system components are as quoted in [21].

Table 1: sub component ratings

Sub-system component	Rating
Power inverter	20 kW
PV module	10 kW
Grid electricity	10 kW allowable maximum grid power sale
Battery	12V 305 Ah 4 per string (48V)

IJARE

Table 2 Sub-system components rating

Some of the important assumptions made in this study in order to reduce the order of dynamics are as follows.

Assumptions

- The exchange rate to dollars (HOMER only allows $ monetary value representation) is assumed to be one to one for easy of currency value interpretation as over 90% of all the components used in the model is locally produced or sourced.
- Monthly maximum temperature of the chosen site (Cape Town) is taken into consideration as it's negatively affects the output power of PV systems.
- Unit cost of electricity is constant during the 25 years project life.
- A representative load profile of a medium income urban dweller is used as a case study
- The utility grid is assumed to be 100% reliable and available that is load shedding is not taken into consideration.
- Satellite solar resource data is used in the simulation study.
- Operating reserves in HOMER is set to 0%.
- Simulation time step in HOMER is set to 15 minutes.
- Both load following is the dispatch strategies used in the study.
- A representative municipality electricity rate tariff in South Africa is used in the study.
- Permit, smart meter and installation costs are not included in this study.

Figure 3 below show the modelled rooftop PV system in HOMER as used in this work.

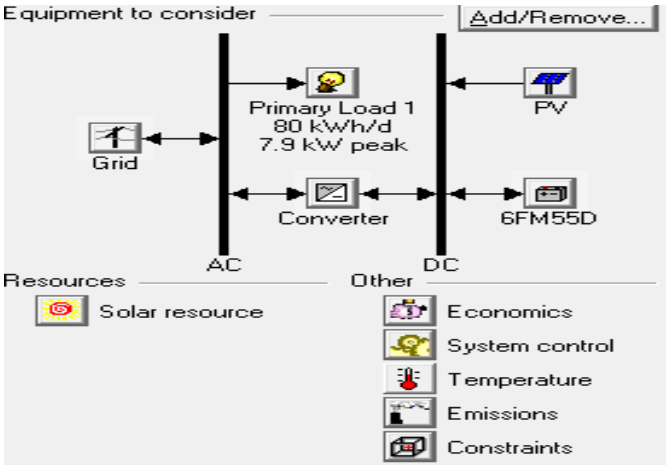


Figure 3 HOMER of grid connected rooftop PV system

For the emissions and particulates of grid electricity, because South Africa primarily use coal for larger proportion of electricity generation, the emissions factor for grid power is taken to be 632 g/kWh for carbon dioxide, 2.74 g/kWh for sulphur dioxide, and 1.34 g/kWh for nitrogen dioxide. The avoided emissions as result of the designed and implementation of the grid connected PV system are calculated by HOMER. At present, this is no monetary compensation for avoided emissions by embedded generation.

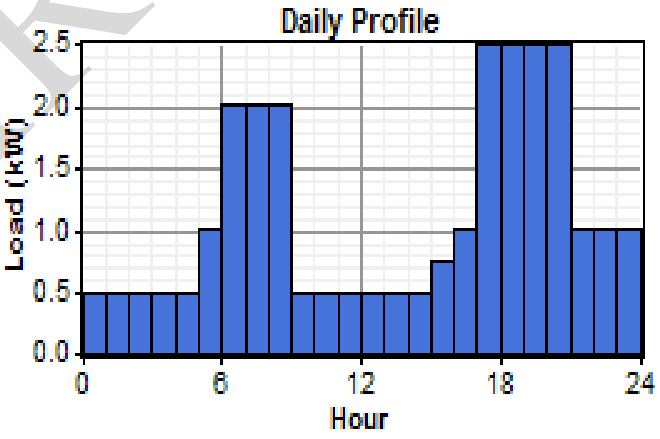


Figure 4 Simulate representative load profile

IJARE

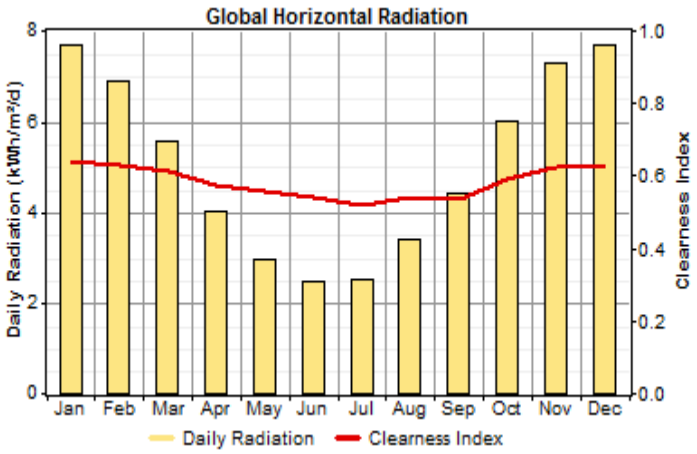


Figure 5 Global horizontal radiation resource of Cape Town

The early morning and evening peaks that is typical of urban load profile is recognized in figure 4. This representative load profile is used to carry out the investigation in this work. Figure 5 shows the solar resource that was imported into HOMER by entering the longitude and latitude of Cape Town [23]. There is generally low solar radiation during winter months and higher solar radiation during summer periods. The peak months on the South Africa electricity grid is winter times. The PV generated energy will definitely lessen the burden on the grid if it is grid connected during winter times.

For the grid electricity price net-metering of ratio one to one is considered, and two other bidirectional power flow scenarios of paying higher price of ratio one to two and lower price of two to one are also considered. A unit price of ZAR1.85 is used in the simulated test case. Economic indicators that are used for economic viability of the system include net present cost, levelized cost of energy, renewable energy fraction, avoided emissions and pollutants, and initial investment cost.

V. Results and discussions

Figures 5 and 7 show the first scenario (scenario A) wherein the price offered for grid sales is ZAR0.925/ kWh and the grid purchase price is ZAR1.85/kWh. The PV production and the grid purchase is 69% and 31% respectively. The net present cost or value is ZAR567 721.00 and the initial investment capital is ZAR468 400.00. The operating cost of the system is ZAR7 700/year. The levelized cost of energy is ZAR1.52 which is higher than what is offered by the grid operator to the owner of the PV system. The renewable energy fraction is 0.694. The avoided emission for carbon dioxide is 506.00 kg/year, sulphur dioxide is 2.20 kg/year, and nitrogen dioxide is 1.07 kg/year.

Figures 8 and 9 show the second scenario (scenario B) wherein the price offered for grid sales is ZAR1.85/kWh and the grid purchase price is ZAR1.85. This is commonly implemented by allowing the energy meter to literally spin in both directions to simultaneously perform credit and debt energy account. The PV production and the grid purchase is 69% and 31% respectively. The net present cost or value is ZAR528 821.00 and the initial investment capital is ZAR468 400.00. The operating cost of the system is ZAR4 726/year. The operating cost of the system is ZAR4 726/year. The levelized cost of energy is ZAR1.42/kWh which is lower (in flow income) than what is offered by the grid operator. The renewable energy fraction is 0.694. The avoided emissions for carbon dioxide are 519.00 kg/year, sulphur dioxide is 2.25 kg/year, and nitrogen dioxide is 1.10 kg/year.

Figures 10 and 11 show the third scenario (scenario C) wherein the price offered for grid sales is ZAR3.70/kWh and the grid purchase price is ZAR1.85. The PV production and the grid purchase is 69% and 31% respectively. The net present cost or value is ZAR433 651 and the initial investment capital is ZAR468 400.00. The operating cost of the system is a positive income stream of value ZAR2 718/year. The levelized cost of energy is ZAR1.16 which is lower (generous inflow income) than what is offered by the grid operator for the grid purchase price. The renewable energy fraction is 0.694. The avoided emission for carbon dioxide is 543.00 kg/year, sulphur dioxide is 2.3 kg/year, and nitrogen dioxide is 1.15 kg/year.

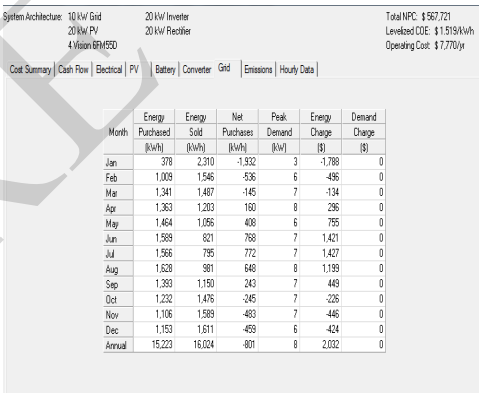


Figure 6: energy purchased and sold (scenario A)

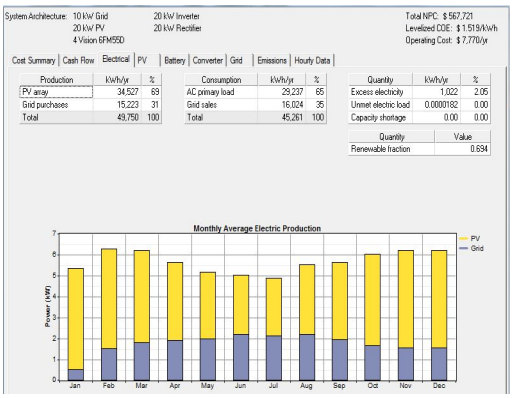
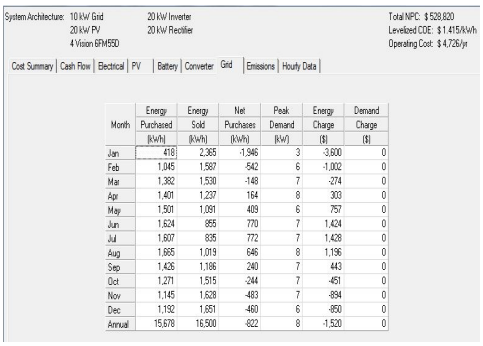


Figure 7: monthly average electric production (scenario A)

IJARE



Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Purchases (kWh)	Peak Demand (kW)	Energy Charge ($)	Demand Charge ($)
Jan	418	2,365	-1,946	3	-3,600	0
Feb	1,045	1,587	-542	6	-1,002	0
Mar	1,382	1,530	-148	7	-274	0
Apr	1,401	1,237	164	8	303	0
May	1,501	1,091	409	6	757	0
Jun	1,624	855	770	7	1,424	0
Jul	1,607	835	772	7	1,428	0
Aug	1,665	1,019	646	8	1,196	0
Sep	1,426	1,186	240	7	443	0
Oct	1,271	1,515	-244	7	-451	0
Nov	1,145	1,628	-483	7	-894	0
Dec	1,192	1,651	-460	6	-850	0
Annual	15,678	16,500	-822	8	-1,520	0

Figure 8: energy purchased and sold (scenario B)

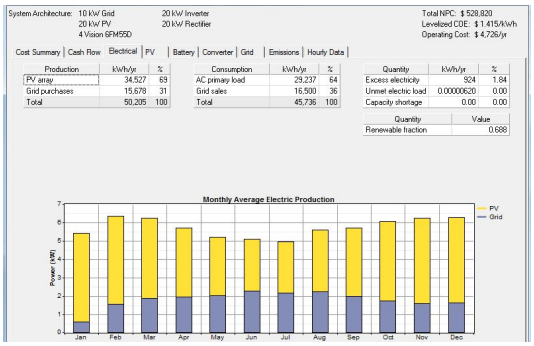
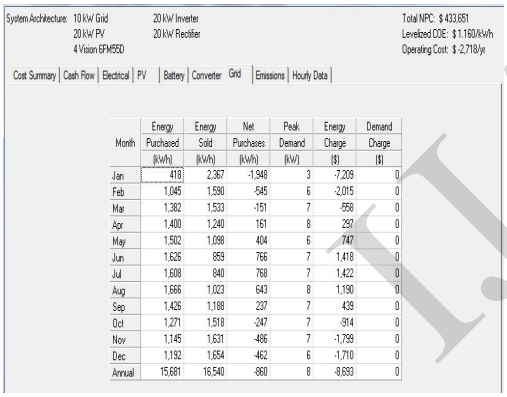


Figure 9: monthly average electric production (scenario B)



Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Purchases (kWh)	Peak Demand (kW)	Energy Charge ($)	Demand Charge ($)
Jan	418	2,367	-1,948	3	-7,209	0
Feb	1,045	1,590	-545	6	-2,015	0
Mar	1,382	1,533	-151	7	-558	0
Apr	1,400	1,240	161	8	297	0
May	1,502	1,098	404	6	747	0
Jun	1,626	859	766	7	1,418	0
Jul	1,608	840	768	7	1,422	0
Aug	1,666	1,023	643	8	1,190	0
Sep	1,426	1,188	237	7	439	0
Oct	1,271	1,518	-247	7	-914	0
Nov	1,145	1,631	-486	7	-1,799	0
Dec	1,192	1,654	-462	6	-1,710	0
Annual	15,681	16,540	-860	8	-9,693	0

Figure 10: energy purchased and sold (scenario C)

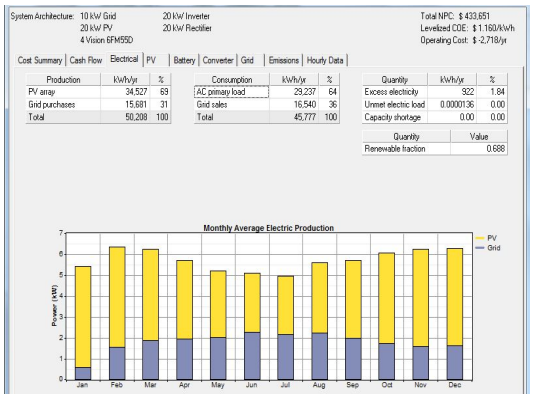


Figure 11: monthly average electric production (scenario C)

Even though the percentage contributions for the PV energy produced and grid electricity consumed are the same for the three scenarios described above, the slight differences in the avoided emissions is mainly due to the randomness introduced in the load generation and other estimated variables in the HOMER software. Avoided carbon dioxide is around 500.00 kg/year, 2.00 kg/year for sulphur dioxide and 1.00 kg/year for nitrogen dioxide. Both first and second scenarios have higher levelized cost of energy compared to the first scenario as well as requiring substantial amount of money for the operation of the system. Third scenario advantageously brings in income of close to ZAR3 000/year. The third scenario also produced energy at the lowest levelized cost of energy of ZAR1.16/kWh. A larger portion of the operating cost is made up of ZAR4 680/year that is billed by the distribution network operation for maintaining connection in order to trade electricity with them.

VI. Conclusions

Three different scenarios were studied to compare the economic performance of the designed and modeled rooftop solar PV system in this paper. A scenario wherein the price of grid electricity purchase is half the sellback price is judged to be the best economically. This is not far-fetched as the price of PV modules is continually decreasing while the grid electricity price is expected to be increasing indefinitely. This is the situation where some distribution network operators and owners (municipality in South Africa) make use of the electricity sales to make huge profits (more than 60% of the total profit in some cases). İn order to avoid higher rate of grid defection by residential electricity consumers, costs to trade with the distribution network operator and owner must be greatly reduced. İt is showed in this work that paying higher for the energy supplied to the grid will encourage higher uptake of the rooftop solar PV system in the residential sector in Cape Town. Monetary values should be credited for created added values such as deferment of infrastructure upgrades, avoided emissions and particulates, increased energy security and autonomy. Creating a residential prosumer in the

IJARE

electricity market will create additional opportunity for the government to tax the income received for electricity sales.

ACKNOWLEDGMENT

This work is based on the research supported by the South African national research foundation (NRF). Any opinion, finding and conclusion or recommendation expressed in this material is that of the authors and the NRF does not accept any liability in this regards. The nrf funds number KIC15090414164 (grant number 98499) is granted and utilised in this regard.

REFERENCES

[1] Ren Shan and Xue HuiFeng, "The monetary quantitative methods of environmental and health benefits of renewable energy", 2nd Conference on Environmental Science and Information Application Technology, 2010

[2] Bugaje, I. M., "Renewable energy for sustainable development in Africa: a review." Renewable and Sustainable Energy Reviews 10.6: 603-612. 2006

[3] Hoffmann, W., "PV solar electricity industry: Market growth and perspective"' Solar Energy Materials and Solar Cells, 90(18-19), pp.3285–3311. 2006

[4] Balcombe, P., Rigby, D., & Azapagic, A., "Motivations and barriers associated with adopting microgeneration energy technologies in the UK"', Renewable and Sustainable Energy Reviews, 22, 655-666. 2013

[5] G De Smedt, M Adonis,"Smart meter for renewable energy microgrid island" Domestic Use of Energy (DUE), 2014 Proceedings of the Twenty-Second, 1-5,2014

[6] Schonardie, M.F. & Martins, D.C., "Application of the dq0 transformation in the three-phase grid-connected PV systems with active and reactive power control", 2008 IEEE International Conference on Sustainable Energy Technologies, pp.18–23.

[7] Lopez-Polo A., Haas R., and Suna D., "Economical drivers and market impacts of urban PV: Promotional drivers"' PV-UP-SCALE Project 2007

[8] P. Lilienthal and L. Flowers, HOMER: The Hybrid Optimization Model for Electric Renewable, in Proc. Windpower '95, American Wind Energy Association., Washington, DC, 27-30 March 1995, pp. 475-480.

[9] National Renewable Energy Laboratory, The Hybrid Optimization Model for Electric Renewables, http://www.nrel.gov/international/tools/HOMER/homer.html.

[10] Raji A. K. and Kahn M.T.E.,"Analysis of distributed energy resources for domestic electricity users", Journal of Southern Africa, vol. 2, no. 1, pp. 50-55, 2012

[11] N Jenkins and G Strbac, UMIST, "Embedded Generation and TIEE Public Electricity System", The institution of Electrical Engineers, printed and published by the IEE, Savoy Place, London WC2R OBL, UK 1997

[12] Sissine, F., "Renewable Energy : Background and Issues in the 110th Congress Resources", Science and Industry Division. CRS Report.

[13] Christo Venter, Atanda Raji, Marco Adonis, "The DC house for low power households-DC-DC converter analysis" Domestic Use of Energy (DUE), 2015 International Conference, 143-146, 2015

[14] B. S, Thansoe, N. A, R. G, K. A.S., and L. C. J., "The Study and Evaluation of Maximum Power Point Tracking Systems", International Conference on Energy and Environment 2006 (ICEE 2006), pp. 17-22, 2006.

[15] AA Aminou Moussavou, M Adonis, Ak Raji, "Microgrid energy management system control strategy" Industrial and Commercial Use of Energy (ICUE), International Conference on the, Cape Town South Africa, 147-154, 2015

[16] Pegels, A., "Renewable energy in South Africa: Potentials, barriers and options for support"' Energy policy. 38(9): 4945-4954. 2010

[17] Rycroft, M., Wagnaar, A. & Sabbione, B., "Rooftop solar PV, an awakening giant", Sustainable Energy, p.58. 2012

[18] Ross, K. and Jordan, B., "Renewable Energy for a Cleaner Future". earthdaynetwork.2012

[19] Gilbert M Bokanga, Atanda Raji, Mohammed TE Kahn , "Design of a low voltage DC microgrid system for rural electrification in South Africa" Journal of Energy in Southern Africa, vol. 25, no. 4, 9-14, 214

[20] Petter Jelle, B., Breivik, C. and Drolsum Røkenes, H., "Building integrated photovoltaic products: A state-of-the-art review and future research opportunities" Solar energy materials and solar cells. 100(0):69-96. 2012

[21] Alternagy, Sub-system components prices, http://www.alternagy.co.za/productcategory/microcare/ (assessed on 01/12/2015)

[22] City of Cape Town, 2013. Electricity Services Tariff Brochure 2013/ 2014.

[23] NASA Surface Meteorology and Solar Energy. http://eosweb.larc.nasa.gov/sse/.

IJARE