Implementing building integrated photovoltaics in the housing sector in South Africa

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Abstract
The installation of Building Integrated Photovoltaics (BIPV) has been increasing rapidly throughout the world, yet little, if at all, has been reported in South Africa. The country has abundant solar energy resource estimated to be between 4.5 and 6.5 kWh/m2/day, yet solar energy contributes less than 1% to the country's energy mix. More than 90% of the country's primary energy comes from fossil fuels leading to an unsustainable per capita carbon footprint of about 9 tCO2e. Previous research has shown that photovoltaics can significantly augment the constrained fossil fuel generated electricity supply. This paper discusses the practical application of photovoltaics as a building element in energy efficient residential housing. The study also aims to determine the feasibility of implementing BIPV systems in the residential sector in South Africa. An energy efficient solar house was designed using simulation software and constructed. Ordinary solar panels were integrated onto the north facing roof of the house. A data acquisition system that monitors meteorological conditions and BIPV output was installed. It was observed that elevated back of module temperatures reaching up to 75°C on sunny days decreased module efficiency by up to 20% in the afternoon. The temperature profiles reveal that BIPV products can significantly influence indoor heating and cooling loads. The research seeks to raise awareness among housing stakeholders and solar industry policy makers of the feasibility of BIPV in South Africa.

Keywords: BIPV generator, energy efficient housing, capacity utilization, economic feasibility, payback period.

1. Introduction

After the transition to democracy in 1994, building activity has been flourishing immensely in South Africa. Government initiatives such as the rural development programme (RDP) have resulted in the construction of about 2.5 million housing units (Department of Human Settlements, 2010). It follows that opportunities to implement energy efficiency measures and renewable energy technologies in the built environment are plentiful. Along with the construction of new buildings, there have been concerted efforts to retrofit and improve the energy efficiency of existing structures. Utilities and individual homeowners are gradually accepting the use of renewable energy technologies to complement grid supply. Photovoltaics is one of the alternative energy sources that can play a significant role in domestic energy supply.

Building Integrated Photovoltaics (BIPV) refers to the use of photovoltaic products as part of the building envelope. The photovoltaic panels perform a dual role – supplying electrical power and protecting the indoor environment from the outdoor weather elements. The installation of BIPV products has been increasing rapidly throughout the world, yet little, if at all, has been reported in South Africa. The country has abundant solar energy resource estimated to be between 4.5 and 6.5 kWh/m2/day, yet solar energy contributes less than 1% to the country's energy mix (DME, 2003). More than 90% of the country's primary energy comes from fossil fuels leading to an unsustainable per capita carbon footprint of about 9 tCO2e (Pegels, 2010). Previous research has shown that photovoltaics can significantly augment fossil fuel generated electricity supply.

The major objective of the study was to demonstrate the feasibility of integrating PV modules in buildings, to test them and to make them known so that they can be used on a large scale. At the same time, the project will provide architects and the

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South African PV community in general with advanced planning tools for PV systems in order to encourage and facilitate integrated PV systems development solutions for the residential sector.

To achieve the stated objectives, an energy efficient solar house was built at the University of Fort Hare, Alice campus. The house has passive solar design features and other energy efficiency measures that reduce household energy demand and a BIPV generator that supplies electrical power. The performance of the energy efficient house and BIPV system was continuously monitored by a data acquisition system.

2. PV theory

The performance of a PV generator is mainly affected by solar irradiance, ambient temperature, orientation, and spectral distribution. A PV module/cell current and voltage (I-V) characteristics are given as (Lasnier and Ang, 1990):

$$I = I_p - I_0\left[\exp\left(\frac{q(V + IR_{se})}{AkT}\right) - 1\right] - \left(\frac{V + IR_{se}}{R_{sh}}\right) \quad (1)$$

where I_p is the photocurrent
R_{se} is the series resistance
R_{sh} is the shunt resistance
A is the diode ideality factor, and
I_0 is the diode saturation current.

The maximum power is given as:

$$P_m = V_m I_m = (FF)V_{oc}I_{sc} \quad (2)$$

where FF is the fill factor,
m refers to maximum power point of the I-V curve
V_{oc} is the open circuit voltage, and
I_{sc} is the short circuit current.

The photovoltaic conversion efficiency is given as:

$$\eta = \frac{V_m I_m}{AG} \quad (3)$$

where A is PV module area, and
G is the irradiance.

BIPV products are usually mounted on building surfaces thereby reducing free air circulation to the back of modules. This tends to increase module temperature and compound temperature effects on the performance of BIPV generators. The effect of temperature on cell efficiency can be deduced from the relation (Skoplaki and Palyvos, 2009):

$$\eta c = \eta_{Tref}[1 - \beta_{ref}(Tc - Tref)] \quad (4)$$

where η_{Tref} is the module efficiency at reference conditions,
β_{ref} is the temperature coefficient
T_{ref} is the reference temperature, and
T_c is the cell/module temperature.

The quantities η_{Tref} and β_{ref} are normally given by the PV manufacturer but can also be obtained from flash tests.

3. Design and implementation

The BIPV system consists of photovoltaic panels, balance of system components and a data acquisition system for recording the photovoltaic output, energy demand and consumption as well as the meteorological parameters. A large number of PV modules with different characteristics are available in the market today. The PV module used in this study has high capacity to frame area ratio (capacity/area) and conversion efficiency greater than 15%. This selection criterion assured the installation of a PV generator that gives more output power in a limited north facing roof area.

A SANYO HIT (Hetero-junction with Intrinsic Thin layer) 190 W solar module was used in this study. The 3.8 kW PV array consists of 20 modules grouped into two equal arrays mounted on the eastern (*E*) and western (*W*) side of the north facing roof. The number of modules to be fitted into the northern roof was deduced from:

$$N_{mod} = \frac{\text{available roof area}}{\text{module area}} \quad (5)$$

Ten module strings were each connected in parallel. Each module string consists of two modules in series. The modules were arranged and numbered as shown in Figure 1.

The longest side of the panels rest on roof trusses whose spacing was made equal to the width of the module. A U-shaped metal bracket, bolt and nut were used to fasten two adjacent modules, at three points, to the roof truss beam as shown in Figure 2.

Mould resistant black silicone sealant and Aluminium water proofing strips were used to seal, bind and waterproof the BIPV panel roof.

A Sunny Island 5048 bidirectional inverter that converts DC to AC power was installed. The inverter has a nominal output power of 5 kW at 25°C, nominal AC output of 230 V and adjustable DC input voltage between 41 and 63 V. A FLEXmax80 maximum power point tracking (MPPT) charge controller was also installed. Maximum power point tracking assures peak performance from the solar array. The charge controller has an output current rating of 80 A and was customized to 52 V_{DC} output voltage required to charge a 48 V_{DC} battery bank. The charge controller output is fed to sixteen batteries connected in four parallel strings of four batteries. Maintenance free solar storage batteries

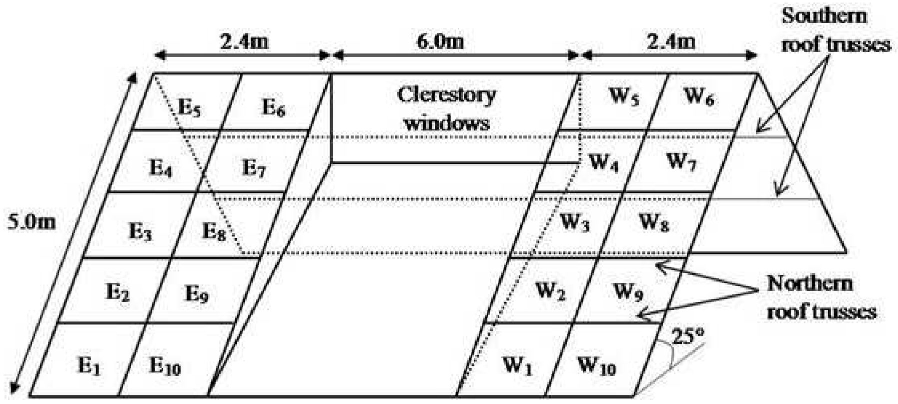

Figure 1: Module arrangement on north facing roof

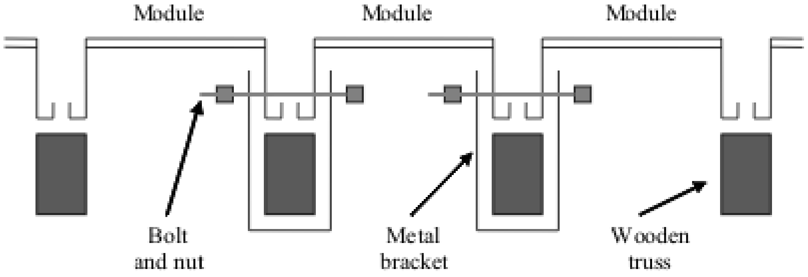

Figure 2: Mounting structure of BIPV panels to the roof trusses

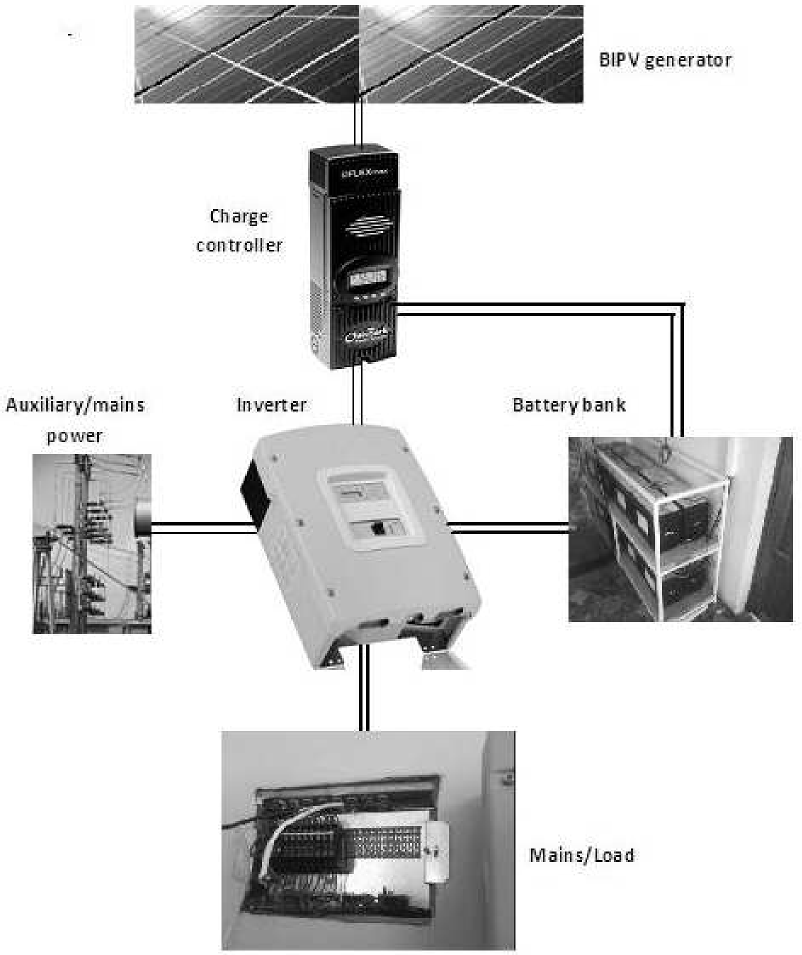

Figure 3: BIPV system connections

(Excis model SMF100) with rated capacity of 102 Ah at 12 V_{DC} were used. Figure 3 depicts the BIPV system connections.

A MATE interface device was connected to the charge controller and Wattplot^{tm} software installed on a PC monitored and displayed BIPV system output.

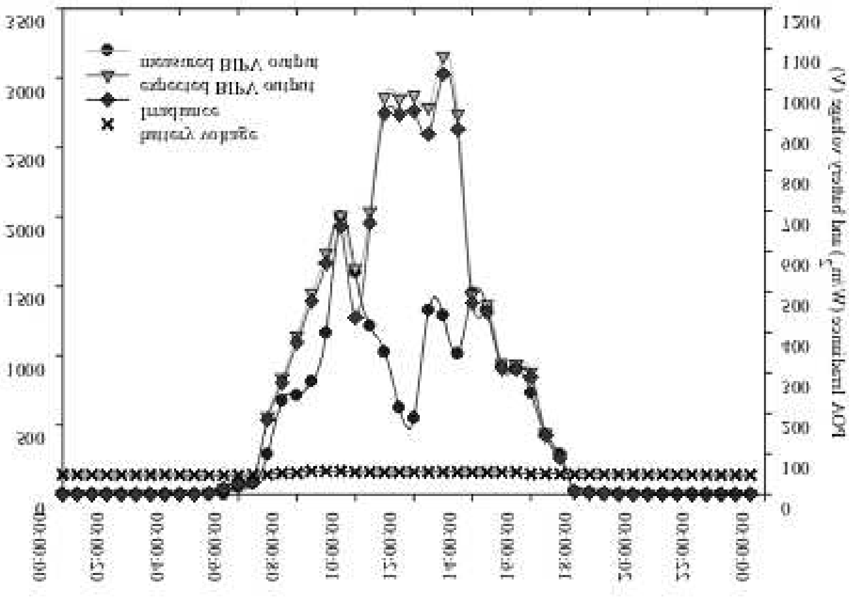

Figure 4: Measured irradiance and BIPV output

4. Results and discussion

BIPV array performance evaluation is based on measurements of I_m, V_m, T_{amb}, T_{mod} and *POA* irradiance. A PVPM device was used to measure and record the mentioned parameters and also determine V_{oc}, I_sc, R_{se}, R_{sh}, and the power coefficients (PVPM Instruction manual, 2010). In addition, the installed data acquisition system also monitors and stores performance data at 30 minute intervals.

4.1 BIPV supply

The average variation of solar irradiance and BIPV output on a typical clear day in December 2011 is shown in Figure 4. The measured output matches the expected peak output of the BIPV array from sunrise to 09:00 hours. At 09:00 hours, battery voltage reaches its maximum of 56 V_{DC}. After 09:00 hours, the charge controller changes its charging mode from 'bulk' to 'float' charging at a constant voltage of 52 V_{DC}.

The float charging stage results in the reduction of power fed to the battery bank such that the measured BIPV output becomes less than the expected BIPV output. The float charging mode is activated whenever the battery state of charge reaches 80% so as to protect the battery bank.

Production factor or capacity utilization is one of the performance indices used to evaluate PV array performance. It is defined as the ratio of actual measured array yield and expected array yield obtained from nominal ratings. With reference to Figure 4, the measured array yield was 11.6 kWh/day, while the expected yield was 23.5 kWh/day signifying a production factor of about 50%. Charge regulation resulted in underutilization of the BIPV capacity. Connecting the BIPV system to the grid is expected to improve the production factor.

4.2. Temperature profiles

The temperature and BIPV efficiency variation throughout the day is shown in Figure 5. The maximum operating temperature of the array was found to be 77.1°C at 12:00 hours when ambient temperature was 35.7°C and solar irradiance was 953.4 W/m^2. It is evident from Figures 4 and 5 that the BIPV operating temperature depends on ambient temperature and irradiance. The elevated back of module temperatures resulted in a decrease in efficiency of up to 20% between 09:00 and 16:30 hours.

The ambient and BIPV operating temperatures are almost equal during night hours, but during the day, the BIPV peak temperatures are more than double the peak ambient and indoor temperatures. This signifies that the BIPV roof is a major heat source during the day and adds significantly to the cooling load requirements of the indoor environment.

4.3 Cost analysis

Table 1 shows the cost breakdown of the BIPV generator and its components. These values are based on supplier prices of 2008.

At 44% contribution, the PV modules present the largest capital investment for the building integrated system. However, between 2008 and 2011, the module prices decreased by about 50% such that the contribution of the modules to the total cost will be less in the future. Operation and maintenance costs mostly involve routine maintenance and battery replacement every five years for the

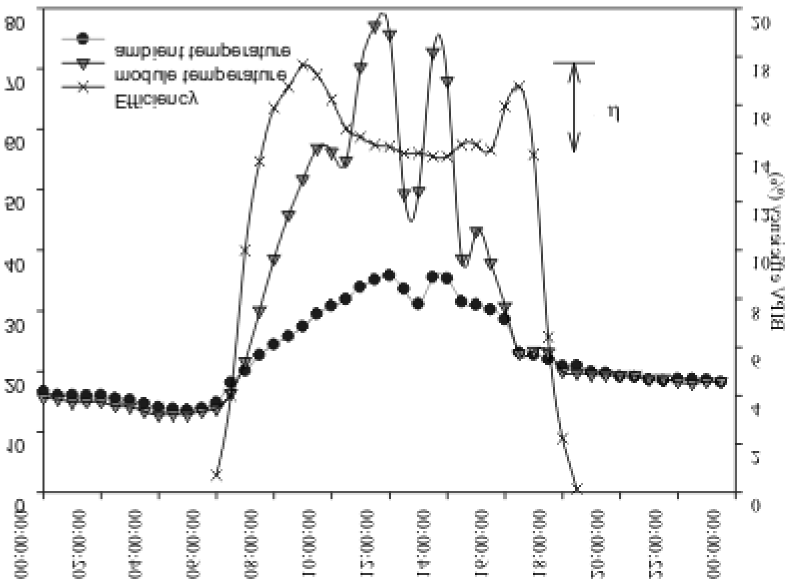

Figure 5: Temperature profiles for a typical sunny day in December 2011

expected 20 year lifespan of PV modules. The grid compatible bi-directional inverter used in this study represents state of the art technology suitable for mini-grid applications. In addition, it is programmable and has data logging capabilities. A cheaper inverter can reduce total BIPV system cost.

Table 1: Cost breakdown of the BIPV system

Component	*Cost factor (ZAR)*	*Contribution to total BIPV system cost*
PV modules	43.00/W_p	44%
Grid-tie inverter	7000.00/kW	19%
Batteries	0.91/kWh	18%
Charge controller	1 100.00/kW	7%
Installation and maintenance costs		12%

A discount rate of 7%, electricity escalation rate of 24.9% and feed-in tariff of ZAR 3-94 was used to determine the economic feasibility of the system over the system lifespan. The discounted payback period was found to be 8 years and 15 years for a grid connected system and a standalone system respectively. The major drawback is that PV installations of capacity less than 1 MW do not qualify for the feed-in tariffs announced by NERSA in 2009 (NERSA, 2010). This capacity threshold needs to be lowered so that residential installations can also benefit from the renewable energy tariff scheme.

The energy efficient solar house was built at a cost per floor area of ZAR 5,375.00/m^2. Figure 6 show that the BIPV system contributed 38% to the total building cost.

The current trend of decreasing module prices in the international market is expected to lower the contribution of BIPV systems to the total building cost.

4.4. Challenges and lessons learnt

Optimum design of BIPV systems requires knowledge of the building's electrical load profile, expected PV output, BOS components, building location and orientation, and the buildings' roof design constraints. The BIPV roof section has to face north (in the southern hemisphere) and the slope of the roof is determined by the latitude of the building site. In addition, the northern roof trusses must be able to accommodate the weight and must match the dimensions of the solar modules.

Solar modules produce DC electricity during daylight hours such that safety procedures are necessary during installations. Module connections described in section 3 resulted in a BIPV generator that has a total short circuit current of 55 A_{DC} and open circuit voltage of 90 V_{DC} at Standard Test Conditions. Live wires need to be insulated and isolated to reduce the risk of electrocution and fires.

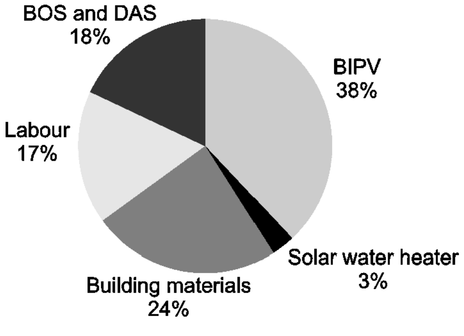

Figure 6: BIPV contribution to the total building cost

Lack of suitably qualified personnel to install BIPV products was one of the challenges faced. The government and the building industry need to train electricians and carpenters (for roof design) on PV installations.

BIPV roofing systems have to perform the same function of normal roofing materials such as water tightness, noise protection, insulation, and generally climate protection. The major safety issues that need to be addressed are:

- Resistance to wind loading and hailstorms
- Water tightness of the roof
- Propagation or the spreading of fires

The implementation of BIPV systems needs to successfully deal with these issues.

5. Conclusions

Since 2009, the ordinary solar modules mounted as BIPV panels have been supplying electrical power to the energy efficient house and also providing climate protection. Initial challenges that were faced were the roof elevation constraints, alignment of the roof trusses, safety issues due to numerous DC cable connections under the roof and leakages during rainfalls.

The BIPV panel back of module temperature fluctuates daily, affected mainly by solar irradiance, ambient temperature, wind speed and the Ohmic power losses as the cells supply energy to the house. Module temperatures of up to 75°C on sunny days indicate that BIPV products can significant affect the indoor thermal environment. In addition, the elevated temperatures can lower BIPV module efficiency by up to 20% at noon. This indicates that a ventilation mechanism that uses air or water needs to be incorporated into BIPV designs in South Africa's weather conditions.

Basing on electricity tariff increases announced by Eskom in 2009, rapid decline in PV module prices, and Feed-in Tariffs (FiT) announced by NERSA, the BIPV generator was found to be economically feasible. Policy instruments need to be revisited so that small scale residential PV installations benefit from renewable energy Feed-in Tariffs. With FiT, the grid becomes the storage thereby minimising or eliminating battery storage. Small residential systems using FiT are the main market drivers for BIPV in developed countries. As a result, the government and municipalities need to consider BIPV products in the current and future housing projects.

References

Department of Human Settlements (DHS) South Africa (2010). '2.4 million RDP houses built since 1994'. *Ministerial response; National Assembly written reply, Question number 2516*.

Department of Minerals and Energy (DME) (2003). White paper on renewable energy. Viewed 24 January 2010 at www.dme.gov.za.

Lasnier F., and Ang T. G., (1990). *Photovoltaic engineering handbook*. Adam Hilgar Press.

National Energy Regulator of South Africa (NERSA) (2010).Viewed 23 march 2010 at www.nersa.org.za.

Pegels A., (2010). Renewable energy in South Africa: Potentials, barriers and options for support. *Energy policy* 38(9), pp. 4945-54.

PVPM Instruction Manual, (2010). Peak power measuring device. Viewed 02 February 2010 at www.pv-engineering.de/en/.

Skoplaki E., & Palyvos J. A., (2009). On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations. *Solar Energy* 83, pp. 614-624