Electrical performance results of an energy efficient building with an integrated photovoltaic system

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Abstract
A 3.8 kW rooftop photovoltaic generator has been installed on an energy efficient house built at the University of Fort Hare, Alice campus, South Africa. The system, located on the north facing roof, started generating electrical power in February 2009. In addition to providing electrical energy, the photovoltaic panels also act as the building roofing material. An instrumentation and data acquisition system was installed to record the indoor and outdoor ambient temperature, indoor and outdoor relative humidity, wind speed and direction, solar irradiance, electrical energy produced by the solar panels and the household energy consumption. This paper presents the initial results of the electrical performance of the building integrated photovoltaics (BIPV) generator and energy consumption patterns in the energy efficient house.

Keywords: building integrated photovoltaics, energy efficiency, energy demand, energy consumption

1. Introduction

The incorporation of photovoltaics into buildings, commonly known as building integrated photovoltaics (BIPV), offers an aesthetically pleasing means of displacing centrally located utility generated electrical power with distributed renewable energy. Building integrated photovoltaic panels replace conventional building elements such as roof tiles, asphalt shingles, corrugated metal sheets, façade elements, and shading devices with photovoltaic modules that perform the same functions and also provide electrical power (Fanney *et al.*, 2001).

The proliferation of photovoltaics as a distributed electrical power source continues to be hampered by initial costs, an inadequate policy framework and lack of performance data. With the National Energy Regulator of South Africa (NERSA) announcing the long awaited renewable energy feed-in-tariffs (REFIT) in March 2009, electrical power generation from renewable energy technologies is expected to increase. Furthermore, the South African government has set a target of 10% demand reduction of energy use in the residential sector by 2015 (DME, 2005) and also set a target of 10 000 GWh/year of renewable energy contribution by 2013 (DME, 2003). These targets give an impetus to academic institutions, research institutes and other stakeholders to spearhead research in energy efficiency measures and renewable energy applications.

Architects, engineers, planners and municipalities would certainly consider the use of integrated photovoltaic building products if there is greater evidence of satisfactory performance and reliability. Despite that capital cost is often the largest barrier, BIPV implementation has also been hampered by lack of predictive performance tools that quantify energy supplied and the achievable energy savings. These tools are required by decision makers in order to make informed decisions concerning the technical and economic viability of BIPV.

Given the limited or non-existent experience with BIPV applications in South Africa, the Fort Hare Institute of Technology designed and constructed an energy efficient building integrated photovoltaic (EEBIPV) house at the University of Fort Hare, Alice campus. The energy efficient house aptly named 'Langalinamandla', meaning powered by the sun, was completed in February 2009. The Langalinamandla housing project integrates renewable energy technologies and energy efficient measures in one building structure. Passive solar house design features, solar water heating, natural ventilation, and BIPV are all part of the design features used in this zero energy house.

The major objectives are to demonstrate the application of renewable energy technologies, particularly photovoltaics in the residential sector, and address the need for performance data and validated performance models. This paper presents the first set of electrical performance results of the BIPV generator. Daily electrical energy supply and household energy consumption profiles together with the greenhouse gas (GHG) mitigation estimates are presented for March 2009, the month the house was occupied by two postgraduate students.

2. Site and climate

The BIPV array was integrated onto the north facing roof of the energy efficient house. The building site has latitude 32.8° south and longitude 26.8° east, at an altitude of 540 m. The site is clear of potential sun blockers on the northern side such as high rise buildings and evergreen trees that would interfere with solar energy collection.

Weather data from the freeware RETScreen clean energy project analysis software version 4.0 (RETScreen, 2008) was used for the initial assessment of climatic conditions of the site. Figure 1 shows the satellite weather data for Fort Beaufort, the nearest weather station situated 20 km west of the building site.

Fort Beaufort meteorological data has been incorporated into the RETScreen software. This world wide meteorological database includes both ground based meteorological data and NASA's satellite derived data sets. This data was used for simulations and initial assessment of the renewable energy technology potential of the site.

3. The photovoltaic system modelling

The current and voltage characteristics of the PV cell are usually modelled by a 5-parameter 2-diode model. The PV cell is taken to be a current source in parallel with a diode, with two resistors modelling the series and parallel internal cell resistance. The current-voltage characteristic of this model is expressed as:

$$I_{PV} = I_L - I_O[\exp\left(\frac{q(V + I_{PV}R_S)}{AK_BT}\right) - 1] - \frac{V + I_{PV}R_S}{R_{SH}} \quad (1)$$

where I_{pv} is the PV cell current
I_O is the diode reverse saturation current
I_L is the photo generated current
q is the electron charge
K_B is the Boltzmann constant
T is the thermodynamic cell temperature
V is the PV cell voltage
R_S is the PV cell series resistance
R_{SH} is the PV cell shunt resistance, and
A is the diode ideality factor.

The ratio of the maximum power to the product of short circuit current, I_{SC} and open circuit voltage, V_{OC} is known as the fill factor (*FF*) , expressed as:

$$P_{max} = FF.I_{SC}.V_{OC} \quad (2)$$

The fill factor describes the quality of the I-V curve and is often used to compare different solar cells under the same reference conditions (Chenni *et al.*, 2007). Figure 2 shows the I-V characteristics measured during the afternoon at irradiance 770W/m^2 ambient temperature 29.8°C using the PVPE I-V test kit.

The efficiency of the PV cell is the ratio of output power to its input power. It is expressed as:

$$\eta_{cell} = \frac{P_{out}}{P_{in}} = \frac{IV}{GA} \times 100\% \quad (3)$$

where G is the solar irradiance and
A_o is the cell area

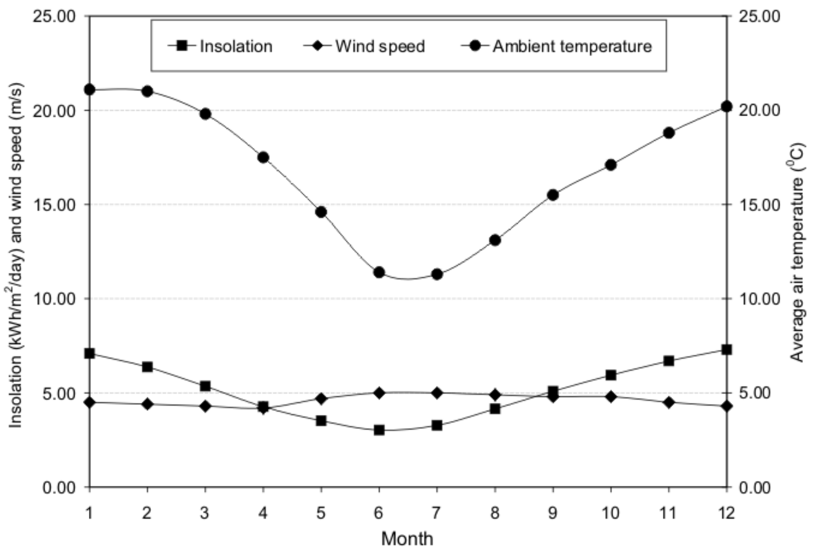

Figure 1: Average monthly ambient temperature, wind speed and solar irradiance

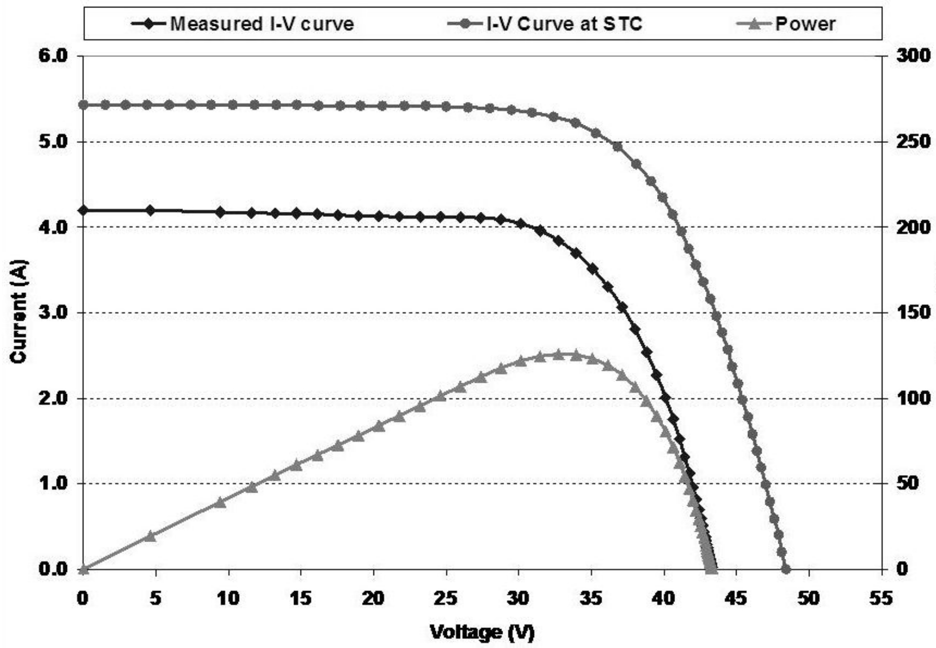

Figure 2: The I-V, power and STC curve of the BIPV module used

The energy demand for a residential load (Wh/day) is given as:

$$E_d = \sum_{i=1}^{n} N_i I_i V_i H_i \qquad (4)$$

where Ni is the number of the i^{th} residential load
I_i is the current drawn by the i^{th} load
V_i is the voltage across the i^{th} load, and
H_i is the daily duty cycle of the i^{th} load (hours/day).

The load demand in Ampere-hours is given by (Bhuiyan *et al.*, 2003):

$$L_d = \frac{E_d}{\eta_{pce} V_{nsv}} \qquad (5)$$

where η_{pce} is the power conversion efficiency
V_{nsv} is the nominal system voltage.

The expected PV output in a given period is calculated as:

$$\text{Peak PV expected} = \frac{\text{daily irradiance} \times \text{peak generator capacity}}{1000}$$

The peak PV output (kWh/day) is the power delivered by the generator when there is no charge controller regulation.

4. The BIPV system description

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

Based on the stated selection criteria, the SANYO HIT (hetero-junction with intrinsic thin layer) solar module was used in this study. The PV array consists of 20 modules grouped into two equal arrays mounted on the eastern and western side of the north facing roof. Ten module strings were connected in parallel. Each module string consists of two modules in series. The HIT 190W module has 66 solar cells connected in series, each cell made of a thin mono-crystalline wafer surrounded by ultra-thin amorphous silicon layers. The module efficiency is 16.1% and the cell efficiency is 18.5%. With a temperature coefficient of -0.30%/°C, the solar cell can maintain high efficiency levels than a conventional silicon solar cell at higher temperatures (Sanyo product information sheet, 2008).

According to the photovoltaic module manufacturer, each module produces 190 W at standard testing conditions (1000 W/m^2, 25°C and an absolute air mass value of 1.5). Thus, the BIPV array has a peak capacity of 3.8kW of direct current electrical power. Table 1 summarizes the electrical and physical specifications of the modules.

Table 1: PV module characteristics

Model: HIP-190N1-BO-02	*Value*	*Unit*
Maximum power, P_{max}	190	W
Voltage at P_{max}, V_{mp}	37.6	V
Current at P_{max}, I_{mp}	5.05	A
Open circuit voltage, V_{oc}	46.4	V
Short circuit current, I_{sc}	5.57	A
Length	144.20	cm
Width	81.00	cm
Thickness of frame	3.50	cm

The longest side of the solar panels rest on the roof trusses whose spacing was made equal to the width of the module. A U-shaped steel bracket, bolt and nut were used to fasten two adjacent modules, at three points, to the roof truss. 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 for converting DC to AC signals was installed. The inverter has a nominal output power of 5kW at 25°C, nominal AC output of 230V and adjustable DC input voltage between 41 and 63V. A FLEXmax80 maximum power point tracking (MPPT) charge controller was also installed at the beginning of January 2009. This charge controller offers an efficient, safe, multi-stage recharging process that prolongs battery life. Maximum power point tracking assures peak performance from the solar array. The charge controller has an output current rating of 80A and was customized to a 54V DC output voltage to the battery bank. The 54V DC output voltage is fed to eight 102Ah batteries connected in two parallel strings of four batteries each.

A meteorological data acquisition system was installed to measure ambient temperature, relative humidity, wind speed and direction and solar radiation at BIPV tilt angle. The data is captured each minute and averaged over 10-minute intervals. Additional data on energy produced by the PV panels was downloaded from the FLEXmax80 charge controller via a MATE interface controller device. The inverter output power, equal to the household energy consumption was recorded on the inverter SD/MMC card. Figure 3 shows the north-eastern view of the energy efficient building integrated photovoltaic house, while Figure 4 shows the SMA inverter, charge controller and junction box.

5. Results and discussion

Two postgraduate students occupied the house at the beginning of March 2009. Recorded data from the inverter, charge controller and the Campbell Scientific data logger was downloaded and analyzed.

5.1 Electrical performance: Demand

All the electrical appliances in the house use alternating (AC) power from the SMA inverter fed through the main distribution board. Listed in Table 2 are the basic appliances in the house.

Table 2: Household appliances

Item	*Units*	*Rated power (W)*
CFLs	10	14
Fluorescent light	1	58
Electric kettle	1	1500
Microwave	1	1500
Refrigerator	1	150
Television	1	60
Home theatre system	1	80

Figure 5 shows the demand profile of electrical appliances and the state of charge of the battery bank. The profiles were derived from daily 30 minute data that was averaged over the whole month. Three prominent demand peaks at 0800 hrs, 1230hrs and 1930hrs are evident in Figure 5. These peaks correspond to the times the house inhabitants were in the house operating the electrical appliances.

Figure 3: The energy efficient BIPV house

Figure 4: Part of the balance of system components

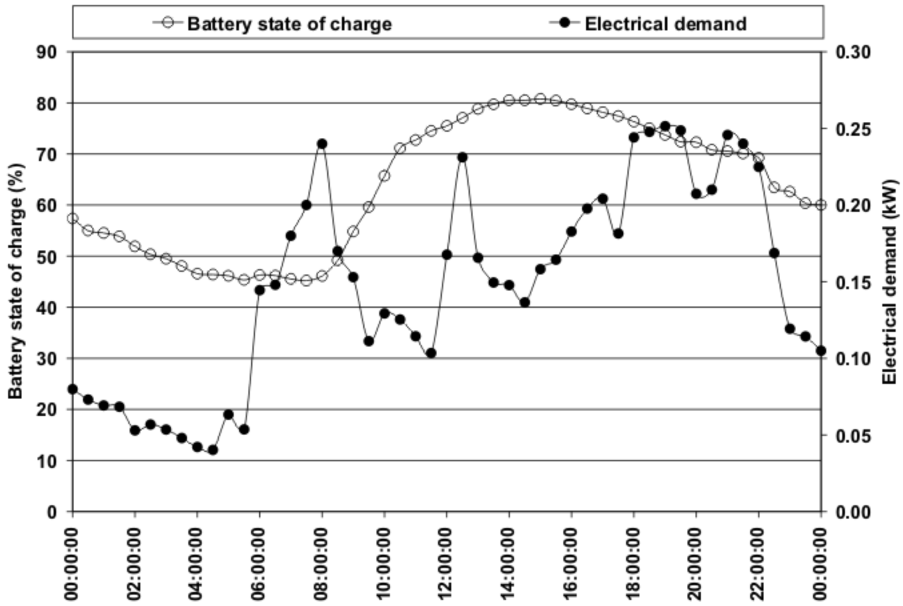

Figure 5: Average battery bank SOC and electrical demand for March 2009

The battery state of charge varies between 45% early morning and 80% during mid-afternoon. The afternoon peaks correspond to increased battery charging from the PV array, a period when solar irradiance is usually highest. During this first month of operation, eight 102Ah batteries were connected whereas the design battery bank has sixteen 102Ah batteries. As a result, the state of charge dropped to 45% overnight, which is just enough capacity and reserve for one day. Considering that the system switches off the electrical loads when the SOC goes below 20%, upgrading the battery bank to sixteen 102Ah batteries becomes a priority so as to ensure enough capacity for three days of autonomy as required.

Figure 6 shows the relation between the incident solar radiation and the battery voltage and current. In response to the incoming solar radiation, the battery voltage rises in the morning before it is clamped to the set 'float' voltage of 54VDC. In the late afternoon there's less irradiation while in early evenings the load discharges the batteries resulting in battery voltage decreasing overnight towards the minimum design value of 48VDC.

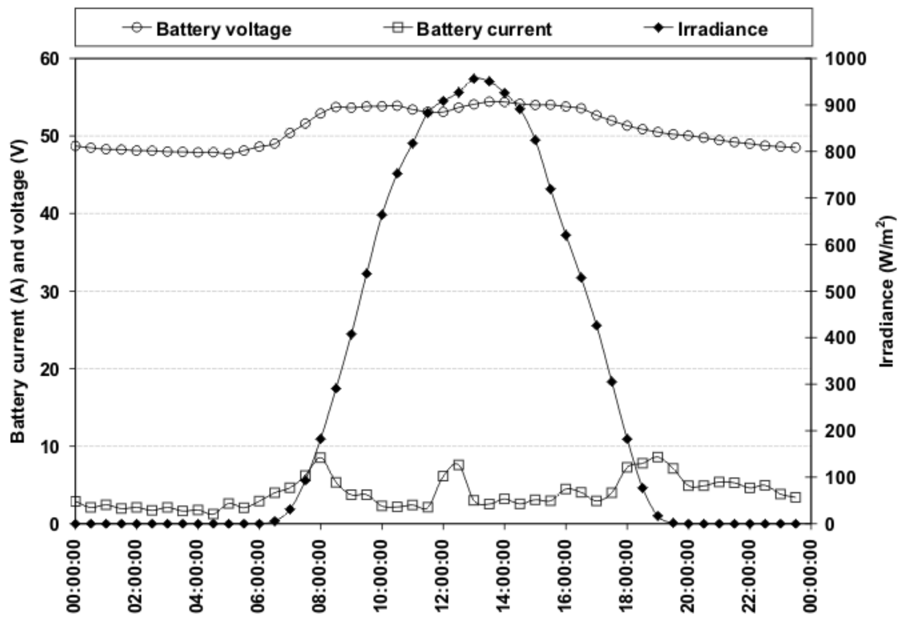

Figure 6: Battery bank voltage and current and solar irradiance

5.2 Electrical performance: supply

The charge controller controls and regulates the battery charging process. The daily regulated output from the PV generator, the expected unregulated output and the recorded solar irradiance at the PV plane of array are given in Figure 7. The daily average irradiance for March 2009 was 6.49kWh/m^2/day and average daily ambient temperature was 20.95°C.

The PV generator delivered 5.23kWh/day on average, whereas the expected PV unregulated output was 24.66kWh/day. This indicates that the PV generator was operating at about 21% of its capacity. In other words, 79% of PV output is lost due to charge controller regulation occurring during most afternoons when the battery bank is full and demand from appliances is low. When the SOC surpasses 70%, the charge controller changes its charging mode from 'bulk' charging to 'float' charging. During bulk charging, all generated electrical power is fed to the battery bank but during float charging; only part of the output charges the batteries. This results in PV generator capacity underutilization mentioned earlier. Connecting the BIPV system to the grid is the only way of fully utilizing the PV output capacity and also generates income from the renewable energy feed-in-tariffs. This constitutes part of phase II of the project.

5.3 Costs, savings and GHG reduction potential

The regulated photovoltaic power output is equivalent to the household energy consumption plus the system losses. Using the National Energy Regulator of South Africa's proposed renewable energy feed-in-tariff (REFIT) of R4-48/kWh levelised cost of electricity for photovoltaics, the savings accrued were calculated and plotted on Figure 8. The savings accrued from power supplied to the house for March 2009 was R120.00.

If the PV system was unregulated and supplying power to the grid, the REFIT return would be R2698.00 and the total net income (avoided cost plus feed-in rebate) would be R2818.00. A techno-economic analysis of the BIPV system was undertaken using the discounted cash flow analysis. Economic variables used were inflation rate 6.3%, nominal interest rate 7% and electricity escalation rate of 35% (for next three years). The payback period was found to be 10.5 years which is very favourable considering that the lifespan of the solar panels is often taken to be 25 years. The life-cycle energy cost of the grid independent BIPV system was found to be R12-16/kWh while that of a grid connected system was found to be R2-26/kWh. Thus, grid connection and feed-in tariffs make PV systems more economically feasible.

During the month under review, the photovoltaic array supplied 162kWh of regulated electrical power to the battery bank and electrical appliances. The average yield in this period was 1.38kWh/day /kWp, corresponding to a yield of 502kWh/year/ kWp assuming uniform electrical demand throughout the year.

The PV output fed to the house in March (162kWh) should result in 195 kg CO_2 equivalent (*eq*) mitigation while the total expected output for the whole month (764kWh) should result in 917 kg CO_2eq mitigation. Figure 8 shows the CO_2eq reduction potential for each day of the month.

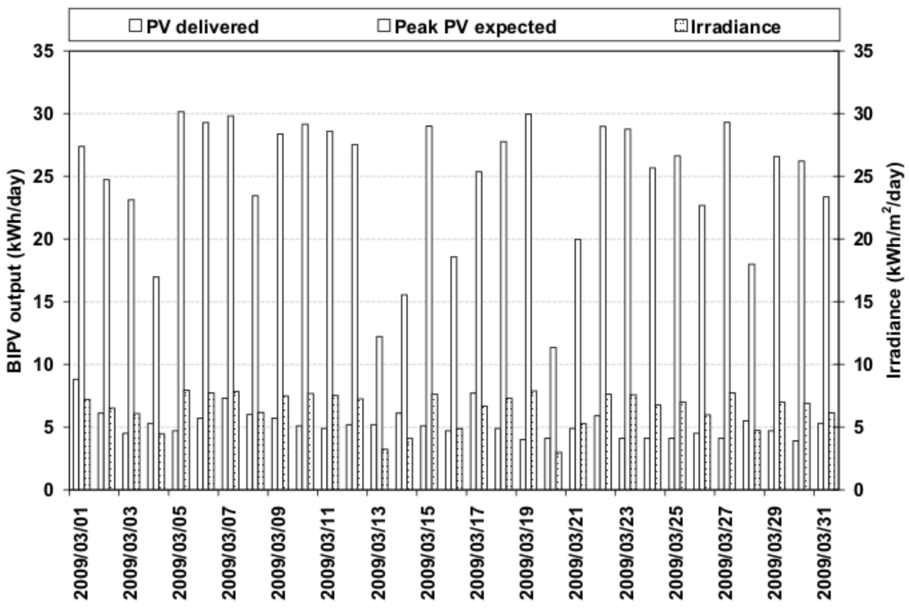

Figure 7: Daily BIPV supply and solar irradiance

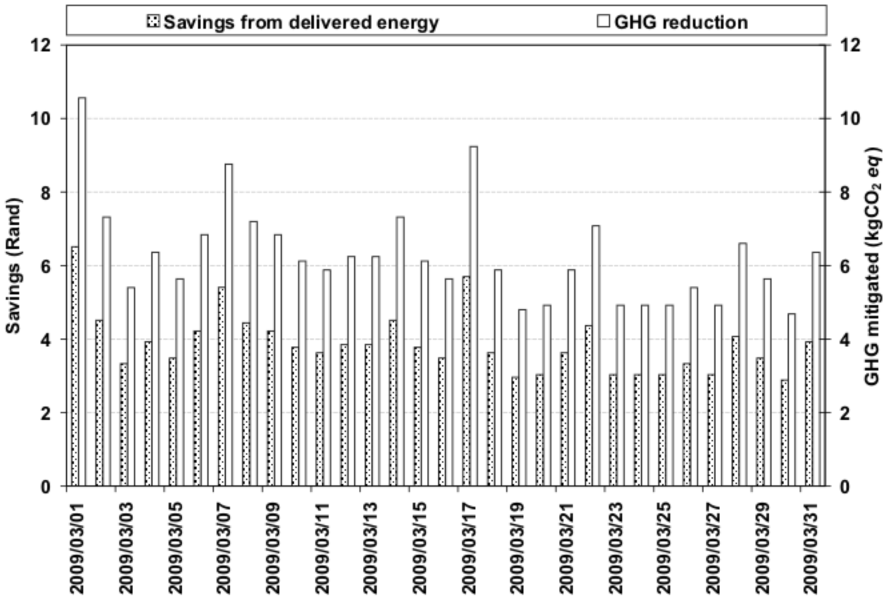

Figure 8: Savings and greenhouse gas reduction potential

6. Conclusion

The house has a total electrical supply capacity of 3.8 kW. The BIPV generator supplied 162kWh in March 2009 which is about 21% of the expected output. The daily electrical energy supplied by the PV system equates to the minimum daily energy saved from the grid and costs R120.00 at prevailing electricity prices. If the PV system was connected to the grid, the unregulated output is projected to generate R2698.00 feed-in-rebate for the month at (R4-48/kWh). This amount is attractive and would result in a payback period of 10.5 years.

The electrical supply to the house is governed by the state of charge of the batteries and the energy demand from the household. With a larger family staying in the house, and more electrical appliances, we expect higher demand and increased regulated output. At present, the energy efficient solar house is independent of grid electricity and the PV system is supplying more power than the daily electrical demand. Phase II of the project will involve the connection of the solar house to the utility grid and monitoring the electrical performance using a net-metering system.

The calculations and figures presented exclude indoor heating and cooling, hot water demand which was met by a solar water heater and cooking done using a gas stove.

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