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Research article

Mitigating climate change through renewable energy and energy efficiency in the residential sector in South Africa

Sosten Ziuku[1] and Edson L. Meyer[2]

[1]Scientific and Industrial Research and Development Centre (SIRDC)
1574 Alpes Road, P O Box 6640, Hatcliffe, Harare, Zimbabwe
Tel: +263 4 860 335/ +263 779 774 546 Fax: +263 4 860 350/1
E-mail: sziuku@sirdc.ac.zw/sostenz@yahoo.com

[2]Fort Hare Institute of Technology, University of Fort Hare,
Private Bag X1314, Alice 5700, South Africa
Tel.: +27 406 022 086 Fax.: +27 406 530 665
E-mail: emeyer@ufh.ac.za

Abstract

The scientific evidence of climate change as a result of greenhouse gas emissions is becoming increasingly obvious. Arguably, fossil fuels are the largest contributor to greenhouse gas emissions. In South Africa, more than 90% of the electricity is generated from fossil fuels and the building sector contributes about 23% of greenhouse gas emissions. The Integrated Resource Plan of 2010 envisages a 16% renewable energy contribution to the Country's energy mix and a 30% reduction in ghg emissions by 2030. This paper highlights South Africa's climate change situation and discusses the application of renewable energy technologies and energy efficiency measures in the residential sector as a means of mitigating climate change. A case study of a prototype energy efficient solar house that was designed and built at the University of Fort Hare is presented. The house has passive solar features, a solar water heater for hot water supply and a building integrated photovoltaic (BIPV) generator that supplies electrical power to the household appliances. An automated data acquisition system comprised of an outdoor weather station and a datalogger was installed. Thermal and electrical performance of the building integrated photovoltaic generator and indoor and outdoor ambient conditions were monitored. Energy performance data recorded over a year revealed that the energy efficient solar house has the potential to mitigate 12.41 tonnes of CO_2e per annum.

Keywords: Energy efficient building, building integrated photovoltaics, passive solar design, greenhouse gas mitigation.

1. Introduction

Climate change is now widely acknowledged as one of the key challenges of the twenty first century. The Intergovernmental Panel on Climate Change (IPCC) has highlighted the important role of buildings in climate change and stated in its 4th assessment report of 2007 that the building sector not only has the largest potential for significantly reducing greenhouse gas (ghg) emissions but also that this potential is relatively independent of the cost per tonne of carbon dioxide equivalent (CO_2e) achieved [1].

The building stock in South Africa amounted to about 12.5 million units in 2006 of which about 8.5 million were formal while about 4 million units were backyard properties, informal units and traditional houses [2, 3]. The Department of housing reported that the housing backlog in 2008 stood at 2.4 million units and the government hopes to reduce or do away with the shortfall by 2014. At present construction rates of about 250 000 units per year for Reconstruction and Development Programme (RDP) housing, the increasing backlog is going to take much longer to eradicate. It is estimated that South Africa's investments in the residential and non-residential sectors will grow on average at 2% per year between 2008 and 2050 which will result in the doubling of the building stock [4]. If ghg emissions remain unchecked, this may result in a twofold increase in emissions. The commercial and RDP housing backlog provides an opportunity to build dwellings that are energy efficient (EE) and also use renewable energy technologies (RETs). In addition, EE measures and RETs, which are proven methods of reducing domestic energy demand and consumption, can also be retrofitted onto existing buildings.

South Africa's electricity supply utility, Eskom generates about 95% of the electricity used in the country. The Country's energy consumption patterns show that the building sector accounts for about 17% of total energy use, 31% of electricity use and contributes 23% of ghg emissions. The country's electricity used to be one of the cheapest in the world, beaten to second place by New Zealand [5]. However, in 2009 Eskom increased its tariffs by 31% and in February 2010, the National Energy Regulator of South Africa (NERSA) granted Eskom a 24.8% tariff increase effective 1st of April. Subsequent increases of 25.8% and 25.9% for the 2011-12 and 2012-13 years were also announced. As a result, the price of electricity will average 65-05c per kWh by 2012 [6]. Increased prices and supply bottlenecks will compel consumers to continue using wood and other fossil fuels in their households irrespective of the existence of the free basic electricity subsidy for poor communities. The use of fossil fuels pollutes the built and outdoor environment. It has been reported that residents living in informal settlements of South Africa experience a serious health risk as a result of using kerosene for heating, cooking and lighting [7]. In addition, Eskom has been experiencing capacity supply constraints as peak demand approaches installed capacity of about 40 GW. The narrow reserve margin of less than 10% resulted in power shortages experienced in 2007 and early 2008 [8].

Eskom is a significant player when it comes to greenhouse gas emissions, reporting 221 million tonnes of CO_2e in the 2009 financial year, about half the country's total emissions estimated at 440 $mtCO_2e$ per year [9]. The high emission values from Eskom result from the fact that Eskom's generating capacity is more than 90% based on abundant low cost coal. On average, Eskom burns about 90 million tonnes of coal per annum polluting fresh water and the atmosphere in the process. Due to the high dependency on fossil fuels for primary energy requirements, the country's emissions per capita of 9 tonnes CO_2e per person in 2005 was above the global average of 5.8 tonnes and six times higher than the sub-Saharan average of 1.4 tonnes [10]. According to the World Resources Institute, SA ranks 14th out of 50 countries in terms of its attributable share of ghg emissions [11]. These figures compel SA to adopt ghg mitigation measures so as to reduce the country's carbon footprint.

This paper discusses the potential of mitigating greenhouse gas emissions in the residential sector through the implementation of energy efficiency measures and the adoption of solar energy as an energy supply option. An energy efficient solar house was built at the University of Fort Hare, South Africa and its performance helps to further understand climate mitigation options in buildings. In addition, South Africa's emissions reduction commitment is conditional on international financing, technology and capacity-building support. The energy efficient solar house project partly addresses the technological aspect of ghg reduction initiatives in buildings.

2. SA government response to climate change

In 1988, UNEP and WMO established the IPCC whose mandate is to produce regular scientific and technical assessments on climate change. This culminated in the UN Framework Convention on Climate Change (UNFCCC) being agreed to at the earth summit in Rio de Janeiro, Brazil. The Convention came into force in 1994 resulting in the adoption of the Kyoto protocol in 1997. The protocol delineates a binding ghg emission reduction target for Annex-I (Industrialized countries) of 5% percent below 1990 ghg emission levels over the 2008 to 2012 period [12]. South Africa ratified the FCCC in November 1997 and the Kyoto protocol in July 2002. As a non-Annex-I party, there are no quantified emission limitation and reduction commitments in terms of article 3 of the Kyoto protocol. However, this scenario may change after the UNFCCC post-2012 Conference of Parties (COP) negotiations. Furthermore, SA being one of the countries with high ghg emissions per capita has a moral, scientific and administrative obligation to formulate, publish and implement national policies that mitigate climate change.

From the time the South African government ratified the UNFCCC and hosted the world summit on sustainable development in Johannesburg in 2002, there's has been increased interest in reducing ghg emissions. Policy instruments such as the White Paper on Energy [13], Standards for Energy Efficiency in Buildings [14], the National Climate Change Response Strategy for SA [15], Capacity Building in EE and RE programmes [16] are some of the instruments put in place that deal with climate change issues in a way that results in ghg emission reduction if implemented. A document titled Vision, Strategic Direction and Framework for Climate Policy [17] has attracted considerable attention as a model for developing countries. The major challenge for most of the policies thus far is the absence of legally-binding enforceable absolute emission reduction targets across most sectors of the economy.

The fundamental issue raised by the Long Term Mitigation Scenarios (LTMS) study was the need to move from a carbon-intensive to a low-carbon economy [18]. However, the country's absolute emissions commitment has not been formally quantified. The best available projection is that the country has to reduce its emissions by 0.2% per year to achieve the 2020 commitment of 34% below the 'Growth Without Constraints' scenario in the LTMS [19]. In a low-carbon economy, emissions were also projected to peak (around 2020 – 2025), plateau for a decade and then start declining. The LTMS represents a landmark in SA climate policy, however implementation will provide a crucial test to the vision and policy framework it presents. The strategic direction offered by the LTMS needs support from quantifiable ghg emission reductions from the use of energy efficiency and renewable energy technologies.

The Integrated Resource Plan of 2010 (IRP 2010) arguably provides the most recognisable action to support the regulatory framework for climate change mitigation and the promotion renewable energy in South Africa since the adoption of the National Energy Act in 2008. The IRP 2010 for electricity envisages a 16% renewable energy contribution to the country's generation capacity. Renewable energy technologies and energy efficiency measures are expected to propel the country towards the goal of reducing ghg emissions by 30% by 2030 [20].

The Stern review reported that the costs of adaptation for the world, should no mitigation occur (called the costs of inaction), will be in the order of 5 to 20 times the cost of mitigation actions required today [21]. Hence South Africa has to play its part in mitigating climate change so as to reduce local and global climate impacts and the associated damage costs.

3. Approach and methodology of the study

Successful implementation of energy efficient measures and renewable energy technologies for climate mitigation in the residential sector hinges on appropriate design of buildings. The initial process in the design involved simulation and modeling. These two processes are fundamental in the construction of sustainable energy buildings. The major purpose of simulation and modeling in the design phase was to optimize building thermal and electrical performance. Without it, energy efficient housing would be based on experience which has evolved over many years through trial and error. Experience varies with climate and cultures, while trial and error in present and future construction is not only impractical and unreliable but also very costly.

The Energy Efficient Building Integrated Photovoltaic (EEBIPV) house was designed using Ecotect™ building simulation software. Ecotect™ is a highly visual and interactive complete building design and analysis tool that links a comprehensive 3D modeler with a wide range of performance analysis functions covering thermal, energy, lighting, resource use and cost aspects [22]. While its modeling and analysis tools can handle any geometry of any size and complexity, its main advantage over most other programs is feedback at conceptual building design stage. It also provides an array of design formats suitable for use with other leading Computer Aided Design (CAD) programs.

The photovoltaic generator and solar water heaters were initially designed and simulated using RETScreen clean energy analysis software. The software is mainly used as a pre-feasibility analysis tool for evaluating energy production, costs and emission reduction potential of RETs. A detailed analysis of the performance of the building integrated photovoltaic generator was done using PV-DesignPro software, particularly looking at ´´what-if`` scenarios for optimization [23]. PV-DesignPro provided in-depth information on likely BIPV system power output, load consumption, necessary back-up power during the operation of the system, and the financial impacts of installing the proposed system. Databases in RETScreen and PV-DesignPro containing hourly values of solar irradiance, ambient temperature, wind speed and direction, and other weather variables were utilized.

The potential energy savings that could be achieved by using the SWH were deduced from the relation:

$$Q = \dot{m} C_p (T_{hot} - T_{cold}) \tag{1}$$

The daily kilowatt-hour energy savings are determined from [24]:

$$kWh_{day} = \frac{1}{1000} \frac{1}{3600} \dot{m} C_p (T_{hot,\max} - T_{cold,\min}) \tag{2}$$

where m is the mass flow rate of hot water
C_p is the specific heat capacity, and
T is temperature.

The total CO_2 emissions from a power grid having electricity generated from fossil fuel combustion are usually deduced from the UNFCCC methodological tools. The ghg emission reduction from RETs was deduced from the relation [25]:

$$Total\ ghg\ emission\ reduction = \sum_t Output \times P_t \times CEF_t \tag{3}$$

where $\sum_t Output$ is the generated power output (Wh)
P_t is the percentage contribution to the grid (%)
CEF_t is the carbon emission factor for specific fossil fuel (CO_2/Wh).

Eskom reported a carbon emission factor of 1.03 kg CO_2e/kWh for electricity generated from coal in the 2009 annual report [26]. In the case of renewable energy electricity generated at the EEBIPV house, the generated electricity output is taken as the avoided grid consumption and the percentage contribution was 100%.

4. Implementation of EE measures and RETs in the case study

The EEBIPV house was built at the University which is located 32.8°S and 26.8°E in South Africa. Measures to reduce ghg emissions from the EEBIPV house can be classified into two: reducing energy consumption and demand through energy efficient measures and replacing fossil fuel generated grid supply with BIPV decentralized power.

4.1 Passive solar design

The sun rises in the east and sets in the west and its trajectory is higher in the summer sky and lower in winter. This seemingly obvious fact is the basis for passive solar design of buildings. Passive solar features which cost next to nothing were incorporated into the house design. The house has a compact shape measuring 8 m^2 by 10 m^2 with a low surface-to-volume ratio of 0.93 to minimize heat losses through the building surface. The longer side of the house or the ridge-line runs east-west with most of the windows located on the northern façade. Combined with overhangs sized to 0.55 m, the house orientation allows maximum winter solar gains and reduces unwanted summer heat gain. The passive solar interventions do not use mechanical or electrical devices to capture, store and distribute heat thus lowering building energy consumption which leads to reduced ghg emissions.

Clerestory windows installed on the north facing roof allow the southern facing rooms to access direct solar irradiance in winter. In addition, the 6m^2 windows increased the north facing window area to 18% of floor area compared to other orientations each with less than 10%. In summer, the clerestory windows may be opened allowing hot air to escape through the roof due to the stack effect. This promotes natural ventilation keeping energy demand minimum. The position of clerestory windows also allows natural daylight to access the indoor space of the house. This reduces artificial lighting thereby improving energy savings. In addition, natural light improves occupant satisfaction and comfort.

4.2 Building integrated photovoltaics

Building integrated photovoltaics refers to the integration of photovoltaic panels onto the building envelope. A 3.8 kW photovoltaic generator was integrated into the north facing roof of the energy efficient house shown in figure 1. The PV modules simultaneously serve as the roofing material and electrical power source. The BIPV generator supplies power to the household loads and charges a 408 Ah x 48 V_{DC} battery bank. The BIPV system also includes a charge controller for regulating battery charging and a 5 kW grid compatible bidirectional inverter. The inverter converts DC output from the PV modules and DC supply from the battery bank to AC power required by household appliances. The use of BIPV panels to supply electrical power to the house effectively replaced utility grid electricity supplied by Eskom. A complete discussion of how the BIPV panels were connected and the PV supply measurement system is given in [27].

Figure 1: PV modules on the EEBIPV house [27]

The house was occupied by two postgraduate students at the beginning of 2009 and its thermal and electrical performance is being monitored.

4.3 Energy efficient lighting

While incandescent light bulbs use electricity to heat the filament white-hot, fluorescent bulbs produce light from the excitation of gases inside the bulb hence consuming less energy. Lighting demand tends to coincide with peak demand, especially in the winter season when the sun sets early and demand peaks in the evening. Compact fluorescent lighting can reduce evening peak demand which usually attracts higher tariffs. The efficient lighting initiative funded jointly by the Global Environmental Facility and Eskom, aims to install around 18 million compact fluorescent light bulbs (CFLs) over 20 years, and is the largest energy efficiency project in South Africa to date [28]. Complementing the efforts of the national utility, 10 CFL bulbs were installed in the energy efficient solar house. Each of the CFL bulbs is rated 14 W and has an estimated lifespan of about 10 000 hours which is much greater than that of incandescent light bulbs whose lifespan is about 750 hours.

4.4 Solar water heating

Considering the high solar radiation rate in South Africa and that water heating accounts for up to 40% of domestic energy consumption, one would expect more widespread use of domestic solar water heaters (SWH). With as few as 10 000 units being installed annually, the need for large scale roll-outs has become

critical [29]. South Africa through Eskom, UNDP, CEF, and other municipalities have been involved in SWH projects since 1999. The biggest barrier to large scale roll-out has always been the capital cost and low electricity prices. However times are changing: electricity prices have been rising sharply, the price of locally made SWH has been going down and more importantly Eskom launched a subsidy programme aimed at installing 925 000 SWH units in five years beginning 2008 [30].
While complementing government's efforts and demonstrating that SWH can work in tandem with other EE measures and RETs in the residential sector, a 4m^2 flat plate collector SWH was installed on the northern roof of the EEBIPV house. The direct coupled system uses the thermo-syphon effect and has a 200 L storage tank for storing hot water. The storage tank was installed above the collector level and is located in the ceiling space. Direct coupled thermo-syphon systems do not have moving mechanical components hence require little maintenance.

4.5 Ceiling

Ceiling installation and ceiling insulation is a common intervention used in energy efficient buildings. Space heating energy consumption can be minimized at the same time improving the thermal comfort and decreasing indoor air pollution. Ecotect^{TM} was used to quantify the indoor space heating and cooling requirements of the EEBIPV house with and without a ceiling for the purpose of selecting a cost effective ceiling material. The ceiling is made of plaster board composite panel that has a gypsum core sandwiched between two sheets of paper linerboards. The 9.5 mm Plasterboard of thermal resistance (R-value) 0.32 m^{2}K/W allows the plasterer to nail the board directly to the studs with relative ease thus saving significant cost on labour.

5. Data acquisition

A data acquisition system (DAS) that stores measured indoor and outdoor meteorological data was installed on the energy efficient house. The automated DAS consists of sensors that measure indoor and outdoor temperature, indoor and outdoor relative humidity, global and plane of array solar irradiance, wind speed and direction and a CR1000 data logger which collects and archives measurement data from the sensors. A multiplexer that increases measurement channels from 8 to 32 was also connected. The data logger was programmed to measure ambient conditions every minute and then record the average values every thirty minutes.

The BIPV output was monitored by a MATE interface device and WattPlot software. The MATE device was connected to the OutBack FLEXmax charge controller and the serial port of a PC computer. WattPlot displays BIPV system output and also logs daily performance data. Time of use dataloggers measure energy consumption by CFL bulbs. The HOBO light on/off logger has a built in light sensor that responds to presence or absence of light. The logger records ON and OFF states with a time and date stamp. The data was downloaded and analysed.

A data acquisition system for measuring the performance of the SWH was also installed. The system measures and records inlet cold water temperature, outlet hot water temperature from storage geyser, and hot water flow rate. The solar energy input is recorded and hot water consumption profiles determined. The logged data and actual real-time data were accessed through a serial communications port. Figure 2 depicts measured profiles of hot water consumption, outdoor ambient temperature, indoor temperature and global and plane of array (POA) solar irradiance for a two day period in winter.

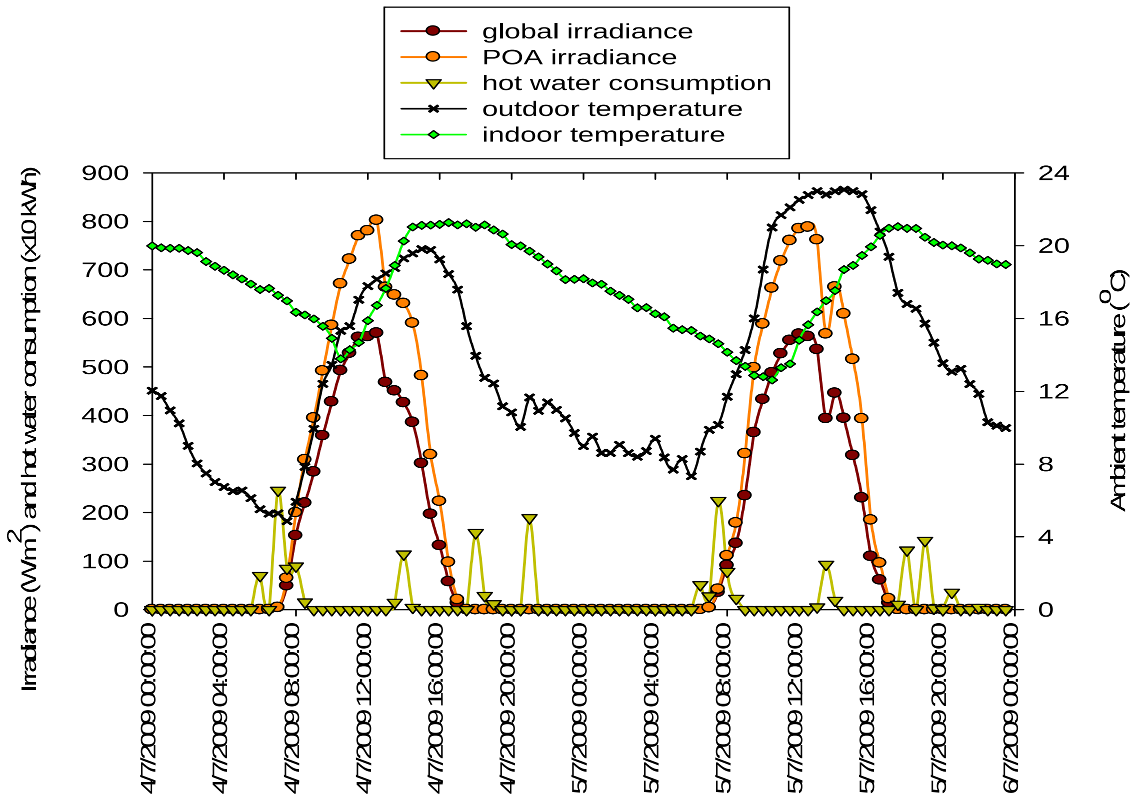

Figure 2: Measured temperature, hot water and solar irradiance profiles

6. Results and discussion

The performance of the EE and RETs components were monitored by the DAS described in section 5. In 2009, the building integrated photovoltaic generator supplied 7224.22 kWh to the battery bank and household loads at a yield of 5.21 kWh/kW$_p$/day. Figure 3 shows the mitigated greenhouse gas emissions as a result of energy savings from the BIPV generator, ceiling and solar water heaters.

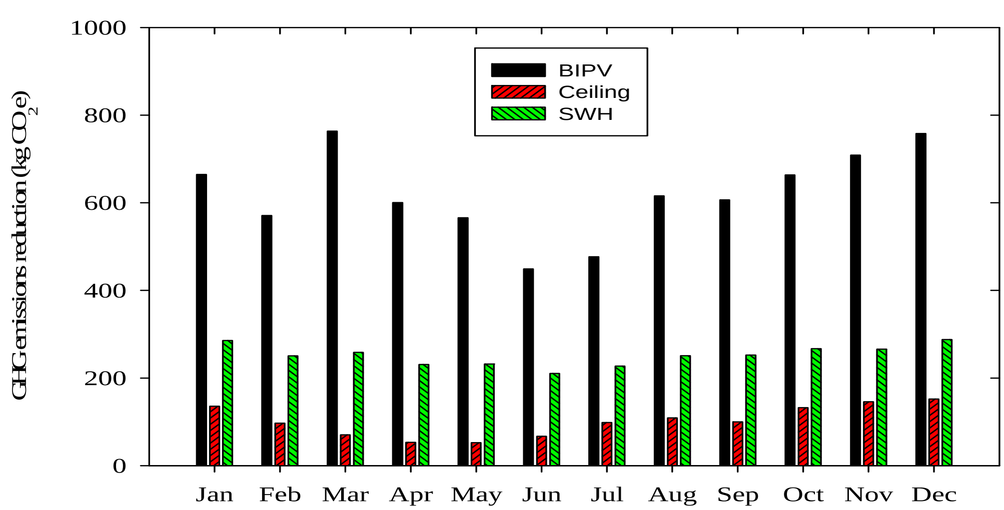

Figure 3: Monthly mitigated greenhouse gases

BIPV electrical supply amounts to the mitigation of 7.44 tCO_2e per year. BIPV supply is taken to be the avoided consumption of fossil fuel generated grid electricity. The use of 10 CFL light bulbs each rated 14 W, resulted in total energy savings of about 712.48 kWh/year. This corresponds to the mitigation of 733.85 $kgCO_2e$ greenhouse gases annually.

Using the measured hot and cold water temperatures, average plane of array irradiance and ambient temperatures, known collector area, collector optical efficiency and loss coefficients (supplied by manufacturer), the SWH was found to have an average yield of 2.01 kWh/m^2/day. The avoided electrical consumption results in the mitigation of 3.02 tCO_2e annually. The avoided coal and water consumptions due to the use of SWH are a tangible benefit to the environment. The influence of plasterboard ceiling on energy losses is illustrated in figure 4.

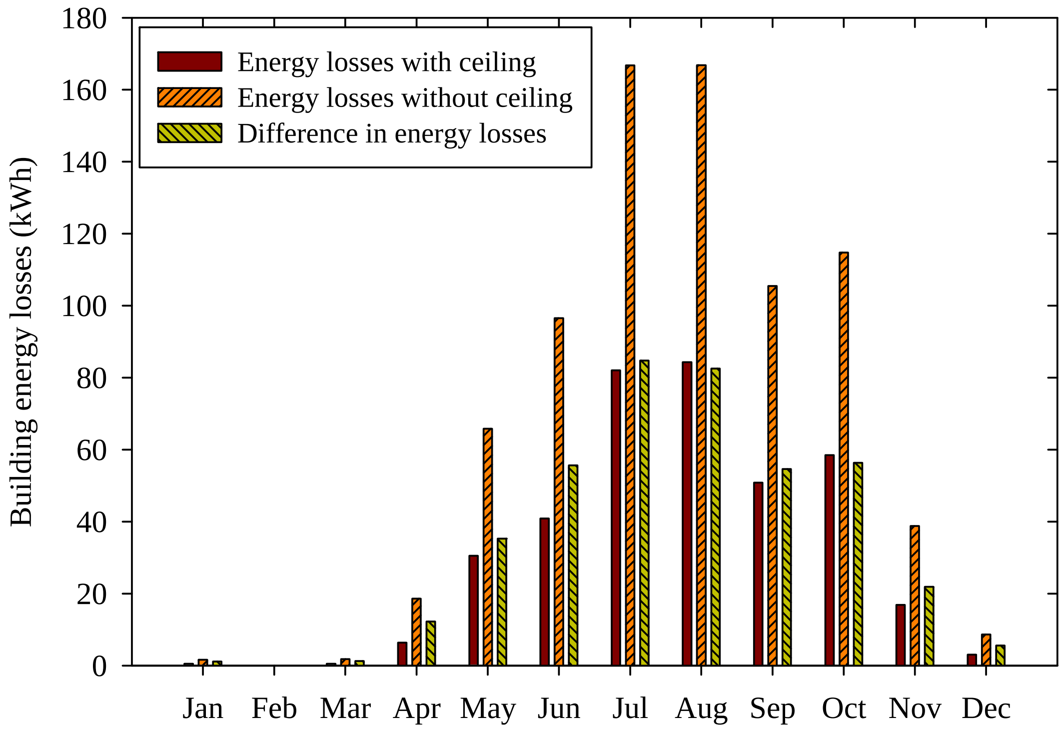

Figure 4: Indoor space energy losses with and without ceiling

Thermal energy losses dominate in the winter period while the heat energy gains dominate in the summer seasons as expected. Excessive energy losses in winter and heat gains in summer are undesirable in energy efficient housing. Installation of the ceiling resulted in a 52% and 42% reduction in annual energy losses and energy gains through the roof respectively. The total space heating and cooling load is the sum of energy required to keep the indoor environment within the thermal comfort range. On average, the annual space heating and cooling load was reduced by 45%. The avoided energy consumption corresponds to a reduction of ghg emissions of 1.21 tCO_2e per annum.

In total, the EEBIPV house interventions quantified in this study have the potential to mitigate 12.41 tCO_2e per year. The 3.8 kW BIPV generator, which replaced utility power supply reduces the greatest amount of emissions at 60% of total emission reduction from the EEBIPV house. The SWH contributes 24%, ceiling 10% and CFLs 6%. These figures reveal that the potential for ghg emission reduction through PV and SWH in South Africa is huge. According to Gcabashe, (2009) some 100 000 private residential houses are built every year, 30 000 are renovated, and about 400 000 electric geysers are replaced. This offers great opportunities for implementing building integrated photovoltaics and solar water heater projects from

conceptual stage. The installation of SWH and BIPV has to be accelerated so as to significantly reduce emissions from the residential sector.
The avoided emissions from the EEBIPV house might look small in the context of South Africa's total emissions but it might be worthy more in the international carbon market. At an international carbon price of US$15/t$CO_2$e in early 2010, the projected emissions reduction is worth US$186.00 per year. This income is quite significant and may lower the payback period of BIPV and SWHs to very competitive levels. In addition, the carbon credit benefits can be helpful in setting up other climate change mitigation and adaptation projects.

7. Conclusion

The generation of electricity using coal and the use of fossil fuels for space heating, cooking and lighting in households has environmental consequences that must be addressed to ensure sustainable development. The potential for EE and RETs interventions to assist South Africa in reducing greenhouse gas emissions has been discussed. In the study electrical supply from Eskom is replaced by building integrated photovoltaics, solar water heaters supply hot water, the installed ceiling reduces indoor space heating and cooling, CFLs replace incandescent light bulbs and passive solar housing techniques were used. These interventions lower energy demand and reduce energy consumption. The avoided energy consumption reduces carbon emissions by 12.41 tonnes of CO_2e per annum with BIPV toping at 60% contribution. Income from carbon credits amounting to US$186-00 per year can help offset the capital costs of SWH and BIPV which is usually cited as the barrier to large scale usage of these technologies. On a national scale, carbon credit receipts can be ploughed back into renewable energy research and projects that mitigate climate change and promote adaptation. Eskom has recently begun the process of increasing its generation capacity by building two new coal-fired power stations and resuscitating three power stations mothballed in the 1990s. This will obviously aggravate the greenhouse gas emission challenges. This paper has shown that using renewable energy technologies and reducing demand through energy efficiency measures in the residential sector does not only take pressure off Eskom's loaded coal-fired power stations but also help South Africa to meet its commitments to reduce high carbon emissions and mitigate climate change.

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