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Techno-economic analysis of a hybrid solar PV-grid powered air-conditioner for daytime office use in hot humid climates – A case study in Kumasi city, Ghana

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ABSTRACT

Air-conditioners are the highest energy consuming appliances in the offices of businesses, public and commercial buildings in hot humid climates. In Ghana, survey conducted indicates that 60–80% of electricity used in offices of public and commercial buildings is for air-conditioning. Many hot climates, and Ghana in particular, are endowed with high solar irradiations. The need for daytime office space cooling is actually as a result of high solar radiation levels.

In the present work, studies have been conducted on the performance of a hybrid solar PV-grid powered air-conditioner for daytime office cooling in hot humid climates with a case study in Kumasi city, Ghana. A standard office of 30 m^2 floor area (105 m^3 office space) in a building with three of the sides sharing walls with adjacent offices, and the front side facing north was used for the study, with the air-conditioner set at a temperature of 20 °C. In the experiment, the pure sine wave hybrid inverter with integrated PWM charge control system was set to solar energy priority and supported by utility grid electricity when solar energy is not sufficient.

It has been determined that for daytime office cooling, a 1040 Wp solar PV system with 200 Ah, 24 V battery configuration has a monthly mean solar fraction of 51% ± 9% for an air-conditioner with nominal cooling capacity of 2.5 kW and maximum power consumption of around 1.19 kW. The energy generation of the 1040 Wp solar PV system has been determined to be around 1211 kWh per year. Financial analysis has revealed that for the hybrid solar PV-grid powered air-conditioner, there is potential savings of US$ 1600 compared to 100% utility grid electricity in 10 years. It has also been estimated using available data that there is a potential of about US$ 3300 savings when the air-conditioner is powered with 100% solar energy compared to 100% utility grid electricity in 10 years, for daytime office use.

1. Introduction

The ambient temperature and relative humidity of hot and humid countries can get as high as 41 °C and 84%, respectively, (Thani et al., 2013; Ghaffarianhoseini et al., 2015). Methods and techniques of improving outdoor thermal comfort using artificial means have therefore extensively been explored (O'Malley et al., 2015; Thani et al., 2012).

According to the ASHRAE (2013) and ISO 7730-2005 standards and other published research works on indoor thermal comfort for people, the indoor conditions should be maintained around 20–25 °C and 50–55% relative humidity. Room air-conditioning is therefore very crucial for providing the necessary indoor thermal comfort for normal human activities and productive office work in hot and humid climates (Jin et al., 2017).

Air-conditioning equipment/systems are the largest energy consuming devices in the offices of public and commercial buildings in hot-humid climates or relatively high atmospheric temperature countries/regions (Al-Ugla et al., 2016; Aguilar et al., 2014). Air-conditioning equipment can consume as much as 50–80% of total electricity consumption of residential, public and commercial buildings in both developed and developing countries (Pérez-Lombard et al., 2008). Cost of electricity to the consumer from conventional fossil-fuel power plants keep on rising due to high transmission and distribution losses in developing countries like Ghana (Gyamfi et al., 2017).

Electricity generation in developing countries have low levels of renewable electricity generation systems, for instance, abundant solar energy in Africa continue to be under-developed (REN 21, 2017;

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Kenfack et al., 2017). Thermal power plants which run on fossil fuel are common (Ouedraogo, 2017). Negative environmental impacts of fossil fuel based electricity generation systems coupled with increasing cost of conventional electricity generation systems is accelerating a paradigm shift away from conventional energy sources to alternate new energy sources (REN 21, 2017; Mahela and Shaik, 2017; Afsharzade et al., 2016; Kerr et al., 2017) including renewable energy for air-conditioning appliances for use in public and commercial buildings (Henning, 2007; Li et al., 2015).

In the work of Al-Ugla et al. (2016), they conducted studies on solar assisted air-conditioning systems for a large commercial building with total floor area of 41,016 m^2 in Saudi Arabia using three different cooling systems (conventional vapor-compression, solar LiBr–H_2O absorption, and solar photovoltaic vapor-compression). They found out that solar absorption system is more economically feasible than a solar PV-vapor-compression and conventional vapor-compression systems for large commercial buildings in Saudi Arabia for daytime use.

A study was conducted by Liu et al. (2017), on the performance of a quasi-grid-connected photovoltaic DC air conditioner in the hot summer zone in Beijing, China. They found out that solar powered air conditioner can conserve grid electricity by more than 67% during summer daytime and by 40–78% during an entire day. They reported that the comprehensive energy efficiency ratio of solar powered air conditioner is 4.6 times higher than that of a conventional air conditioner.

In the work of Aguilar et al. (2017), they conducted studies on a solar powered air-conditioning system supported by the grid. The air-conditioner with nominal cooling capacity of 3.52 kW was used for a 35 m^2 floor space in Alicante, Spain. They reported that energy efficiency rating (EER) and solar fraction (SF) of close to 15 and 65% respectively could be achieved when the system was monitored for 6 months.

In the work of Li et al. (2015), they demonstrated that reliable solar powered air-conditioning system can be operated both in the cooling and heating mode to achieve reduction in peak load of electrical grid in the hot summer and cold winter in the city of Shanghai, China.

It has also been demonstrated in various research works that solar air-conditioning systems are possible for both residential homes and offices of commercial buildings (Li et al., 2017; Saghafifar and Gadalla, 2016; Fong and Lee, 2014; Gugulothu et al., 2015; Al-Alili et al., 2014) and can even be more prominent in areas where solar irradiance are above 600 W m^{-2} (Huang et al., 2016).

In the publication of (REN 21, 2017; Kenfack et al., 2017; Alemi and Loge, 2017) it has been demonstrated that solar energy based technologies are more technically feasible, economical and sustainable if energy efficiency is first considered. Energy efficiency is also crucial for reducing electricity consumption and cost in both the residential and commercial sector. In many countries, there is therefore strict regulations on energy efficiency standards and labels for refrigeration and air-conditioning devices (Gyamfi et al., 2017).

Modern compressor designs for refrigeration and air-conditioning systems are adapting variable speed compressor technologies (DC inverter technologies) which are more energy efficient compared to single speed compressors. Reduction in the energy consumption (30–40%) of air-conditioners with variable speed compressor technology make them possible to be powered by renewable energy resources.

Renewable energy based electricity generation systems are recording decline in overall system cost with very low impacts on the environment (REN 21, 2017; Herche, 2017). The levelized cost of energy (LCOE) of solar energy systems for electricity generation has been declining for the past decade and now competes favorably well with fossil-fuel based energy generation systems (REN 21, 2017). Renewables, and in particular solar energy, are therefore now considered as good energy supply options for running electrical appliances in buildings (Varga et al., 2017; Allouhi et al., 2015; Zouaoui et al., 2017; Daut et al., 2013).

In Ghana, the cost of electricity per month (usually 30 days billing cycle) for the non-residential sector is on the average about UScents 25 for 0–600 kWh and UScents 40 for 601 kWh or more of electricity consumed. In many of the offices of public and commercial buildings in Ghana, single unit split-type air-conditioners have been installed to provide indoor thermal comfort. Survey conducted in some public and commercial buildings in Ghana has gathered that for a standard office cooling (30 m^2 floor space), a single unit split-type air-conditioner consumes on the average about 2500–2850 kWh of electricity per year, for only daytime office use between the hours of 8:00 am–6:00 pm. This translates to electricity cost of about US$ 620–695 per year.

Ghana and most countries in Africa are endowed with high solar irradiations (Abubakar et al., 2016; Adejumo et al., 2017; Akuffo and Brew-Hammond, 1993) which can be utilized for solar electricity generation for daytime use.

The need for office space cooling in the daytime is as a result of high environmental temperatures mainly caused by solar heat fluxes (solar irradiations) through the atmosphere to the surface of the earth. In hot and humid climates, as we have in Ghana, the seasonal space cooling demand is in phase with solar irradiation levels (insolation).

The purpose of this study is therefore to assess the technical and financial viability of solar PV air-conditioning for daytime office cooling in public and commercial buildings in Ghana. The specific objective of the present study is to determine the fraction of solar energy that can support daytime energy demand of an air-conditioner for cooling a standard office (of about 30 m^2 floor area) located in a hot-humid climate. In addition, the electricity cost savings of the system relative to the grid for daytime office use is explored.

2. Methods and materials

2.1. Climatic data

Ghana is situated in the tropics between latitudes 5°N and 11°N, and longitudes 3°W and 1°E. Kumasi city is located at latitude 6.72°N, longitude 1.6°W and at an elevation of 288 m. There are two main rainy seasons in the year, separated by a short relatively dry and cloudy period in August. The major rainy season is from March to June/July. The minor rainy season is from September to October. The months from November to February are usually dry with December and January experiencing Harmattan season during which period dry winds blow southwards across the Sahara desert carrying dust which raises the turbidity of the atmosphere and increases the attenuation and dispersion of the solar radiations (Akuffo and Brew-Hammond, 1993). Though the macro climate of Ghana is generally described as hot and humid in most days within the year, there are three interlaying seasons: (i) the wet season; (ii) the dry season and (iii) the harmattan season.

The monthly mean dry bulb temperature and relative humidity which have been measured for the periods 1976–1984 (Akuffo and Brew-Hammond, 1993) and 2012–2016 (measured with Sutron Automatic Weather Station installed at the solar laboratory at KNUST in Kumasi) are presented in Table 1.

It is to be noted that the average dry bulb temperature reported in Table 1 (which is over a 24-h period per day for the month) is relatively lower than the daytime dry bulb temperature (which is from sunrise to sunset).

The corresponding monthly mean daily solar irradiations on a horizontal surface are shown in Fig. 1.

From Fig. 1, it is observed that the monthly mean daily solar irradiation data for the location is between 3.3 and 4.9 kWh m^{-2} from the lowest irradiation month in August to the highest irradiation month in April.

2.2. Characteristics of the office space

A standard office of 30 m^2 floor area (105 m^3 office space) was used for this study. The office is situated in a building with three of the walls