Feasibility study and environmental impact of using a photovoltaic system to secure relays of mobile communication systems

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Abstract

Renewable energy sources are being considered an alternative for the provision of an uninterrupted supply of power to cover the extensive mobile services. The main purpose of this research was to determine a cost-effective way of achieving environmental sustainability of electricity supply in GSM mobile phone applications using photovoltaic systems. A specific installation of Base Transceiver Stations and Base Station located in an arid and remote area was used as a case study. Using PV solar systems to secure a GSM relay in remote areas with hot climate is a very attractive alternative because of the solar irradiation accessible in the desert. The economic study carried out using the "Hybrid Optimization Model for Electric Renewable" simulation tool showed that the best configuration of the solar photovoltaic system for the case study in the present work consisted of 6 kW photovoltaic panels, 4 kW converter and 24 storage batteries. The solar energy contribution in the electricity consumption was around 38% and the other 62% was supplied by the power grid. The total Net Present Cost (NPC) of the solar system was 43,946$. Regarding the environmental impact, all energy scenarios investigated showed a significant improvement in the environmental life cycle; especially the emissions of carbon dioxide were reduced by 65% by replacing the diesel generator backup system with the photovoltaic-assisted system.

Keywords: GSM Station; Photovoltaic-assisted system; Diesel generator; HOMER, Environmental impact

Nomenclature

APG:	Annual power generation (kWh/year)
CO_2_ER:	CO_2 emissions rate (g-CO_2/kWh)
CO_2_TELC:	Total CO_2 emission on life-cycle (g-CO_2 per cycle)
COE	Cost of Energy ($/kWh)
LT:	Lifetime (year)
NPC	Net Present Cost ($)
P:	Power (kW)

Abbreviations

ASI	Assisted
BSC	Base Station Controller
BTS	Base Transceiver Stations
COE	Cost of Energy
DG	Diesel Generator
GSM	Global System for Mobile Communications
HOMER	Hybrid Optimization Model for Electric Renewables
LCA	Life cycle assessment
MPPT	Maximum Power Point Tracker
MSC	Mobile Switching Center
NPC	Net Present Cost
PV	Photovoltaic
UPS	Uninterrupted Power Supply

1. INTRODUCTION

The mobile telecommunication industry is one of the fastest growing sectors of the global economy. The ever increasing demand for mobile telecommunication services in developing countries is the main driving force for this significant economic growth. Power generation employed by this industry in remote areas used to be based on diesel generators, which have an enormous negative impact on the environment. Moreover, the operation and maintenance of diesel generators account for about 78% of the total cost of operations of GSM BTS sites [1]. Therefore, the use of fossil-fuel generator to supply power to GSM BTS sites increases the unit cost of cellular mobile services. Besides, the environmental consequences of harnessing and utilizing fossil fuels are assuming alarming proportions [2-5]. Evaluating the synergies between the environmental and economic considerations of electricity generation supports sustainability and sound policy-making [6].

The operators of mobile telephony are facing difficulties to provide the whole territory in some developing countries, especially in Africa with a continuous coverage. Furthermore, the remote areas used to be without a reliable, uninterrupted power supply. The use of renewable energy sources is a very interesting way to overcome the electrical grid fluctuation problems that these remote areas suffer. To provide better mobile service coverage, the number of mobile telecommunication stations (BTS, BSC stations, etc.) installed in remote areas was significantly increased. These stations need a reliable and uninterruptible supply of power to ensure mobile service continuity. For this reason, diesel generators were used as the main back-up power system to insure a continuous power supply to the BTS-BSC stations. However, this has resulted in higher diesel consumption and increased air-pollution [7].

Offering great potential, and most importantly a stable power supply, the solar photovoltaic (PV) systems could be used to satisfy the energy demand for the BTS-BSC stations meanwhile reducing fuel consumption, operating cost (maintenance cost) and global warming by mitigating gas emissions to the atmosphere [8-9]. Due to the originality of the application investigated in the present paper, very scarce information is available in the open literature. Isaadi et al. [10] investigated three different command controls for a PV system intended to power-up mobile communication BTS-BSC relay stations located in Bab-Ezzouar, in Algeria. Three Maximum Power Point Tracker (MPPT) controllers were targeted to retain the proper working of the BTS-BSC station equipment, namely the Perturbation and Observation (P&O), the Conductance Incrementing (CI) and the Improved P&O techniques, using MATLAB®/Simulink®, all depending on the climate conditions i.e. temperature and solar irradiance in the area. The results showed that the improved MPPT P&O method was the best control strategy for the area under study.

It was reported in open literature that renewable power systems using the HOMER simulation tool were economically viable for use in grid applications especially those located in remote areas. Kusakana and Vermaak [11] investigated an installation of a hybrid PV-wind system to power a BTS mobile station in rural areas of the Democratic Republic of Congo. Three main agglomerations were considered in this investigation, namely, Kabinda, Mbuji-Mayi and Kamina. Using the HOMER simulation tool, climatic conditions i.e. temperature; solar irradiance and wind speed of the three cities were established. The wind-PV system was composed of 7.5 kW wind generators, a 10 kW PV array, a 7.5 kW inverter and 85 batteries. The energy cost of the hybrid system was calculated at 0.372 $/kWh, a quarter of the cost of that of the diesel generators. An economical study showed that the hybrid wind-PV system was more effective than stand-alone PV or wind systems. Anayochukwuand Onyeka [12] presented a theoretical study of a hybrid PV-Diesel backup power system for a BTS mobile station in rural areas of the Enugu province of Nigeria. The PV-DG system consisted of a 16 kW DG and 10.7 kW solar PV collectors connected to a 25 kW AC/DC converter and a 96 battery storage bank. With a daily 254 kWh BTS energy load and with 4.92 kWh/m² of solar radiation available per day, a supervisory control system was developed for the PV power generation to be the primary energy source with the battery storage bank as backup in case of cloudy days and the diesel generator as a final backup energy source. An economic and environmental study was made using HOMER and the results showed a saving of 14.88 tons (15%) of carbon dioxide emissions and a saving of 3,314,186$ (14.5%) of the total Net Present Cost (NPC) compared to the DG standalone power supply system. A 25 year lifetime at 6% annual interest rate was calculated for the PV-DG system. Yang et al. [13] used solar energy combined with diesel backup generator to supply power to the base station in mobile communication system. They developed a software at integrated management platform to monitor the electricity supply, the temperature and humidity in the base station. The system developed integrating the power system and software management platform solved the problems of electricity supply, maintenance and high expense of management of the remote base station device. Lubritto et al. [14] presented on-site experiments concerning energy consumption of BTSs, power saving actions and application of renewable energy supply for BTSs. Two rural sites in which a photovoltaic plant was built in collaboration with a telephony provider. The annual electricity production in the two sites was estimated at 2640 and 2880 kWh, which represented approximately 3 Ton of not emitted CO_2eq/year for each BTS. The authors concluded that the energetic productivity of the system depends on the geographical location, on the surface available to implement the photovoltaic plants and on the effects of shadow.

The difficulty in supplying energy to power the mobile phone networks in remote areas is encouraging both enterprises and researchers to look for solutions and preferably those which do not have a negative impact on the environment. One of the ways in which this could be achieved is to replace fossil fuel powered systems, such as diesel generators, by renewable energy powered systems.

This paper deals with the use of solar energy for the provision of the electricity consumed by GSM (Global System for Mobile communications) systems both for the regular power supply as well as in the case of grid failure. The main objective was to determine a cost-effective way of achieving environmental sustainability of electricity supply in GSM mobile phone applications using photovoltaic systems. The environmental impact of using renewable energy sources was analysed employing the Life cycle assessment (LCA) approach. The use of solar energy would not only benefit the environment, but economy and energy use in general. The penetration rate of renewable energy, economic analysis and carbon dioxide emissions are discussed.

The configuration proposed could be considered as an alternative to the diesel generator backup system as it would reduce fuel consumption and with it the emission of air pollutants. A Mobile BTS-BSC installation located in an arid remote area was considered as a case study. The challenge was to provide a continuous supply to the GSM networks located in warm remote areas characterized by abundance of solar energy. The HOMER simulation tool was used to determine the economical configuration of the PV system, taking into account the Uninterruptible Power Supply (UPS) command. Depending on the real power demand and the specific climatic conditions of the remote area, the surface area of the PV panels and the battery storage size were optimized.

2. MATERIALS AND METHODS

2.1 Description of HOMER and SimaPro

HOMER means Hybrid Optimization Model for Electric Renewable. HOMER was developed the National Renewable Energy Laboratory (NREL), USA. It performs three types of studies, namely Simulation, Optimization and Sensitivity analysis. The simulation operation mode performs energy balance calculations based on system configuration. The optimization operation displays a list of configurations based on total net present cost. The system takes into account the calculations for installation, replacement, operation and maintenance, fuel and real interest. HOMER evaluates design for standalone and grid connected power systems. The results provided by HOMER are displayed in various forms of tables and graphs, which help to compare different configurations and evaluate them on their economic merits. HOMER simulates the operation of a system performing calculations for each of the 8,760 hours in a year [15].

SimaPro is a professional tool used to collect, analyse and monitor the sustainability performance data of company's products and services. The software can be used for a variety of applications, such as sustainability reporting, carbon and water footprinting, product design, generating environmental product declarations and determining key performance indicators. SimaPro can apply for LCA expertise, to help empower solid decision-making, change your products' life cycles for the better, and improve the company's positive impact [16].

Data for materials and design specifications used for the PV-ASI system were obtained from data sources and life cycle inventory available in the literature. It is usually expected that no life cycle impacts happen during operation of PV systems. In this study, we also overlooked any lifecycle impacts of system decommissioning and disposal or recycle, as we are uninformed of any reliable data for these processes.

2.2 Description of the case study

The province of Adrar located in the south of Algeria at 27°52' latitude, 0°17' longitude and an altitude of 263 m, was chosen for the case study. The corresponding average solar radiation per day is 6.16 kWh/m²/day [17]. The province of Adrar is still not totally connected to the electric grid because of its size which is more than 483,000 km^2, and the areas that are covered have power interruption problems, so the mobile operators are using diesel generators as backup power systems to ensure an uninterrupted power supply to their GSM relay stations. A GSM relay station consists of [18-20]:

- A Base Transceiver System (BTS) composed of an antenna controlled by different electronic components such as amplifiers, power supplies, etc.
- Base Station Controllers (BSC); each BSC controls a number of BTS. It can be considered as a communication node to and from the BTS.
- The Mobile Switching Center (MSC), which is the central node of the mobile telephone network.
- Air Conditioning system to insure proper climatic conditions for the electronic components in the system.

As reported previously, the area of this case study is characterized by an interesting solar energy potential. The monthly average values of solar radiation, based on NASA global satellite data available in the Homer package, are shown in Figure 1. As can be observed, the solar radiation reaches its maximum value of 7.67 $kWh/m^2/day$ in June and is almost constant throughout the summer period, which corresponds to the season of electrical fluctuations (June-August). The minimum solar radiation is recorded in December with an average value of 3.53 $kWh/m^2/day$.

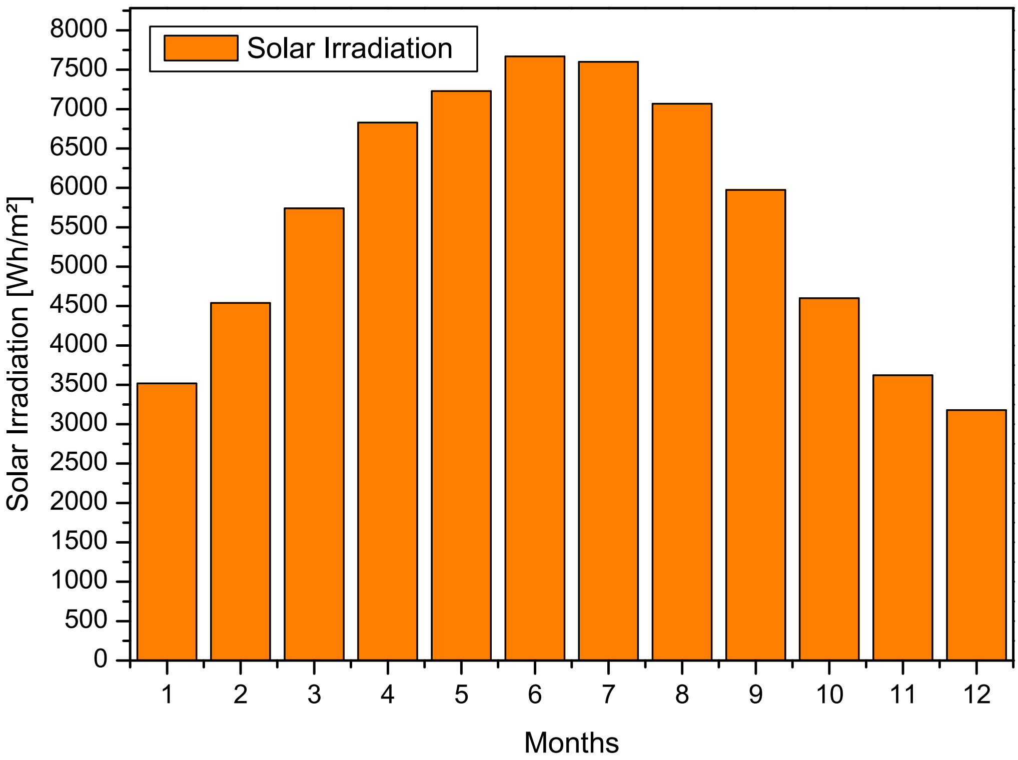

Figure 1. Monthly average solar irradiation in the area of the case study

A parallel photovoltaic array was considered in the simulation process to ensure a synchronized bi-directional power flow between the battery bank and the solar PV source. The objective was to stabilize the power supply, thus, increasing system efficiency [21]. The system control strategy was configured in order to store the excess of energy produced by the PV array when this is greater than the GSM energy demand. The battery bank used to store the power surplus was configured and modelled according to the PV solar surface and the GSM relay energy demand. The energy stored is then used to fill-in the deficit when the load demand is greater than the energy generated by the PV system.

The Photovoltaic Uninterrupted Power Supply (PV-UPS) control strategy was integrated into the system configuration and was used for two main reasons:

- Emergency power system: to ensure a continued electrical power supply in case of power failures caused by power grid fluctuations.
- Reduce power consumption: by adopting two main operation modes: i) When the power grid is available, the energy provided by the PV panels will keep charging the batteries and the excess of energy is converted via an inverter to an alternative 230V (AC) electric current to be used in powering-up the system. ii) In the case of power grid failure (black

out), the electrical circuits are switched-On automatically and the system would work with solar PV power system.

The PV-UPS configuration is to ensure a continued power supply to the GSM relay. Figure 2 shows the main components of the system configuration using a PV-UPS. Two inverters, both synchronized in voltage and frequency, are used, the former for the On-Grid normal operations, and the latter for the Off-Grid PV operations. This is to ensure an automatic switching over from normal to emergency mode without interruption. This system configuration supports single-phase or three-phase power supply mode depending on the application.

The Maximum Power Point Tracker (MPPT) technique was also adopted in this investigation. The network equipment was optimized and adapted to the climatic conditions of the case study. This method helped to operate with maximum power output at different climatic conditions, thus, maximizing system efficiency [22].

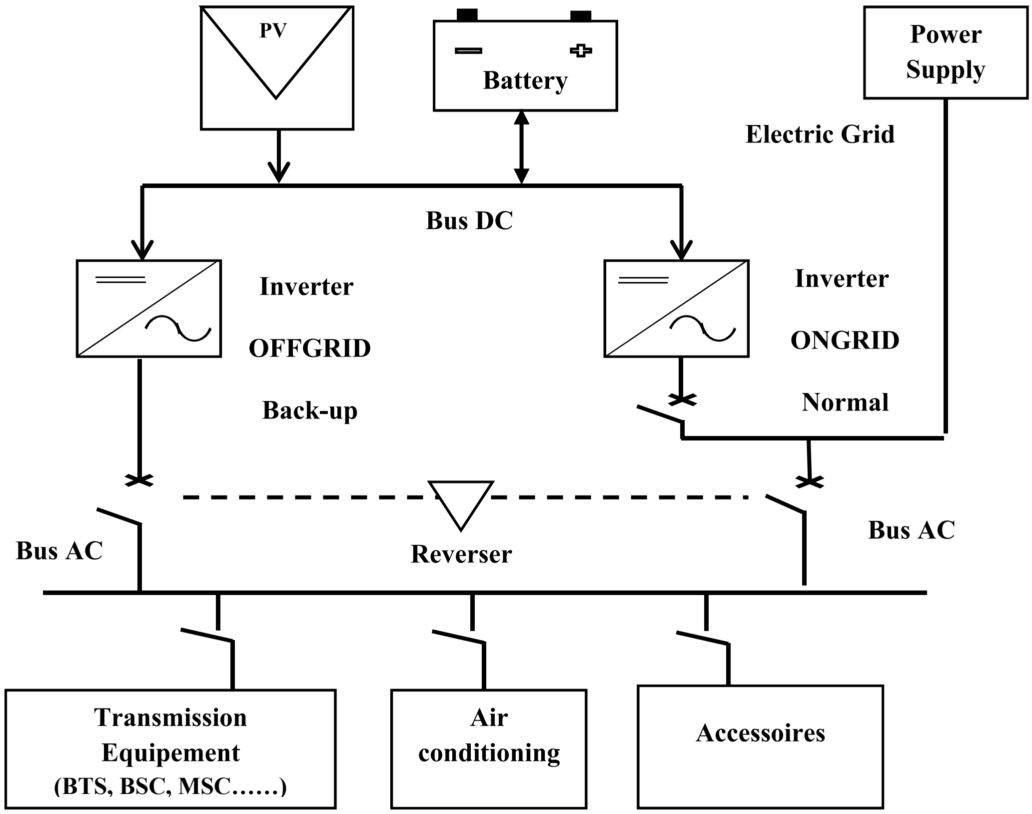

Figure 2. Configuration of a PV- GSM system

2.3 Environmental modeling

Life cycle assessment (LCA) method was used to evaluate the environmental impacts associated with the use of photovoltaic solar energy to supply power to mobile telephony systems. The rate of CO_2 emissions was determined by the following equation [23].

$$CO_2\_\mathrm{ER} = \frac{CO_2\_\mathrm{TELC}}{\mathrm{APG} * \mathrm{LT}}$$

The CO_2 emission rate is a useful index to know how much the PV system can mitigate global warming. When measuring the energy and environmental performance of a product system, the life cycle assessment (LCA) methodology is usually employed. LCA takes into account the direct and indirect impacts throughout the entire life cycle of the product, including material sourcing, manufacturing, operation, transportation, disposal, etc. As illustrated by many authors, LCA is recognized as an invaluable tool to assess the energy and environmental profiles of a PV product system [24].

Data for materials and design specifications used for the PV-ASI system were obtained from data sources and life cycle inventory available in the literature. The life cycle inventory (LCI) phase of the LCA includes data compilation of materials, energy flows and environmental releases involved in the entire life cycle of the PV system. In order to create the inventory, the required data for all unit processes included in the system boundary were collected separately. In particular, the inventory data involved in the production of PV modules from wafers, ingots, solar cells to PV module assembly were provided, collectively, by eleven European and US photovoltaic companies participating in the European Commission's Crystal Clear project. The corresponding data sets were published in separate papers by Sagani et al. [25], de Wild-Scholten and Alema [26], Phylipsen and Alsema [27] and Fthenakis and Kim [28]. On the other hand, the data of metallurgical grade silicon production were taken from SimaPro 7.1 Eco invent database [16]. Ecoinvent is the most widely accepted LCA database, which was established using European industrial data. It's worthy of note that we did not consider inverters manufacture, mounting systems (both manufacture and installation) and cable wiring, mainly because of their little impact on the environmental impacts, which accounts for less than 10% in total [29]. The data collection phase for each component (LCI) was followed by LCA. It was also assumed that there are no life cycle impacts during the operation of the PV systems. The life cycle of the PV system ends with its decommissioning, resetting this way the initial conditions of the site of installation. The common approach of dealing with the decommissioning of PV modules is to assume that they are disposed at landfills [30]. In order to assess the potential environmental impacts of the PV system investigated in the present work, both the CML 2 baseline 2000 [31] and the Eco-indicator 95 [32] methodologies were employed. The Global Warming Potential (GWP) was used as an environmental indicator, which was developed to permit comparisons of the global warming impacts of different gases. Precisely, it is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO_2).

3. Results and discussion

HOMER software was used in this study to evaluate the feasibility of a Photovoltaic Assisted (PV-ASI) solar system [15] as a backup power system for a GMS relay. Figure 3 shows the configuration and main components of a PV-GSM system.

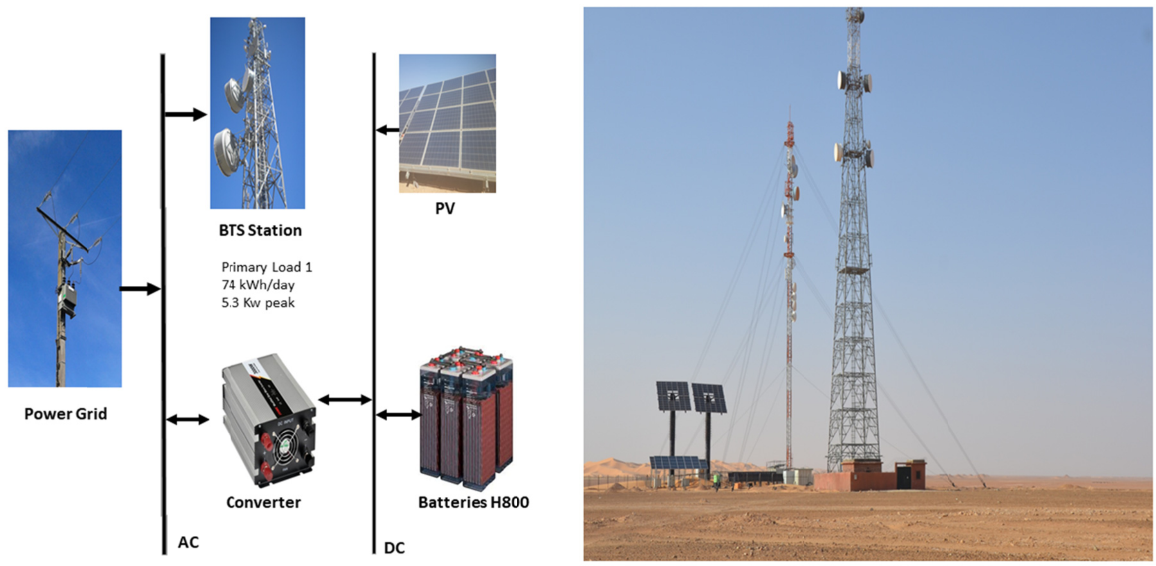

Figure 3. Schematic illustrating the main components of a PV-GSM system and real case study in Adrar

3.1 Energetic and Power consumption

The power supplied by the grid to the GSM relay has an Alternative Current (AC) of 230-400V which is converted to a Direct Current (DC) for powering telecommunication equipment in full operation mode. The power consumption of a typical GSM relay varies according to the rate of power required, the GSM relay type (Rooftop or Pylon) and to the cooling requirements for the electronic components. The total energy consumed by a GSM site can be measured or estimated using the total current consumption of all components of the system. In this investigation, the energy consumption data, shown in Figure 4, were supplied by a mobile GSM company in Algeria for both Pylon and Rooftop configurations. As can be observed in this figure, the Pylon GSM stations consume more electrical power than the Rooftop stations. This is due mainly to the larger size of equipment installed in pylon configuration to ensure a greater coverage. From this figure, it is clearly seen that the average power consumption of both types of GSM stations in the summer period (Jun, July and August) is higher than for the rest of the year. This can be explained by the massive use of air conditioning (AC) necessary to cool the electronic equipment brought about by the high ambient temperatures recorded in the area under study.

The Homer simulation tool allows us to select different configurations for the PV-ASI system by varying the PV array, the converters and the grid power contribution. Therefore, the initial capital cost, the total Net Present Cost (NPC) of the installation and the renewable energy contribution rate can be calculated. Table 1 summarizes the 23 configurations simulated in the present work.

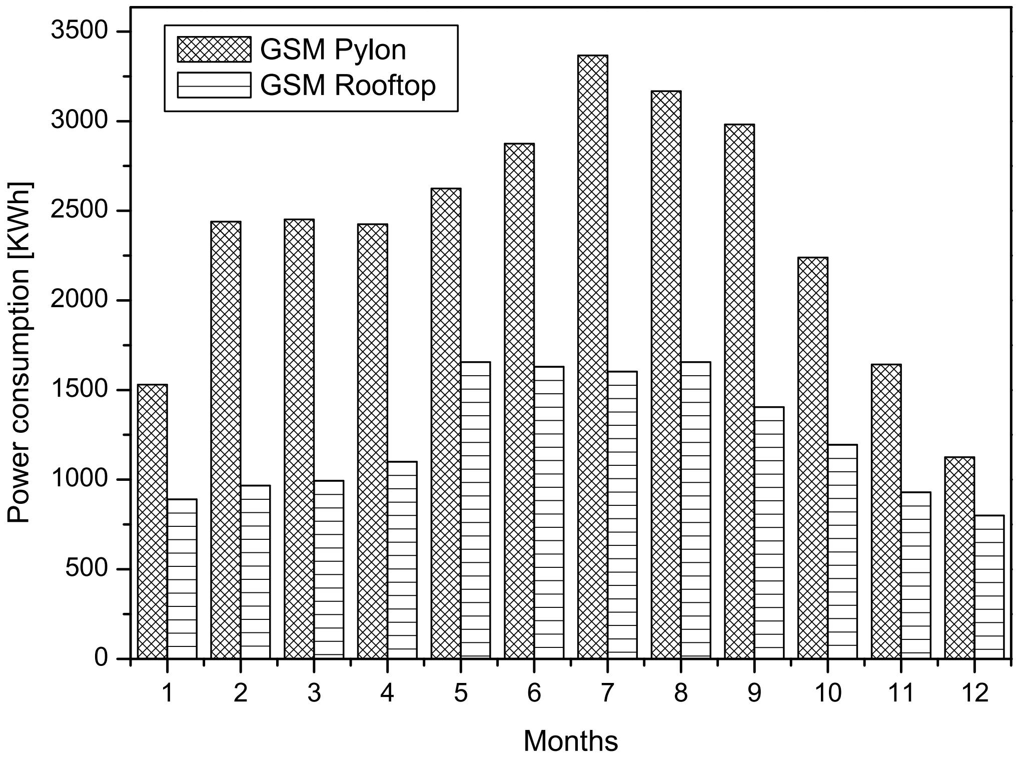

Figure 4. Power consumption of the two types of GSM stations

Table 1. GSM power system configurations and output parameters calculated by the HOMER simulation tool

PV (kW)	H800	Conv. (kW)	Grid (kW)	Initial Capital [$]	Operating Cost ($/yr)	Total NPC [$]	COE ($/kWh)	Ren. Frac.	Capacity Shortage
6	24	4	5	24,120	1,407	43,946	0.116	0.38	0.01
6	24	5	5	24,870	1,434	45,086	0.119	0.38	0.01
6	24	6	5	25,620	1,463	46,236	0.122	0.38	0.01
6	36	4	5	25,680	1,470	46,392	0.122	0.38	0.01
7	24	4	5	27,120	1,373	46,474	0.122	0.44	0.01
6	24	7	5	26,370	1,491	47,386	0.125	0.38	0.01
6	36	5	5	26,430	1,497	47,531	0.125	0.38	0.01
7	24	5	5	27,870	1,399	47,590	0.125	0.44	0.01
6	24	8	5	27,120	1,519	48,535	0.128	0.38	0.01
6	36	6	5	27,180	1,526	48,681	0.128	0.38	0.01
7	24	6	5	28,620	1,427	48,738	0.128	0.44	0.01
6	48	4	5	27,240	1,532	48,836	0.128	0.38	0.01
7	36	4	5	28,680	1,436	48,918	0.129	0.44	0.01
8	24	4	5	30,120	1,342	49,029	0.129	0.50	0.01
6	24	9	5	27,870	1,548	49,685	0.131	0.38	0.01
6	36	7	5	27,930	1,554	49,831	0.131	0.38	0.01
7	24	7	5	29,370	1,456	49,888	0.131	0.44	0.01
6	48	5	5	27,990	1,560	49,976	0.131	0.38	0.01
7	36	5	5	29,430	1,462	50,035	0.132	0.44	0.01
8	24	5	5	30,870	1,366	50.121	0.132	0.50	0.01
6	24	10	5	28,620	1,576	50,835	0.134	0.38	0.01
6	36	8	5	28,680	1,582	50,980	0.134	0.38	0.01
7	24	8	5	30,120	1,484	51,038	0.134	0.44	0.01

As can be observed from Table 1, the solar energy fraction increases on increasing the PV array contribution. However, increasing the amount of battery storage or the inverter capacity does not affect the solar energy fraction, on the contrary, it increases the installation price. Considering a constant power grid supply of 5 kW and a solar fraction of 38%, the best configuration for the Photovoltaic Assisted solar system is a 6 kW solar PV capacity, 24 batteries and a 4 kW DC/AC converter for a total Net Present Cost (NPC) of 43,946$. The solar fraction ratio could be increased to 50% by increasing the solar PV power contribution up to 8 kW resulting in an NPC of 49,029$.

Using PV solar systems to power-up a GSM relay in remote areas with hot climate is a very tempting alternative because of the solar irradiation available. However, PV cells are very sensitive to high ambient temperatures, and their performance decreases when environmental temperature increases e.g. the case of the site under study.

Figure 5 shows hourly ambient and cell temperatures over 1 year (8760 hours). From this figure, it can be observed that a maximum ambient temperature of 44 to 45 °C is registered during the summertime period (June, July and August). On the other hand, the corresponding cell temperature can go above 70 °C which means using adequate PV cells that can support these severe climate conditions. In these climatic conditions, the hourly electric power produced by the PV system is presented in Figure 6 for the Pylon configuration of GSM Stations. The total period of renewable power supplied by the system to the GSM relay is 4,379 h/year, which represents around 50% of the total number of hours in the year.

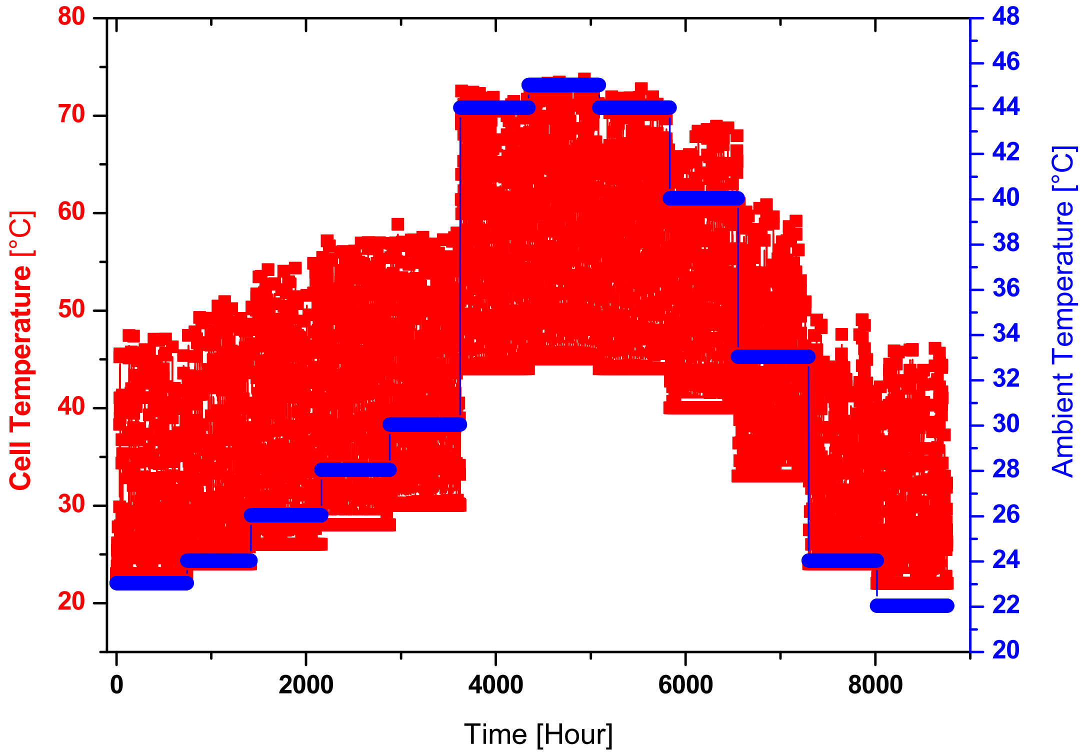

Figure 5. Hourly ambient and PV cell temperatures over 1 year (8760 hours)

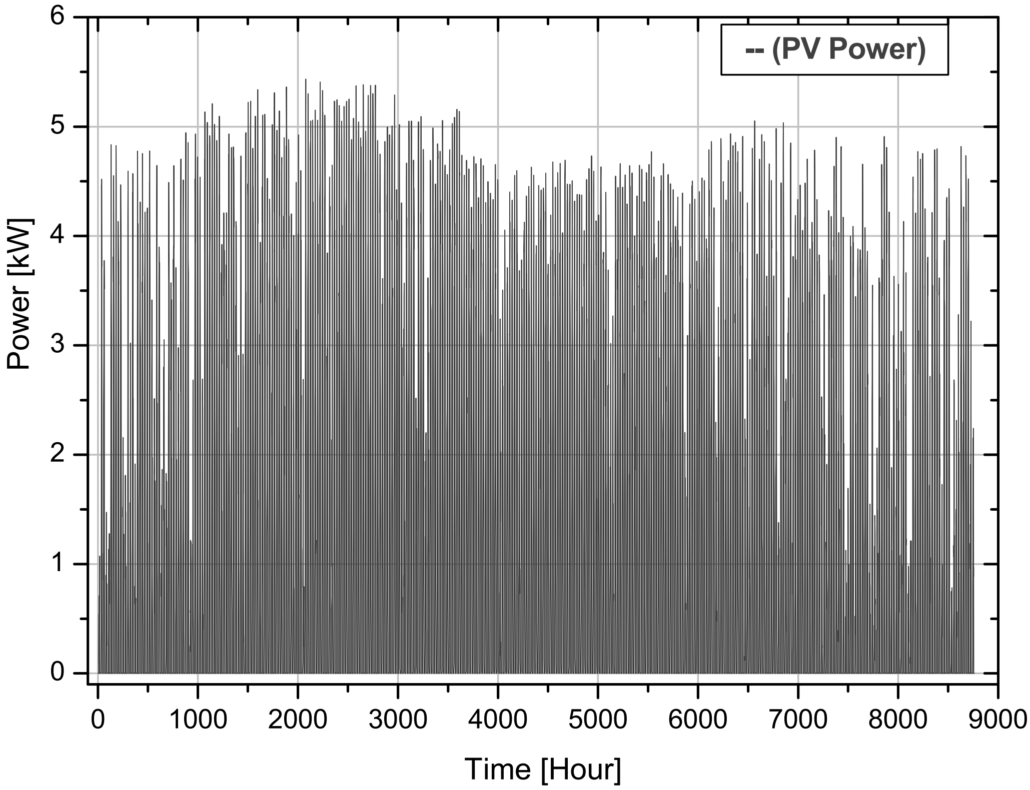

Figure 6. Daily electric power produced by the PV-ASI system over 1 year (8760 hours)

The average monthly power charge of the battery bank is represented in Figure 7. As can be observed in this figure, the average battery charge power is lower in the summertime period than during the rest of the year. This is due to the control strategy adopted in the system configuration, which contemplates that the electricity produced by the PV field be directly supplied to the GSM relay in order to satisfy the demand for electric power which coincides with the high consumption in air conditioning power over this period. For the rest of the year, the excess power produced by the PV field is stored in the battery bank to be consumed when needed.

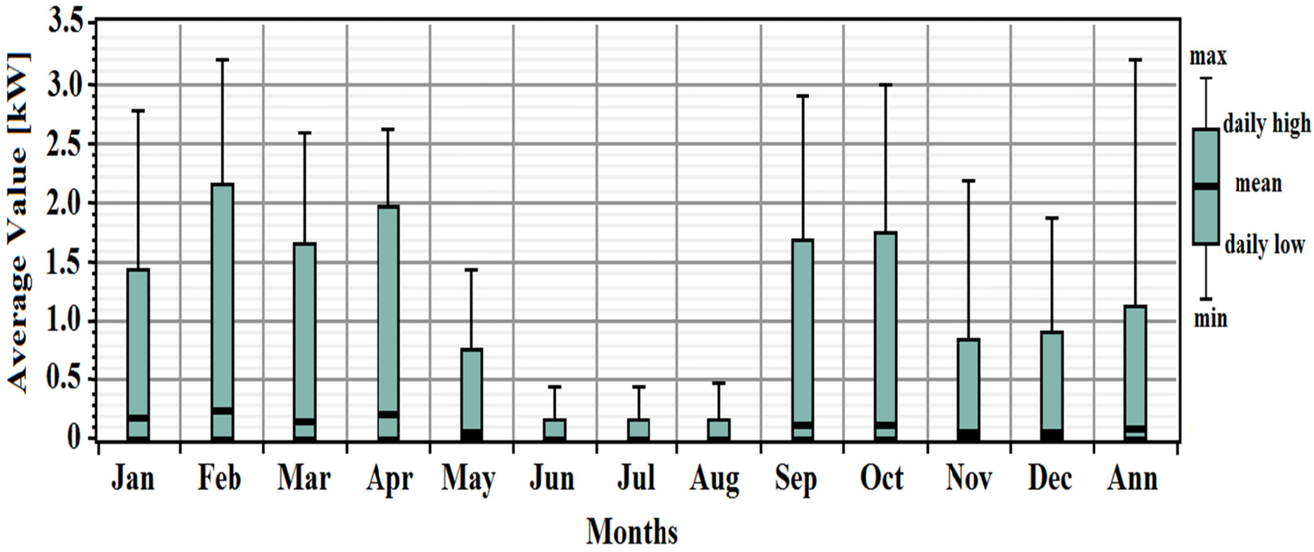

Figure 7. Monthly average battery charge power over 1 year

For the first solar PV-ASI system configuration shown in Table 1, the total electricity produced by the PV array is 10,670 kWh. This production represents 38% of the total contribution and consequently the remaining 62% (17,157 kWh) represents the power grid contribution with a total production of 27,827 kWh per year. Figure 8 shows the monthly average electricity production where PV production and grid power contributions secure all the power demand for the GSM relay in a year without any need for the support from diesel generators. Nema et al. [33] proposed the most feasible configuration for a standalone PV/Wind Hybrid Energy System with diesel generator as a backup for cellular mobile telephony base station site in isolated areas of Central India. The authors considered the power requirements for GSM telephony base station site was about 2kW continuous, the load demand about 47 kWh/day and 2 kW peak. They reported that the total electrical energy demand of the mobile telephony base station was fulfilled by the combination of 30% PV, 50% wind and 20% by diesel generators.

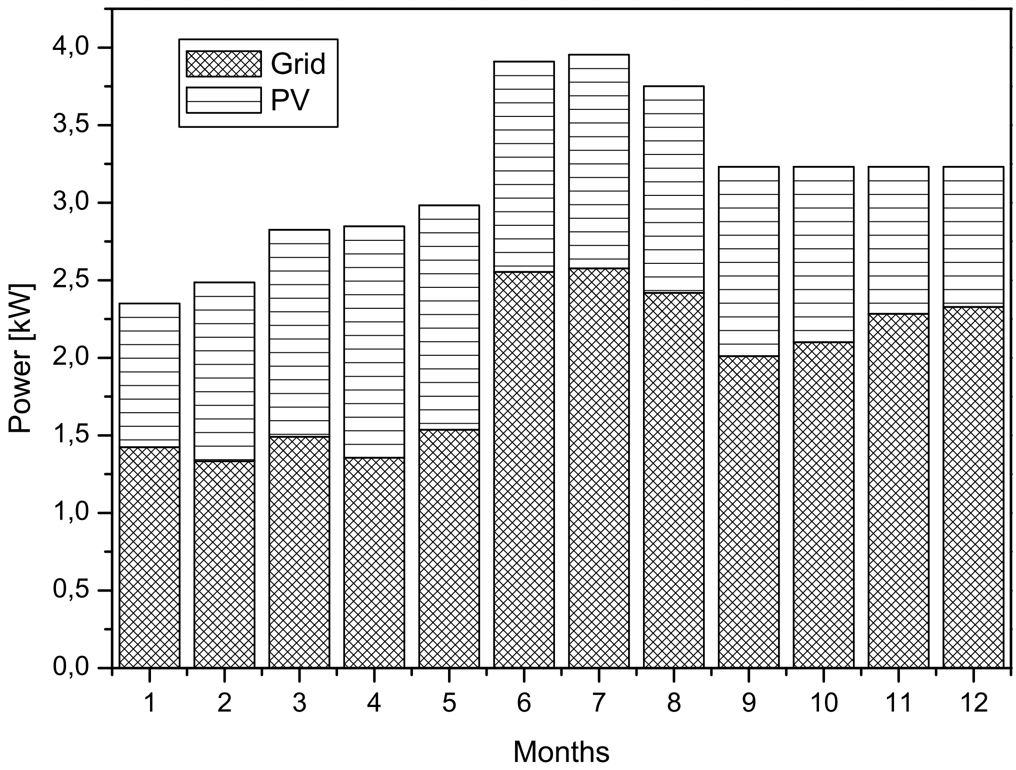

Figure 8. Average monthly PV/Grid power over 1 year

3.2 Economic analysis

An economic analysis is very important for all mobile operators as it permits them to determine the optimal system configuration that produces the correct amount of energy to cover the demand at the lowest investment cost. As can be seen in Table 1, the most economical PV-ASI configuration which can satisfy the power demand of a GSM relay is a 6 kW photovoltaic system with 24 batteries and a 4 kW inverter. The capital investment of the system amounts to 43,946$.

Figure 9 shows a cash flow summary of all the system components, such as PV panels, power grid, and battery bank, etc., which corresponds to the optimal configuration selected for the case study.

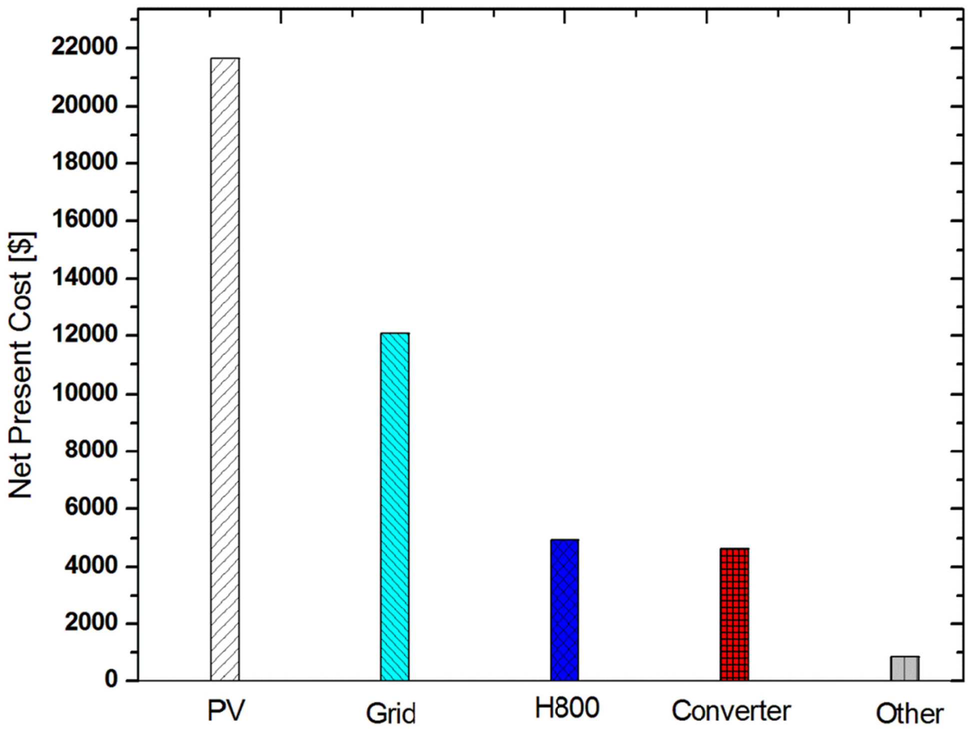

Figure 9. Cash flow summary showing the cost of the configuration for the PV-ASI GSM relay station

As seen in this figure, the most part of the Net Present Cost (NPC) corresponds to the PV array sub-system at 21,643$, followed by the cost of the power grid consumption. More detailed economic data are given in Table 2 which shows the costs for 1 and 25 years of investment periods. The cost of PV collectors represents the largest proportion at 1,277$ and 18,000$ for the 1and the 25 year investment periods, respectively. The corresponding battery bank costs are 221$ and 3,120$, respectively, and 213$ and 3,000$ for the converter.

It is worthy of note that the PV-ASI system is an attractive option with a total cost of 3,118$ for 1 year of service and 43,946$ for 25 years of service without the use of a diesel generator power supply. Several other studies have confirmed this choice [34-37].

Table 2. Detailed costs of the PV-ASI power system for a GSM relay station

Component		**Capital [$]**	**Replacement [$]**	**Operating and maintenance [$]**	**Saving [$]**	**Total [$]**
PV	One year	1,277	481	60	-283	**1,536**
	25 years	18,000	6,784	846	-3,987	**21,643**
Grid	One year	0	0	858	0	**858**
	25 years	0	0	12,090	0	**12,091**
Batteries	One year	221	75	96	-44	**348**
	25 years	3,120	1,058	1,353	-622	**4,909**
Converter	One year	213	102	32	-21	**326**
	25 years	3,000	1,443	451	-295	**4,599**
Other	One year	0	0	50	0	**50**
	25 years	0	0	705	0	**705**
System	One Year	1,711	659	1,096	-348	**3,118**
	25 years	24,120	9,285	15,445	-4,904	**43,946**

The cash flow per concept of the PV-GSM system is presented in Figure 10 for an investment period of 25 years. With a contribution of 38% of the PV-ASI system, the initial cost of the PV cell array represents the largest part of the investment. The operating and replacement costs are low however, thanks to the contribution rate of the renewable energy.

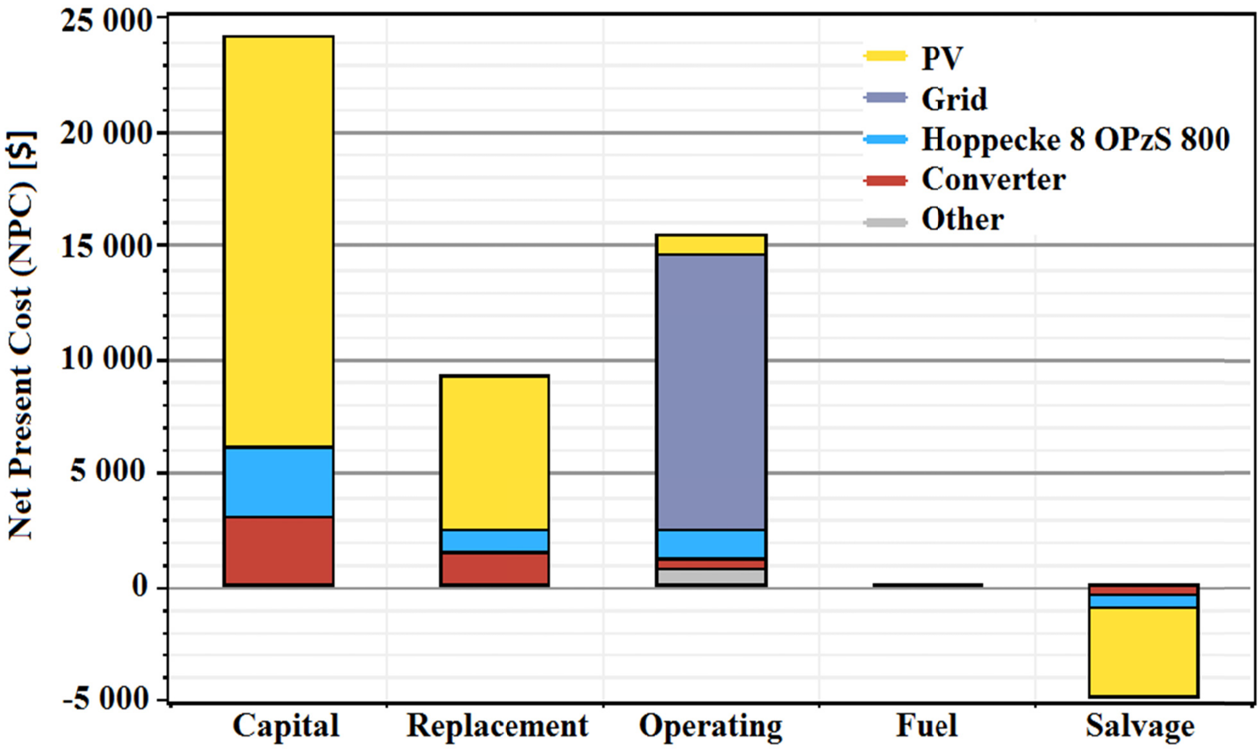

Figure 10. Cash flow per concept of the PV-ASI system

The cash flow by cost type of the PV system for a 25 year period is shown in Figure 11. As can be expected, the system is characterized by a high initial cost but very low ongoing operation and maintenance costs. The first cost generated by replacements is observed after 15 years of operation.

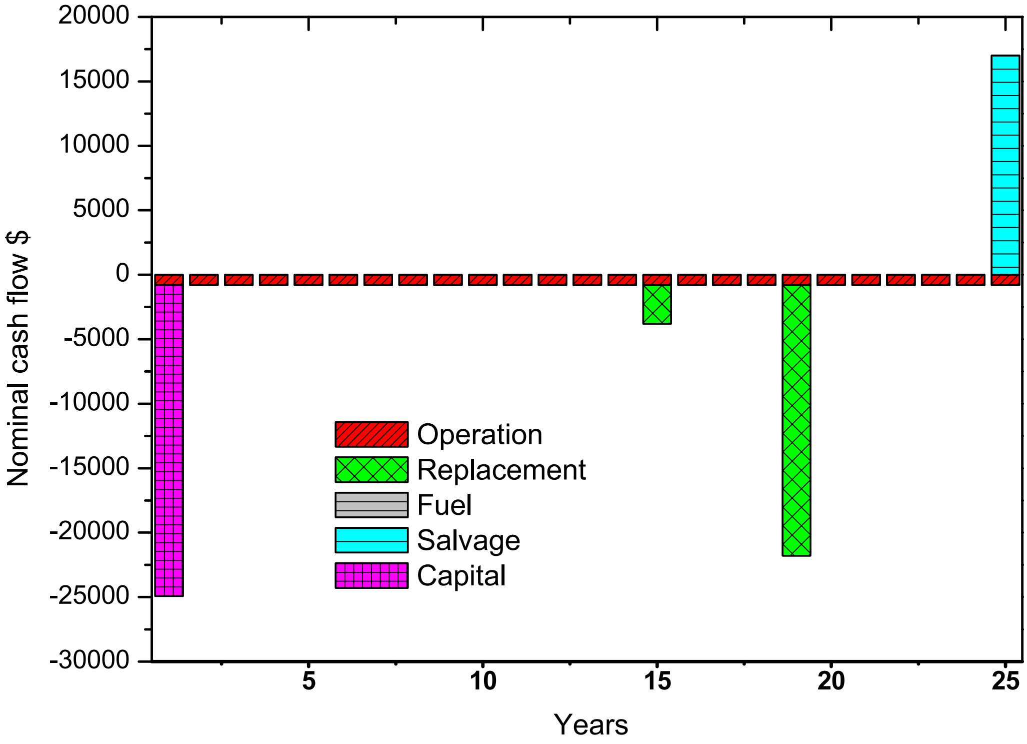

Figure 11. Summary of the cash flow by cost type of the PV system for a 25 year period

Taking into account the high cost of the battery storage bank in the PV-ASI system, the battery bank that already existed in the diesel generator (DG) was used for the GSM relay station. This reduced the total cost of the PV-GSM system. Moreover, because solar irradiation is available throughout the year in hot remote areas, the PV system could be considered a real alternative and economically viable solution compared to the DG backup system. The most significant data for both the PV-GSM and the DG-GSM systems are summarized in Table 3.

The cost of a photovoltaic power system is higher than that of a conventional power system due to the higher initial cost of the PV-ASI components [38]. However, due to the huge advantages i.e. uninterrupted power supply, longer lifetime and lower fuel consumption the PV-ASI system still represents an attractive alternative to diesel generator backup systems.

Table 3.Summary of the characteristics of both PV-ASI and DG systems

Parameter	DG system	PV-ASI system
Autonomy [hour]	13.0	18.3
Life duration (year)	05	25
Electricity bill [$]	1,588.30	654.90
Total system cost [$]	30,420	43,946
Greenhouse gas emissions CO_2 [kg/year]	31,210.6	10,843

3.3 Environmental aspects

As commented previously, replacing the diesel generator with a PV-ASI system contributes to reducing pollutant emissions. Total carbon dioxide emissions were estimated at 10,843 kg/year when the PV-ASI system was used and 31,210.6 kg/year when a generator diesel generator was employed. There is a reduction of around 65% in carbon dioxide emissions when a PV-ASI system is used instead of a diesel generator. In other terms, the CO_2 emissions rate of the PV-ASI system was 40.64 (g-CO_2/kWh) and 72.76 (g-CO_2/kWh) when a generator diesel generator was employed (Figure 12). These data are in good agreement with previous investigations available in the open literature. Ito et al. [23] reported in their study a CO_2 emissions rate in the range 43–54 (g-CO_2/kWh). Liu et al. [29] found that the 25-year lifetime GHG emission intensities of DRI’s PV systems of the eight tightly clustered DRI’s PV systems ranged from 35 to 58 (g-CO_2/kWh), while the GHG emissions of natural gas-produced electricity were 648 (g-CO_2/kWh).

The larger the GWP, the more that a given gas warms the Earth compared to CO_2 over that time period. The time period usually used for GWPs is 100 years. GWPs provide a common unit of measure, which allows analysts to add up emissions estimates of different gases and allows policymakers to compare emissions reduction opportunities across sectors and gases [39]. Moreover, 23 kg/year of Nitrogen oxide and 47 kg/year of Sulfur dioxide pollutants can be reduced by replacing the diesel generator with a PV-ASI system as shown in Table 4. Renewable energies are clean sources of energy and optimal use of these resources minimizes environmental impacts [40-51].

Table 4. Summary of the pollutant emissions of the PV-ASI system

Pollutant	Emissions (kg/year)
Carbon dioxide	10,843
Carbon monoxide	0
Unburned Hydrocarbons	0
Particulate matter	0
Sulfur dioxide	47
Nitrogen oxides	23

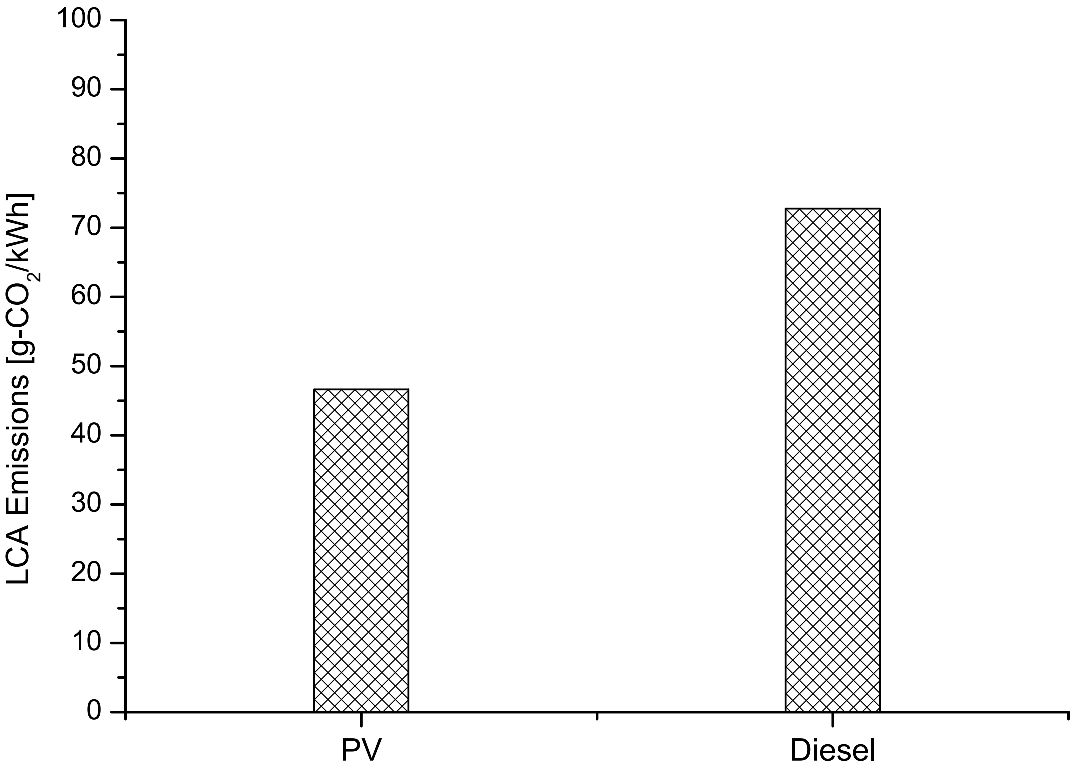

Figure 12. LCA CO_2 emissions rate of the PV-ASI and DG systems [g-CO_2/kWh]

4. CONCLUSIONS

An environmental study was carried out to analyze the use of a PV-ASI solar system to power up GSM relays. Due to economic and LCA environmental aspects, the configuration of the system chosen was that of a PV solar system used as an alternative to a diesel generator for backup. The aim was to ensure an uninterrupted supply of power to the BTS-BSC plants, regardless of the condition of the supply from the power grid. This choice would also contribute to the reduction of pollutant emissions. The most relevant results of this investigation are summarized as follows:

- The cost analysis showed that the best configuration would be a 6 kW solar PV with a 4 kW inverter and a bank of 24 batteries amounting to a total Net Present Cost (NPC) of 43,946$. The system would have 18.3 hours of autonomy. In this case, the solar contribution would be around 38% as opposed to 62% electricity from the power grid.
- A solar contribution of 50% could be achieved by increasing the solar PV power up to 8 kW and at a total Net Present Cost (NPC) of 49,029$.
- The environmental study showed that the total carbon dioxide emissions were 10,843 kg/year with the PV-ASI system as opposed to 31,210.6 kg/year using diesel generators. This would mitigate 65% of carbon dioxide emissions if a PV-ASI system was used instead of diesel generators.
- The final PV solar electric power cost was evaluated at 0.116$/kWh.
- A 100% PV-ASI standalone system could be considered for use in the climatic conditions of the isolate areas if the solar PV contribution was increased. It was further shown that the use of PV technology presents important environmental benefits because solar irradiation is available throughout the year in desert areas.

Acknowledgements

Saïd Bentouba gratefully acknowledges the University of Adrar for funding his internships at Rovira i Virgili University of Tarragona (Spain).

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