

Renewable energy sources for power supply of base station sites

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Abstract — *An overview of research activity in the area of powering base station sites by means of renewable energy sources is given. It is shown that mobile network operators express significant interest for powering remote base stations using renewable energy sources. This is because a significant percentage of remote base station sites on the global level are still diesel powered due to lack of connections to the electricity grid. Besides huge expenses that mobile operators pay for diesel fuel and its transport to base station sites, it is pointed out that such base station sites represent major pollutants due to enormous green-house gas emissions. Since base stations are major consumers of cellular networks energy with significant contribution to operational expenditures, powering base stations sites using the energy of wind, sun, fuel cells or a combination gain mobile operators' attention. It is shown that powering base station sites with such renewable energy sources can significantly reduce energy costs and improve the energy efficiency of the base station sites in rural areas. In addition, technical descriptions of the different power supply systems based on renewable sources with corresponding energy controllers for scheduling the flow of energy to power base station sites are discussed. According to the presented, hybrid systems which combine different renewable energy sources outperform those with only one energy source, and depend on the configuration of base stations installed on a particular site, such systems can offer autonomous functionality throughout the year.*

Keywords — *base station, renewable, power, supply, green, solar, wind, diesel, generator, fuel-cell, energy, wireless, mobile*

1. Introduction

Energy consumption and carbon dioxide (CO₂) emissions has recently become the subject of special interest to the mobile telecommunications industry. In Murthy (2012), it is emphasized that base stations (BSs) are the most energy intensive consumers in the cellular networks of mobile operators. Hence, during last year's, significant attention was given by equipment manufacturers, mobile operators and researchers from academia to the solutions dedicated to improving energy efficiency of BSs in cellular networks. For achieving this, some of the recognized techniques are: energy-efficient hardware or BS site design, dynamic management of network resources through sleep modes and cell zooming, a self-organizing network (SON) concept or using renewable energy sources to power BS sites.

As an example of the use of energy efficient hardware design, the Nokia Siemens Networks Flexi base transceiver station (BTS) has been introduced to the market (NSN, 2009). This type of BTS is energy-efficient and features multi-radio technologies inside one hardware unit. The advantages of these BSs are: reduced installation time and material costs, reduced size and weight (for 20%), reduced energy consumption (70%) due to usage of remote radio heads and power amplifiers with improved efficiency, readiness for using renewable energy sources and flexible location: either indoor or outdoor without the need for air conditioning and.

As an example of energy saving through innovative BS site design, company Ericsson introduced the Ericsson Tower Tube (Ericsson, 2011). It is an ergonomically designed concrete tower having lower environmental impact than traditional steel and consuming up to 40 percent less power from a life cycle perspective. This is due to the fact that such a concept is based on wind powering the BS that is positioned at the height of the tower tube, which helps to reduce feeder loss and eliminate the need for

active cooling. The solution supports different antennas and radio equipment, multi-operator site sharing, and enables a reduction of the space leased by telecom operators.

However, to achieve significant energy savings, an approach based on the dynamic management of wireless network resources seems to be the most promising. Such expectations have led to previous studies on energy efficiency improvements at the level of complete Wireless Local Area Networks (WLANs) (Lorincz and Bogarelli, 2010; Lorincz, 2011, p. 540; Lorincz, 2011, p. 648; Lorincz, 2010, p. 195). By means of integer linear programming and heuristic algorithms, we propose different optimization models based on the dynamic management of network resources. When dynamic management of the access point's activity is implemented, the obtained results show that significant energy savings can be accomplished for the case of large-scale WLANs. These optimization models have been extended for wide area cellular access networks. In Lorincz (2012, p. 24), analysis of possible energy savings is studied for cases when dynamic management of macro BSs activity and corresponding transmit powers will be implemented. This analysis also shows enormous energy saving potential if dynamic on/off powering of BSs and transmit (Tx) power adjustment takes place in accordance with space and time variations of traffic patterns. Influence of adjusting BS Tx power (known as cell zooming) and daily variations of traffic pattern on instantaneous BS power consumption were investigated in Lorincz (2012, p. 4310) and Lorincz and Dimitrov (2012), respectively. Furthermore, the analysis of the influence of introducing BSs of newer technologies (e.g. Long Term Evolution – LTE) on network energy metrics is performed in Lorincz (2012, p. 161).

The concept of SON is proposed as the latest 3GPP concept to reduce mobile network complexity and operating costs (Lorincz, 2014). Although mostly related to the LTE networks, it is considered a core part of mobile networks and can be applicable to other access networks (NGMN, 2006; Stewart, 2012). The main concept of SONs is based on self-organization and the management of network elements in order to achieve optimal network performance and quality. The SON is defined around functional domains which cover all aspects of network operations, including: self-planning, self-configuration, self-optimization and self-healing (NGMN, 2006; NGMN, 2008; 3GPP TS 36.300, 2013). Energy saving is one of the SON use cases which is dedicated to the reduction of energy consumption. It is based on the assumption that matching network capacity as close as possible to real traffic demand at any moment can reduce energy expenses (Feng, 2008; 3GPP TR 36.902, 2011).

For providing continuous service, BSs located in remote and inaccessible areas require an uninterruptible long life and a safe power supply. Renewable energy sources are found to be very promising in satisfying such demands, since the BSs installed in remote and inaccessible locations mostly lack connection to the electric grid. In this paper, several BS power supply systems that are based on renewable energy sources are presented and discussed. The rest of the paper is organized as follows: in Section 2, general classifications of possible BS power supply systems found in today's practical implementations are described. Section 3 presents power supply systems that combine renewable energy sources and energy from the electricity grid. Standalone power supply systems based solely on renewable energy sources are discussed in Section 4. In Section 5, independent hybrid power supply systems based on more than one renewable energy source are presented. In Section 6, hybrid systems that use renewable energy sources and a diesel generator as a backup power supply are analyzed. Finally, some concluding remarks are given in Section 7.

2. Overview of power supply systems

At present, there are more than four million macro BS sites installed worldwide, each consuming an average 25 MW per year (Hasan, 2011). From 2007 to 2013, the number of installed macro BS sites is almost doubled in developing regions and further increase of installed macro BS sites is expected in upcoming years. Generally, BS sites in terms of power supply modes can be divided into two broad categories: on- and off-grid macro BS sites. On-grid macro BS sites are those with permanent connection to the electricity grid, which ensures constant power to the site. They are characteristic in urban areas,

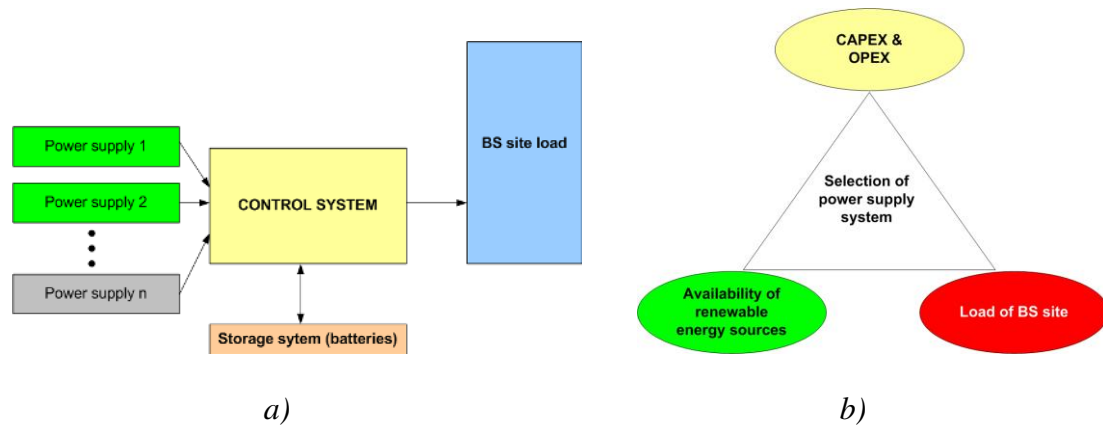


Figure 1. a) Structure of hybrid or standalone power supply system for BS sites, b) Process of selecting power supply system

such as roofs of buildings and for locations where the delivery of electricity represents acceptable investment costs. Network operators still do not express significant interest in transferring on-grid sites into sites with a hybrid power supply, which would combine energy from the electricity grid with renewable energy sources. This is due to larger investment costs and slow return of investment imposed when a power supply system based on renewable energy sources is installed on a site already connected to the electricity grid. Also, a lack of space for installation of photovoltaic (PV) panels or wind turbines is an additional reason for small usage of renewable energy sources for powering BS sites in urban locations.

Macro BS sites without connection to the electricity grid are called off-grid BS sites. Generally, the power supply modes of these sites can be divided into four categories:

- i) Independent systems that use a diesel generator as a source of energy;
- ii) Independent standalone systems that solely use wind or solar energy;
- iii) Independent hybrid power supply systems that are based on a combination of wind/solar/fuel cell energy;
- iv) Independent hybrid power supply systems based on a combination of a diesel generator and some combination of wind/solar/fuel cell energy.

In 2012, approximately 40% of installed BS sites in the developing regions of the world are off-grid BS sites (Taverner, 2010). The independent systems based on diesel generator as a source of energy are mostly installed in remote areas. Such power supply systems can cost ten times more in comparison with on-grid BSs sites for which estimated average yearly OPEX equal to \$3,000 (Hasan, 2011).

Furthermore, for standalone systems can be said that are based on only one renewable energy source. On the other hand, hybrid power supply systems combine two or more sources of energy to power the BS site. They may contain a number of power generation devices such as photovoltaic panels, wind turbines, or fuel cells interconnected with or without micro-hydro and/or fossil fuel generators. Standalone and hybrid power supply systems are generally independent of large centralized electricity grids. In the case of many developing countries, standalone and hybrid systems are seen as a means of providing power to BSs located in remote areas (Faruk 2012). In addition, both power supply systems are of interest to mobile operators in locations of BS sites where the costs for expansion of electrical grids is prohibitive and transportation costs of diesel are expensive.

There are two main advantages to using renewable energy sources for the case of standalone or hybrid power supply systems of BS sites. The first advantage considers a reduction or complete elimination of mobile operator operational expenditure (OPEX) directly related to expensive fuel needed to run diesel generators. Also, harvesting renewable energy sources for the power supply of BS sites allows for the cleaner generation of electrical power, which contributes to the reduction of CO₂ emissions generated by diesel generators. Due to this, the current trend among mobile network operators in both developed and

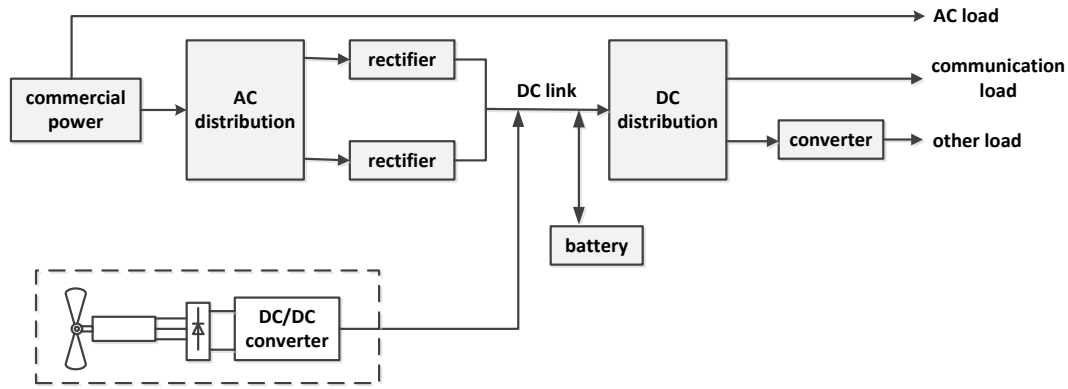


Figure 2. Power supply system based on wind and commercial energy

developing countries is to transition from diesel powered BS sites to macro BS sites based on standalone or hybrid power supply systems.

The general structure of a hybrid or standalone power supply system of a BS site is presented in Figure 1. Accordingly, each power supply system must contain next elements: a number of energy sources, load, the control system and a storage system (battery bank). The number of energy sources must be selected in order to ensure a continuous supply of power at the BS site for the whole year. Load is related to the energy needed for continuous power at a site and is mainly influenced by BS configuration and a number of different technologies (2nd, 3rd or 4th generation) installed at the site. Load will be larger in the case of BSs having stronger configuration (e.g. higher number of transceivers, power amplifiers, remote radio heads, and so on) or if there is a greater number of installed BSs of different technologies at the site.

Besides BSs as the main generator of load, other elements installed also contribute to the total load of the site. Such elements can be air conditioning for temperature regulation, a microwave system for monitoring and configuration of the BS, data transfer equipment (switch, router), and the control system itself. The control system is the center of optimization and performs operational overview, scheduling, coordination, execution, and load management. All these tasks focus on optimal regulation of energy flow from the various energy sources to the load and energy storage system.

Batteries installed on a BS site are used for the storage of energy in periods when energy sources produce more energy than the BS site consumes. In periods when the BS site consumes more energy than the energy sources can produce, energy accumulated in the batteries is used so that the site has an uninterrupted power supply. The number of batteries and corresponding capacities (in Ah) must be selected based on their comparative advantage, while maintaining uninterrupted supply and acceptable power quality. For proper functioning, batteries must be kept in the temperature ranges prescribed by the battery manufacturers. Due to this, appropriate air conditioning needs to be present to eliminate temperature peaks and fluctuations that can harm the batteries. This is a nontrivial challenge to the maintenance staff of a mobile operator, since the cost of batteries represents a significant item in the total CAPEX of the BS site installation.

Hence, the configuration of a hybrid or standalone power supply system depends on three factors (Figure 1b): cost of system installation (CAPEX) and operation (OPEX), availability of renewable energy sources, and the load generated by the equipment installed at the BS site. Therefore, the power supply system should be selected to optimize available resources in relation to different constraints, which must then result in improved performance, economy and reliability. For the case of hybrid or standalone power supply systems, some challenges in accomplishment of such constraints have been presented in the following sections.

3. On-grid hybrid power supply systems

The power generation system described in Shuang (2011), in addition to commercial energy, uses wind energy for the power supply of BSs. In order to capture maximum wind energy, a maximum power point

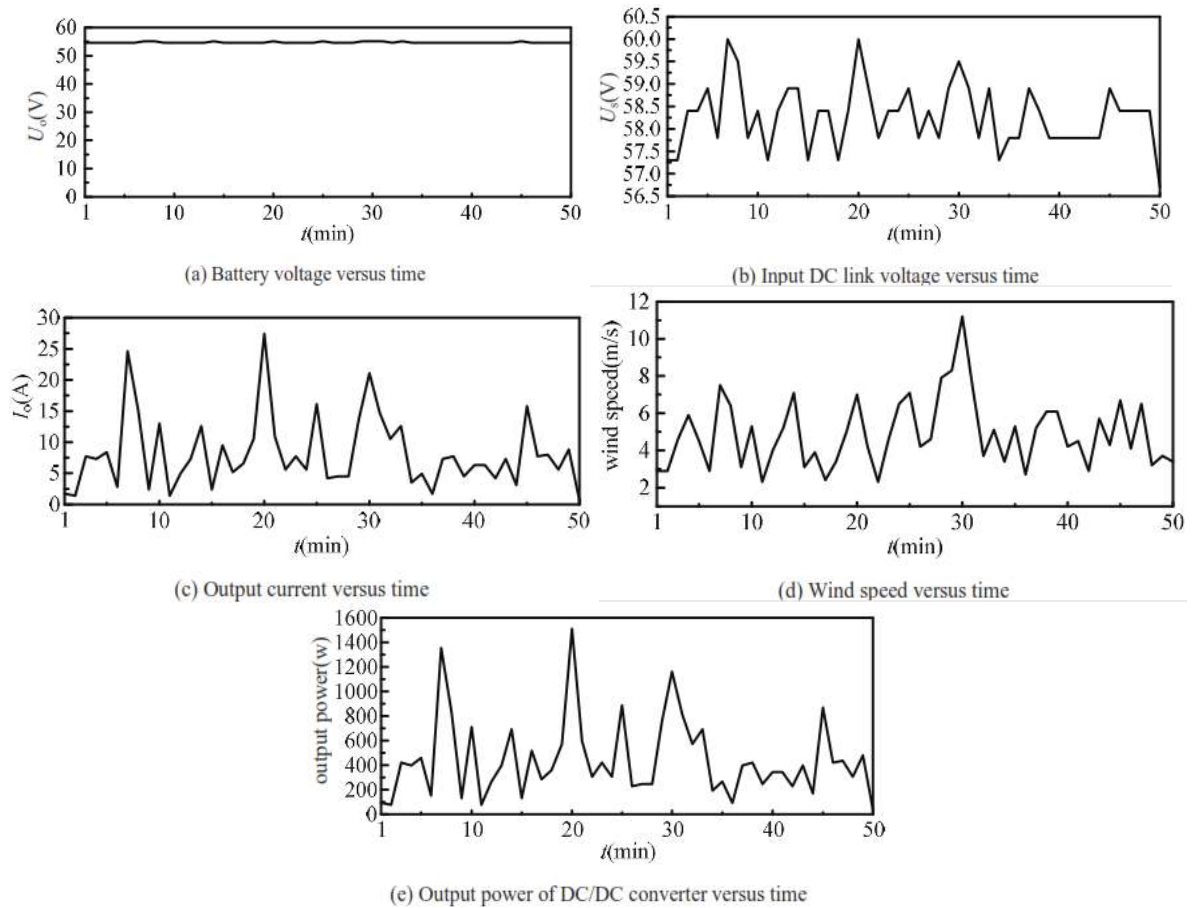


Figure 3. (Shuang, 2011) a) Battery voltage, b) Input DC link voltage, c) Output current, d) Wind speed, and e) Output power of a DC/DC converter during intervals of fifty minutes

tracking (MPPT) scheme based on optimal wind and turbine speed ratios is proposed. This scheme is realized with a dual-loop control strategy.

A schematic diagram of the proposed system is shown in Figure 2. The system can be divided into two parts: a commercial power supply system and the system for conversion of wind energy into electrical. Commercial AC (alternate current) power is converted to DC (direct current) power by a converter. The AC power is used to supply the BS site and for charging lead batteries when there is no wind. The main purpose of the batteries is storing excess wind energy produced from a number of wind turbines. The wind energy conversion system consists of a wind turbine, diode bridge rectifier, and a DC/DC converter. Based on the voltage values at the input (U_s) and output (U_o) of the DC/DC converter (Figure 2), the system is designed to operate in four different modes: buck mode (U_s is greater than U_o but less than discharge voltage), boost mode (U_s is less than U_o), discharge mode (U_s is greater than discharge voltage) and brake mode (U_s is greater than the brake voltage or some serious fault has occurred). Certain data such as input voltage, battery voltage, output current, and wind speed are transferred to the remote server by General Packet Radio Service (GPRS) data transfer. Figures 3a), b), c), d) and e) present for intervals of fifty minutes: battery voltage, input DC link voltage, output current, wind speed, and the output power of a DC/DC converter running in buck mode, respectively. According to the results presented, the proposed buck/boost converter is promising for the radio BS applications. It is also shown that advantages of using wind energy include the simple structure of the power supply system, low cost of installation and ease of management.

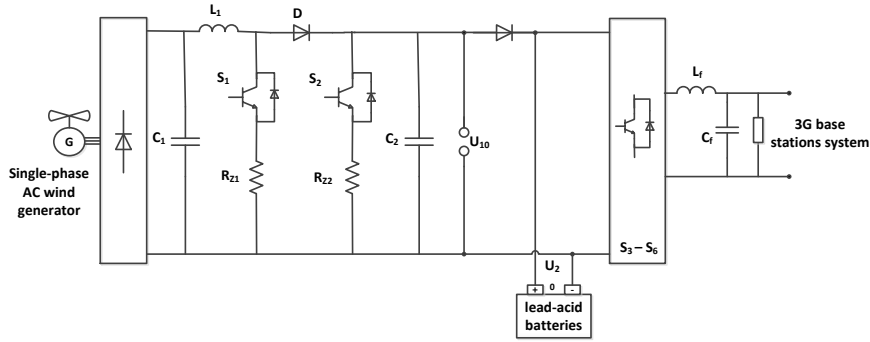


Figure 4. Control system of wind powered BS site

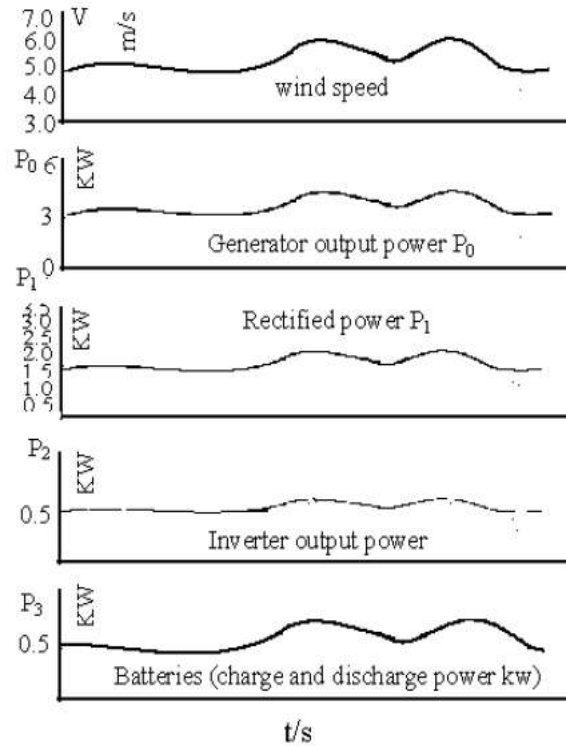


Figure 5. (Yiming, 2009) Simulation results obtained using the MatlabSimulink tool

4. Standalone power supply systems

In Yiming (2009), the control system for the power supply of 3G BSs is studied. The proposed system is a standalone type that uses wind energy to power the BS site. In this study, the control strategy for the establishment of the continuous operation of these BS sites is presented and tested by simulations and experiments. For the proposed system, BS site operation is independent and not associated with the power from the electricity grid.

As shown in Figure 4, this system is composed of small wind turbines, a single-phase AC generator (synchronous or asynchronous with permanent magnet), a three-phase non-controlled rectifier, a power bridge, boost converters, a single-phase inverter, a filter, and lead-acid batteries. The batteries are used to maintain the continuity of power supply.

The basic model shown in Figure 4 is created using the MatlabSimulink tool and a simulation is performed for many different conditions. The main parameters of the simulated model are as follows: wind turbine with an estimated output power equal to 3 kW, estimated wind speed of $v=7$ m/s, tilt angle 0° , a synchronous generator nominal voltage $U_n=130$ V (DC voltage after rectification), the stator resistance $R_s=0.558 \Omega$, and the stator inductance $L_d=L_q=5.25$ mH.

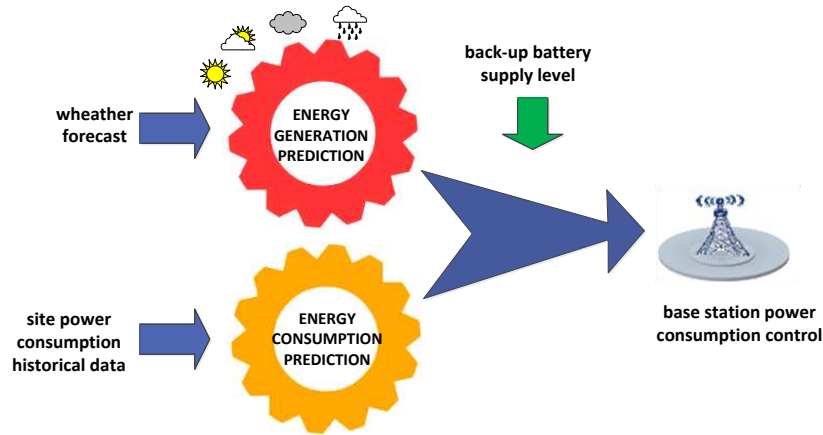


Figure 6. Diagram of BS powered model based on intelligent energy management

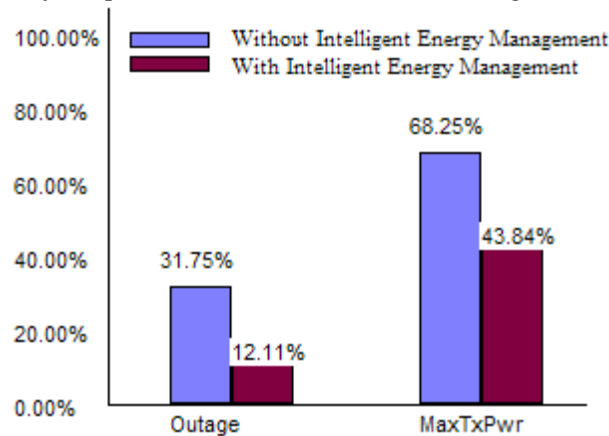


Figure 7. Valerdi (2010) Percentage of outage time and maximum output power per year (with and without intelligent management)

Simulation results are shown in Figure 5. By using the dual closed-loop of a current filter inductor, it is possible to properly track changes of wind direction and strength, and eliminate the impact of these changes on the power supply of 3G BSs. In addition, simulation and experimental results show that the proposed model provides a good power supply for the analyzed 3G BS sites.

Besides a previously presented standalone power supply system that is based solely on wind energy, Valerdi (2010) describes the system which uses solar energy as another source for the power supply of BSs. These solutions are environmentally and technically proven. However, in cases of real implementation there are several disadvantages that limit their use, such as: instability of the sun as an energy source and the number and size of PV elements needed to power a BS site. To avoid such limitations, the paper describes a model adapted to the services provided by the BS(s). Such a model of power consumption control at a BS site, which is based on intelligent energy management, is illustrated in Figure 6. The model is a function of weather changes specific to the selected renewable energy source, energy stored in the batteries, and historical data of energy consumption of BSs during certain periods.

Figure 7 shows the annual outages of four solar panels (180 pW, 1580 (L) x 808 (W) mm) and a 300 Ah battery for Barcelona, both with and without the use of an intelligent energy managed service. In Figure 7., a significant reduction in annual outage due to the intelligent management mode (from 31.75% to 12.11%) can be noticed. The BSs which use such a power supply system will work 87.89% of the time, while without the intelligent energy managed service the BS will work continuously only 62.25% of the time. This is unacceptable from an operator point of view in terms of service duration offered to the users. A solution for this case is to increase the number of PV panels, mounting diesel generator, and so on, which can lead to an increase in investment costs and OPEX.

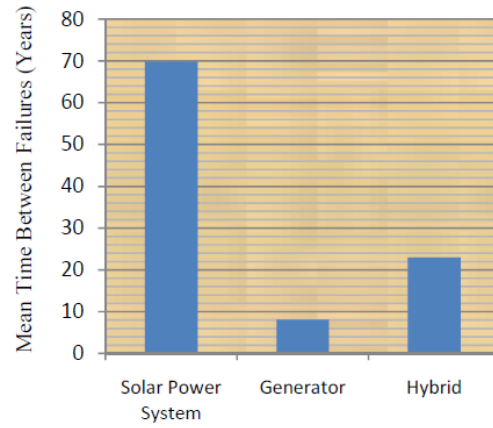
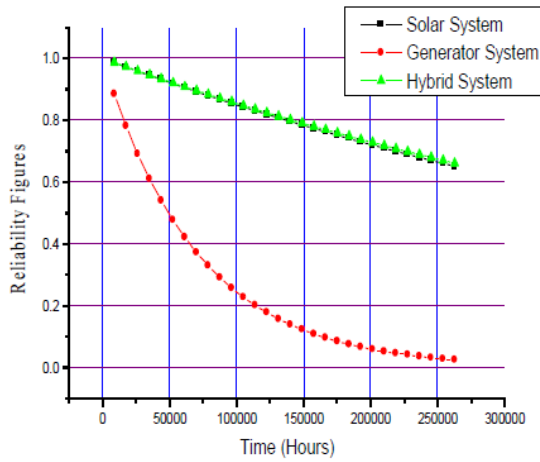


Figure 8. Faruk (2012) a) Reliability of hybrid power system and b) Mean time before failure

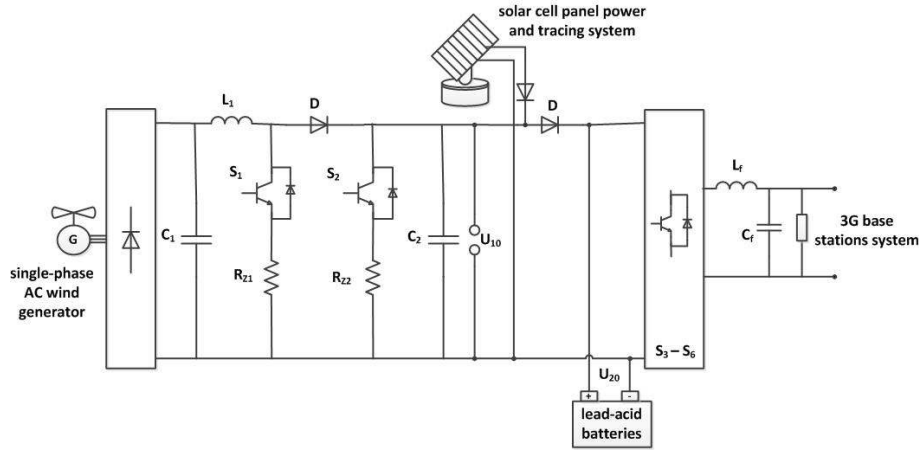


Figure 9. Wind and solar (hybrid) power supply system for 3G BS site

For powering a BS site, a different power supply system based on: solely solar power, solely conventional diesel generator, and the hybrid power system was evaluated in Faruk (2012). In the hybrid system, a diesel generator is used as the backup power supply. The rate of reliability and mean time between failures (MTBF) of the system were analyzed over a thirty year period. In Figure 8a), a graphical representation of the reliability rate of the hybrid system is compared with a system that uses only solar energy and a diesel generator.

Analyses have shown that the rate of reliability after a working period of 15 years is higher than 80 percent in the hybrid system, while for the diesel generator it drops to 15 percent. It was found that the proposed system has high reliability and is somewhat better than a system powered by only solar energy. According to Figure 8b), this system will be able to work in a satisfactory manner for 23 years before complete failure. This is satisfactory when compared to the eight years for a system that uses only a diesel generator.

5. Hybrid power supply systems

To provide continuous power supply for the 3G BS site, an independent hybrid system presented in Figure 9, which uses a combination of wind turbines and in parallel connected solar cells, is described in Weijun (2009). For the case of different weather conditions, wind turbine and solar cells are

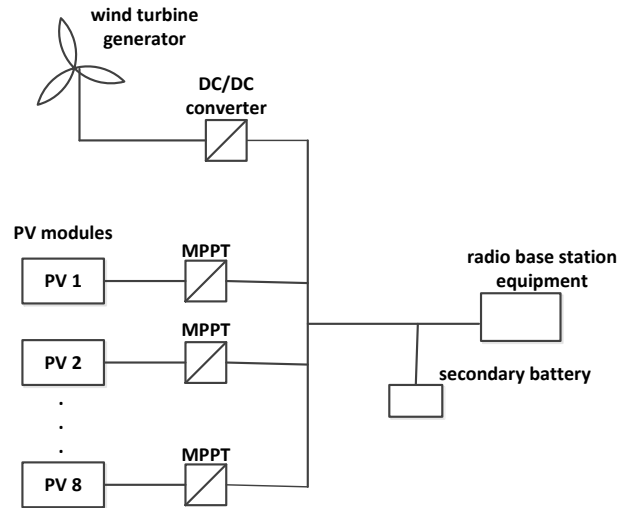


Figure 10. Configuration of autonomous power supply system

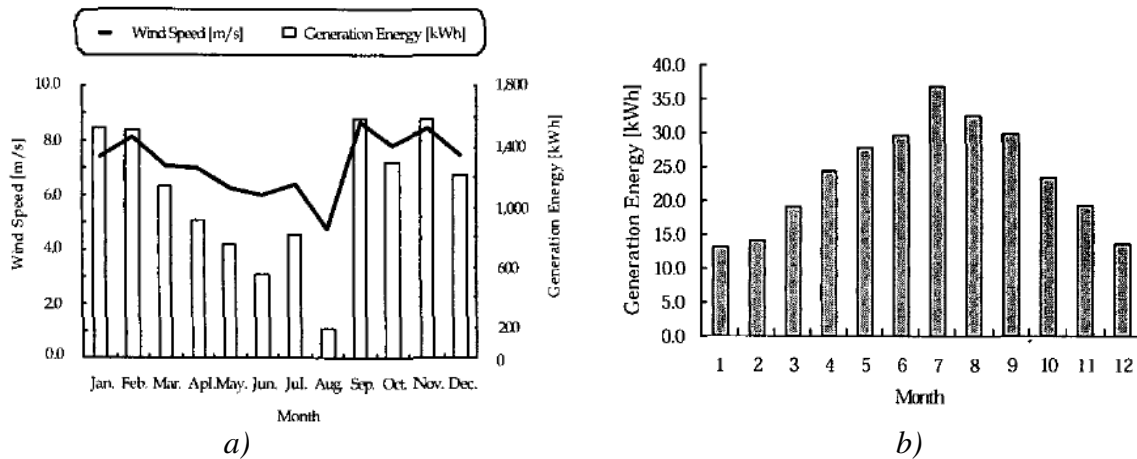


Figure 11. Hashimoto (2004) a) Monthly wind speed and wind turbine energy generation, and b) Monthly energy generation of PV panels [12]

complementary sources of energy, and it is assumed that such a hybrid system can ensure the power supply of a 3 kW BS site. On the basis of experimental models and simulations generated by the Matlab Simulink tool, good results in terms of supplied and stored energy for such 3G BS systems were obtained. In Hashimoto (2004), an autonomous hybrid system containing a wind turbine and PV panels as the only sources of energy used to power a 3 kW radio base station site on Yonaguni Island, Japan is proposed. According to Figure 10, besides BS equipment, the proposed system contains: a 2 kW wind turbine, 1.4 kW PV modules, DC/DC converters, solar panels, a controller (MPPTs), and a battery pack. Solar panels are directly connected to the tower of the wind turbine which has DC/DC converters connected in serial. For operation with a maximum output power, the control of the PV panels is based on MPPTs. Figure 11a) shows the monthly electricity production of such a system obtained according to the characteristics of the wind turbine. It is recognized that more electrical energy is produced in the winter period, with almost eight times higher electricity production in November when compared with those in August. However, energy generated by the wind turbine in August is not enough for the BS to be fully sustained. Figure 11b) shows changes in the production of electricity generated from PV panels during a year. It can be seen that production in the summer period is 2.5 times higher than in the winter period. However, the production of energy from the PV panels in August is about five times lower than what is produced by wind turbine. Hence, by combining both sources of energy such a configuration of power supply system still does not satisfy energy needs to ensure uninterrupted operation of the BS site during summer.

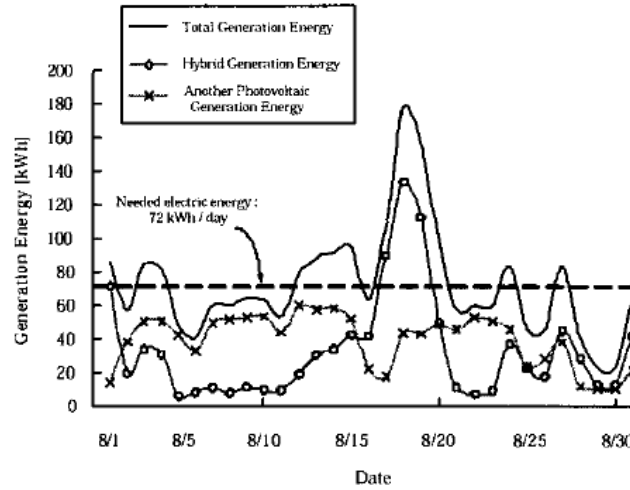


Figure 12. Hashimoto (2004) Energy production with and without additional PV panels

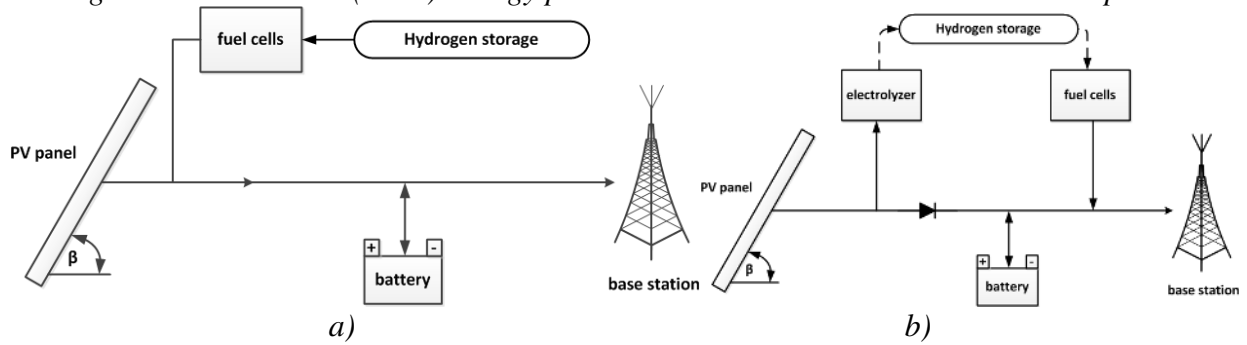


Figure 13. a) Power supply system based on solar and hydrogen energy and b) Power supply system with hydrogen on site generation

As an example, it is possible to estimate the number of wind turbines needed for uninterrupted power during the summer months on the basis of the energy produced in June. According to Figure 11a), this energy is twice as low as in November. Thus, energy consumption of the BS site can be estimated as 2,160 kWh ($3 \text{ kW} \times 24 \text{ h} \times 30 \text{ days}$) per month. According to the graphs presented in Figure 11a), the energy produced by one wind turbine in June is equal to 575.3 kWh.

To satisfy monthly energy consumption of the BS site in June, it is necessary to setup four wind turbines, since $4 \times 541 \text{ kWh} + 30.2 \text{ kW}$ satisfies the monthly energy consumption of 2,160 kWh.

On the other hand, total energy consumption of the BS site in August is 2,232 kWh. The energy produced by four wind turbines that month will be 1,017 kWh. The difference between produced energy and energy needed for the uninterrupted power supply of the BS site during this month is 1,215 kWh. A possible solution for satisfying such a difference can be found in the installation of more PV modules to produce an additional 1,215 kWh of energy. This production can be achieved if the installed strength of the PV modules is increased by 6.4 kW. Hence, for the uninterrupted power supply of the analyzed BS site for the whole year, it is necessary to have four wind turbines of the total installed strength equal to 8 kW and PV panels of installed strength equal to 7.8 kW.

Figure 12 shows the production of energy for the analyzed system in August. It can be noticed that the hybrid system with additional PV modules is unable to satisfy the power supply needs of the BS site for the month of August. Due to this, for uninterrupted power supply of the BS site during August, besides wind turbines and additional PV panels, a 177 kWh (three-day) battery is needed.

Another hybrid power supply system for remote BS sites based on solar and hydrogen energy is analyzed in Bezmalinovic (2013). In the paper, common approach of using diesel generators as a back up power supply system of hybrid BS sites has been challenged by the introduction of fuel cells. Use of fuel cells as an alternative to the diesel generators seems to be promising solution in the times of uncertain fuel prices

Table 1. (Bazmalinovic, 2013) Parameters of analyzed power supply system and results of analyses obtained for different limited annual hydrogen consumptions

Power Supply System Number	Hydrogen costs	Annual consumption (kg/y)	Fuel Cells strength (kW)	Number of batteries	Photovo. panels strenght PV (kWp)	Number of storage elements 50L/200 bar	PV Panel slope (°)	levelized cost (\$/kWh)
System 1	5\$/kg	15	0.5	10	3	10	55	0.662
System 2	5\$/kg	9	0.5	12	3.3	6	55	0.675
System 3	20\$/kg	15	0.5	10	3	10	55	0.722
System 4	20\$/kg	9	0.5	12	3.3	6	55	0.711

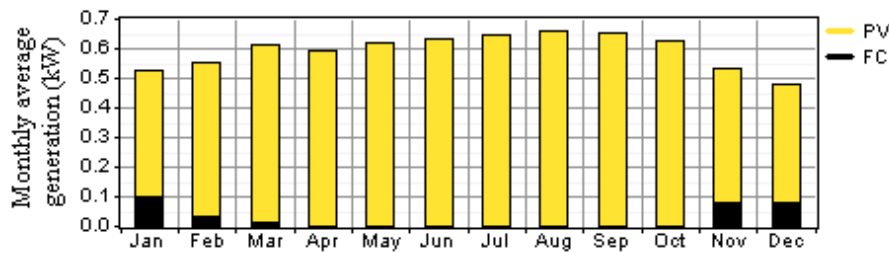


Figure 14. (Bazmalinovic, 2013) Averaged monthly electricity production of power supply system based on PV modules and fuel-cells

and awareness considering necessity of reducing carbon dioxide emissions. Life-cycle of fuel cells technology is comparable with those of diesel generators and this technology is proven and reliable source of electricity. The main drawback of the fuel cells technology is still relatively high unit cost of the fuel cells and hydrogen in comparison with fossil fuels, due to still undeveloped market of these technologies. On the other hand, fuel cell technology has many technical and environmental advantages in comparison with diesel generator such as: simple and cheaper maintenance, quiet operation, zero emissions, higher flexibility and energy conversion efficiencies (Bezmalinovic, 2013).

According to Figure 13a), analyzed power supply system contains PV panels, fuel cells, hydrogen storage and battery. System does not need to contain converter since fuel cells directly produce DC current. Analyses are performed for estimated maximal yearly load of 500 W for BS site located in one Croatian island. Total strengths of PV panels and fuel cells with the number of 300 Ah batteries for each of four analyzed hybrid power supply systems (1-4) are presented in Table 1. Analyses are performed using HOMER simulator for different hydrogen prices and annual hydrogen consumptions. It is shown that price of the hydrogen is more dominant in the total power supply system cost than the fuel cells' price. This is because initial investment in 500 W fuel cells is much lower than operating cost dedicated to hydrogen fuel expenses. It is also shown that taking into account hydrogen storage expenses significantly increases system costs (kWh price), what makes fuel cells less competitive in comparison with diesel generator. To increase competitiveness of fuel cells as technology, limiting annual hydrogen consumption combined with more refueling during a year is proposed as solution for powering BS sites.

In the Table 1, influence of the limited annual hydrogen consumption on levelized cost of electricity for different hydrogen prices is also presented. Limiting annual hydrogen consumption to 15 kg per year together with 2 refuelings a year results in the need for 10 storage tanks (50 liter/200 bar). Additionally, limiting hydrogen consumption further to 9 kg per year results in the need for only 6 tanks with 2 refuelings. As resented in Table 1, for the fuel cells' price of 2000 \$/kW limiting annual hydrogen consumption to 15 kg per year is better in the case of cheap hydrogen scenario (5 \$/kg). In the case of expensive hydrogen scenario (20 \$/kg) system with 9 kg per year limitation is better (Bezmalinovic, 2013).

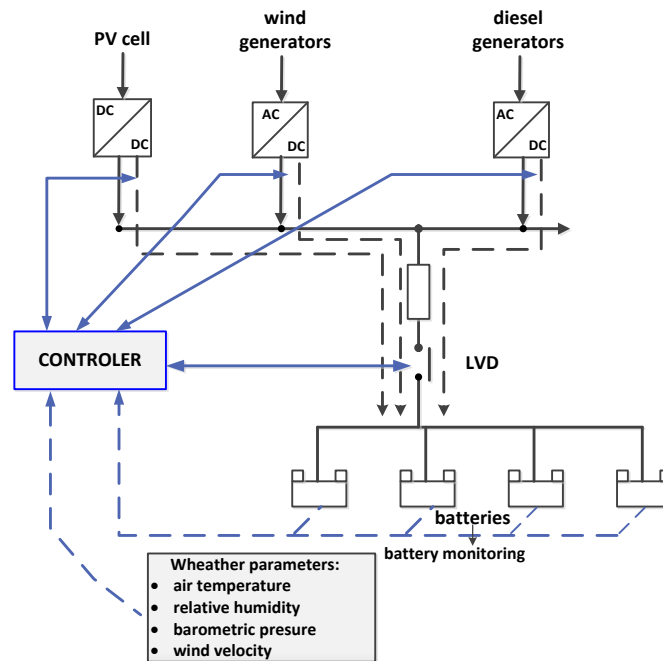


Figure 15. Intelligent control of energy flow in a hybrid power supply system

Also, in Figure 14 averaged monthly electricity production of power supply system 1 (Table 1) based on PV modules and fuel-cells is presented. Annual engagement of fuel cells' is 503 hours with 4% of total electricity production ratio. In the countries with huge hydrogen price (above 50\$/kg), fuel cells could never compete with diesel generators. In this case possible solution is presented on Figure 13b). Power supply system is based on "on-site" generation of hydrogen through water electrolysis with excess electricity from PV.

6. Hybrid power supply systems with diesel generator

A hybrid power supply system for BSs based on solar and wind energy, with a diesel generator as backup is presented in Panajotovic (2010). This system contains a controller for intelligent control of energy flow (Figure 15), which has additional parameters to use the actual weather conditions and state of batteries. For optimal modeling and design of the hybrid system, it is essential to have accurate weather data. Also, it is necessary to define the capacity and reliability of the power supply system to be used for powering the BSs. The consumption of diesel in such systems must be reduced to a minimum and the majority of energy for charging the batteries must be provided from renewable energy sources. The parameters important for the performance of the batteries, such as low voltage disconnection (LVD) and maximum charging current are usually set on a fixed value. Weather parameters such as air temperature, relative air humidity, air pressure, and wind speed must be measured for each micro location.

The task of the hybrid power supply system is to ensure whenever possible energy from the solar panels and/or wind turbine for the power supply of BSs and for charging batteries. When wind or solar energy is not enough to charge the batteries, then renewable energy sources are used. If the renewable energy sources are not enough to power the BSs, then additional energy will be redeemed from batteries or a diesel generator. If the batteries are discharged then the diesel generator will be used as a power supply and to charge the batteries. These batteries must be protected from overcharging and the maximum value of the charging current must be defined during system setup. The batteries must be recharged as quickly as possible and the period of charging is higher when the charging current is lower, and vice versa. Such an operational mode is used in most of current hybrid systems to ensure continuous power supply.

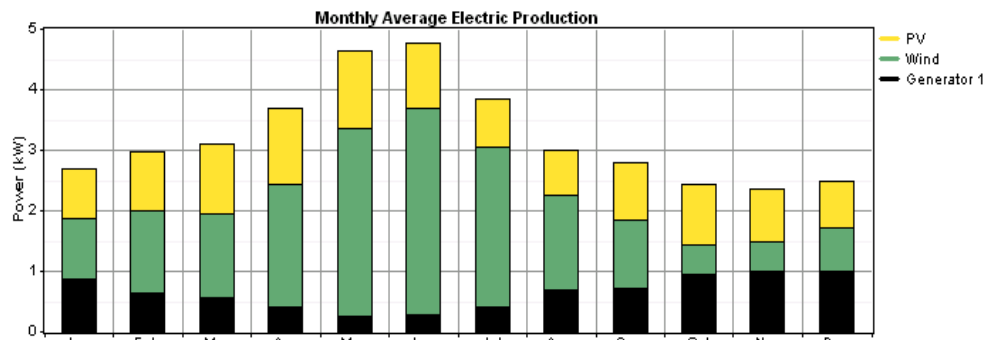


Figure 16. Nema (2010) Average monthly electricity production of a hybrid energy supply system

Represented by the idea of intelligent control of a hybrid power supply system, it aims to reduce: consumption of diesel fuel, emissions of CO₂ in the environment, and logistical and operational costs.

Nema (2010) proposes the most cost-effective configuration of an independent hybrid power supply system. It uses solar panels and wind turbine with a diesel generator as a backup power supply in remote areas of central India. In order to select an appropriate combination of energy sources, the availability of particular renewable energy sources for specific BS locations are studied.

According to the presented data, installation of the PV system to power BSs must be preceded with precise data considering solar radiation for a specific area. These data are used for calculation of the potential energy production of PV panels with other data, such as the orientation or angle of the PV panels to be installed.

In the case of powering a BS site through the use of wind energy, it is necessary to obtain data about the wind speed for a certain area and for a certain height of wind turbine. Based on these data, it is possible to estimate the potential energy production of the wind turbine(s).

In order to install appropriate capacities of wind turbine(s), PV panels, batteries, inverters and (if necessary) a diesel generator, it is necessary to have accurate data regarding maximal instantaneous power consumption of the BS site. Based on these data, it is possible to select the components of a power supply system to guarantee continuous 24/7 power supply of the BS site during different periods of the year. When analyzing possible power supply components of such a hybrid system, it is necessary to consider the impact of four variables: wind speed, solar irradiation, fuel costs and the cost of the batteries. In Nema (2010), simulation was performed for each hour during the year and for each power supply type and system configuration. The appropriate solution that was capable of satisfying the demand to power the corresponding BSs was selected.

Figure 16 shows the average monthly electricity production of such hybrid BS power supply systems. For such a system, the total electricity production is able to fulfill the demands of BSs in the next combination: 30 percent of the produced energy will be generated from PVs, 50 percent is produced by wind turbine, and the rest is produced by diesel generator (20%). Based on the simulation results and with regard to current installation costs, such a system is suitable as an autonomous solution for powering BSs in remote areas of central India. The proposed hybrid power supply system should ensure energy supply continuously throughout the year.

Based on this study, it can be noticed that the hybrid system is more durable in comparison with a traditional diesel generator. According to labor and maintenance costs, return of investment for such autonomous BS sites will be 2-4 years in a sunny and windy area. Although the current price of such a power supply system is high, maintenance costs are lower in comparison with the BS site powered solely by a diesel generator. Due to this, such hybrid systems are more economical for installation in remote and rural areas that lack power grid connection. The costs of diesel fuel in cases of such hybrid systems has been reduced by 80 percent in comparison with a traditional power supply system based on the use of a diesel generator. Also, emissions of carbon dioxide and other greenhouse gases into the atmosphere are significantly reduced.

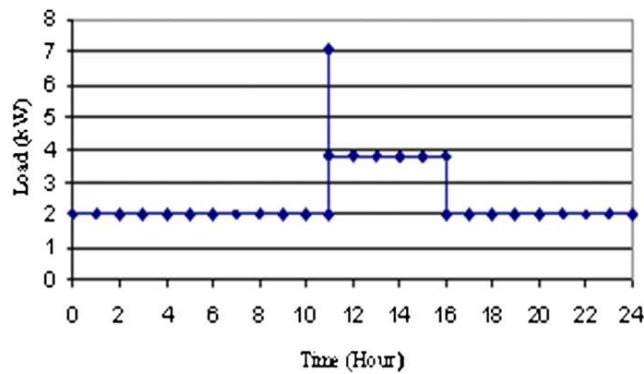


Figure 17. Kusakana (2013) Profile of daily load

Table 2. Kusakana (2013) Simulation results for site: A, B and C

Site:	Site A	Site B	Site C
PV (kW):	11	10	10
XLR:	2	2	2
L16P:	82	82	88
Converter (kW):	7.5	7.5	7.5
Initial Capital:	\$119,250	\$115,150	\$116,200
Operating Cost (\$/yr):	3,109	2,969	3,041
Total NPC:	\$196,975	\$189,375	\$192,225
COE (\$/kWh):	0.372	0.357	0.363
Ren. Frac.:	1.00	1.00	1.00
Capacity Shortage (%):	0.00	0.00	0.00

Another hybrid power supply system used in the rural areas of the central India is described in Sthitaprajna (2012). For this hybrid system all necessary weather data were collected and simulations were performed using the Matlab Simulink tool for each month in the considered year. The power supply system is analyzed separately for 25 PV panels (with a maximum power of 175 W) and one 1000 W wind turbine. Through the integration of results, an appropriate hybrid system was chosen for the power supply to produce continuous power of 4.75 kW for a BS. A diesel generator is used only as backup or during cloudy days when solar energy is insufficient. After setting up the hybrid system, diesel fuel consumption was significantly reduced (for about 80%), while emissions of CO₂ and greenhouse gases were reduced by 90 percent.

The possibility of using a hybrid system as the primary energy source for the power supply of BSs, in remote urban areas of a country situated in the middle of Africa, is investigated in Kusakana (2013). For this purpose, three different BSs sites (A, B and C) that have renewable energy sources (solar and wind) were analyzed. There are four possible operation modes of power supply system: only diesel generator, only solar energy, only wind energy, and a hybrid system. Selection criteria of the operation mode include financial viability, fuel consumption, and emissions of CO₂ during the activity period (20 years). Simulations were performed using a HOMER simulator (Homer, 2013) for each hour on an annual basis. Input parameters for the simulation are technical data of the hybrid power supply system, such as: wind speed, solar radiation, daily load (presented in Figure 17), cost of components, and other technical specifications of the supply system. The obtained results were analyzed for the hybrid systems and the criteria for comparison was: the initial capital (IC), operating costs per year (OC), total net present cost (NPC), the cost of energy (COE), and capacity of the system.

Elements of the system's architecture with the capacity of renewable energy components and various costs are shown in Table 2. For example, in the case of site A – an optimal hybrid system containing 11 kW PV panels – two wind turbines, 82 batteries (L16P), and a 7.5 kW inverter has IC of \$119.250, NPC of \$196.975, OC of \$3.109 per year and COE of 0.372 \$/KWh.

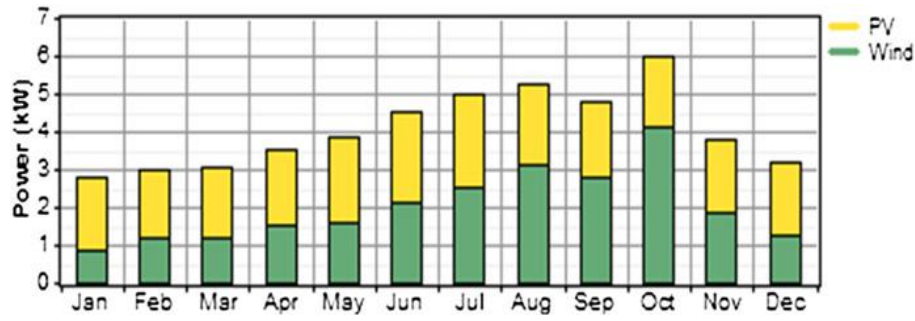


Figure 18. Kusakana (2013) Average amount of power produced each month

Table 3. Kusakana (2013) Simulation results for a power supply system based solely on PV panels, wind turbine or diesel generator

Site:	PV Panels	Wind Turbine	Diesel Generator
PV (kW):	18	-	-
XLR:	-	7	-
Label (kW):	-	-	1
Battery (L16P):	131	102	88
Converter (kW):	7.5	7.5	7.5
Initial Capital (IC):	\$ 102,725	\$ 212,150	\$ 116,200
Operating Cost (OC \$/yr):	4,227	2,934	3,041
Total NPC:	\$ 208,400	\$ 285,500	\$ 192,225
COE (\$/kWh):	0.393	0.539	0.363
Ren. Frac.:	1.00	1.00	1.00
Capacity Shortage (%):	0.00	0.00	0.00

The results for the other two sites are similar to those of site A, with a small difference in the number of batteries and installed power of the PV system. This is due to different availability of renewable energy sources on different locations of BS sites. From the simulation results, it can be noticed that the lack of power supply capacity for each site is zero. This means that independent hybrid systems at each location have been well adapted so that the required energy for the BSs can be provided at any moment.

Figure 18 shows the production of electricity for each month (annualized) for one of the analyzed sites. Contribution of the PV panels or wind turbine in total electricity produced during each month can be perceived. Electricity production is greatest in August and October, and weakest in the winter months (January and December). This is mainly because of higher or lower contribution of wind energy during these months.

Kusakana (2013) highlights other possible options regarding sources of power supply for BS sites. For power supply systems that solely use solar energy, wind energy or diesel generator, the results are presented in Table 3. These results were obtained for the same BS site with power supply capacities that could satisfy the energy demand of that particular site. By comparing the results, we can conclude that the diesel generator has the lowest ICs compared to other systems, but that the annual operating and maintenance costs are significantly higher than those of the other two systems. Only 20 percent of diesel generator fuel is spent on the production of electricity, while the rest is lost into the environment as heat. Apart from being very expensive for maintenance and operation, a diesel generator contributes to the pollution of the environment. Considering the total operating period of a BS site, power supply systems based on renewable energy sources are more cost-effective and an environmentally better solution in comparison with power supply systems based on fossil fuels.

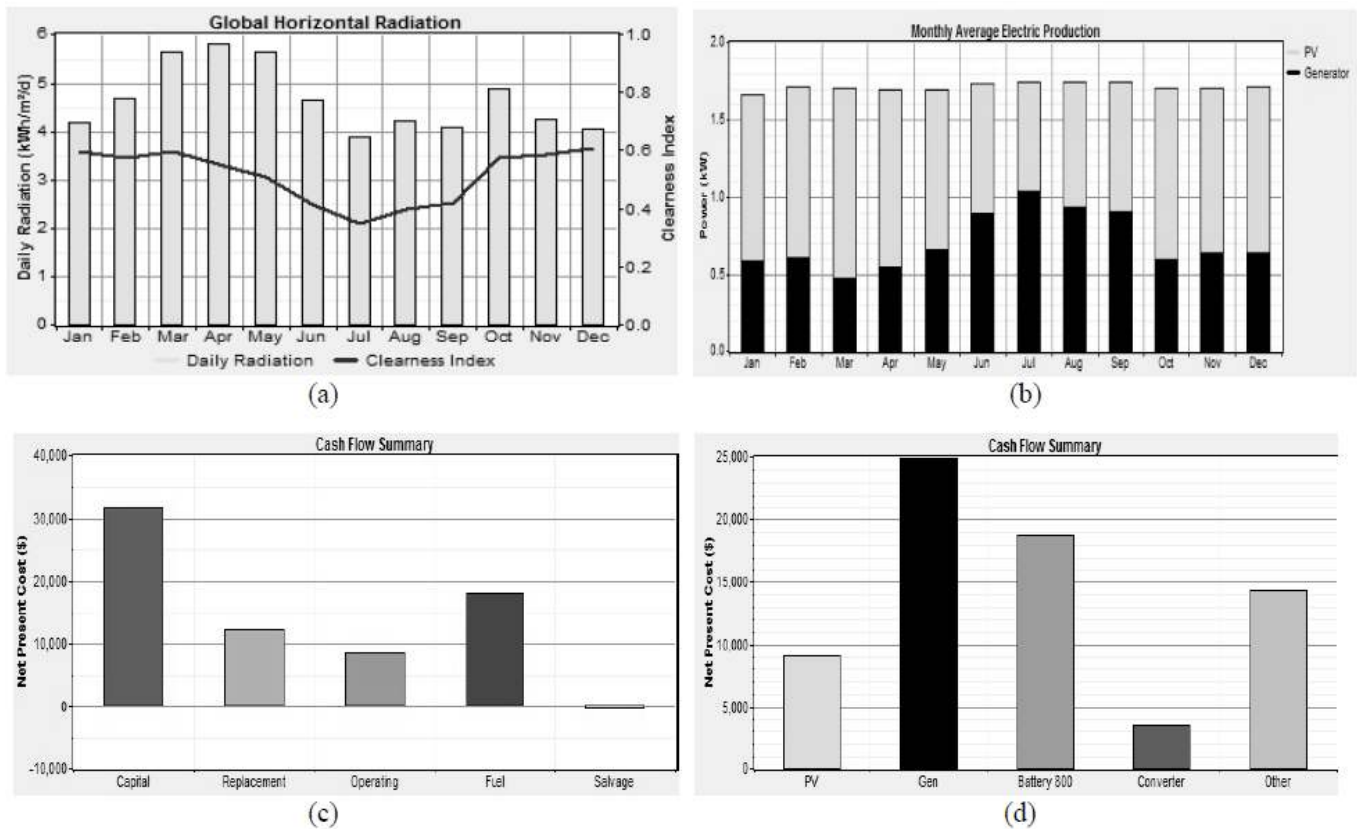


Figure 19. Chowdhury (2012) Simulation results: (a) monthly global horizontal radiation, (b) monthly average electric production, (c) summary of total costs, and (d) summary of component expenditures

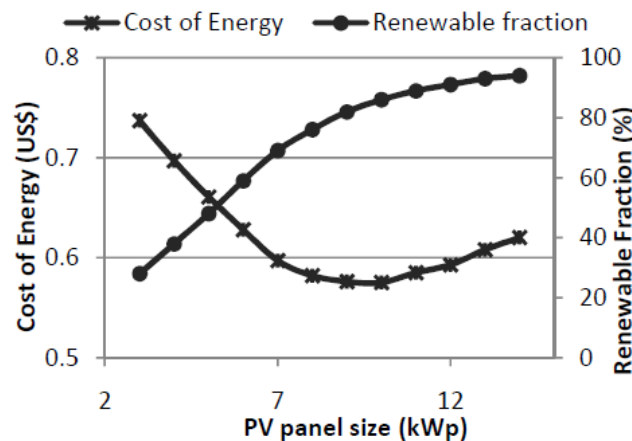


Figure 20. Chowdhury (2012) Impact of installed capacity of PV panels on cost of energy

In Chowdhury (2012), a HOMER simulator is used since the hybrid system is based on solar energy and a diesel generator. For such a system the investment and operating costs were analyzed. The power supply system for this scenario must ensure constant power of 36 kWh per day for the BS site. For such a power supply system, PV panels of 6 kW, a 10 kVA diesel generator, and two 2.800 Ah batteries were used. In the periods when the diesel generator was active, produced energy is used to power the BS and for charging the batteries. Figure 19 shows the simulation results for such a power supply system. It can be noticed from Figure 19a) that annual production of energy obtained from the PV panels is proportional to solar radiation. The contribution of solar energy in the total amount of produced energy is 59 percent, while a diesel generator contributes 41 percent (Figure 19b). The biggest cost is the initial capital, then the cost of fuel (diesel), and the cost of batteries and generator replacement (Figure 19c). The most

expensive component is the diesel generator (fuel cost is included in the price of the generator) (Figure 19d). The cost of solar panels is the second lowest among the five types of initial expenses. It is assumed that the generator will operate 2.5 to 3 hours per day and provide electricity for 8 to 10 hours. The obtained results highlight that the cost of this system is \$0.625 per kWh of electricity.

It is also shown that energy costs can be reduced by increasing the number of PV panels. Assuming that all other system components remain unchanged, Figure 20 shows the effect of changing the number of PV panels with respect to energy costs. The capacity of solar panels has been changed from 3 kWp to 14 kWp. Even though an increase in the capacity of installed PV panels leads to an increase in initial costs, the cost of energy is reduced. For such a system the optimal capacity of PV panels is 10 kWp, with a minimum cost of energy equal to \$0.575 per kWh.

From the perspective of current market conditions and the price of the equipment, initial investment costs in such a PV system are greater than in those of a system powered solely by a diesel generator. However, during the operational phase a significant part of the cost of the diesel generator comes from the price of fuel, which is highly variable and unpredictable. Although initial investment in a power supply system harvesting solar energy is higher, dependence on solar energy has significant advantages in eliminating unknown costs in the near and distant future. This reduces the financial and operational risk and creates a more reliable long-term source of energy.

7. Conclusion

In this paper some of the possible approaches for the power supply of mobile BS sites using renewable energy sources are presented. Configuration of a hybrid or standalone power supply system based on renewable energy sources depends on the cost of installation and operation of the system, availability of renewable energy sources, and load generated by equipment installed at the BS site. The selection of a power supply system must result in optimization of the available resources in relation to the different constraints that ensure uninterrupted performance and reliability of a service offered by BS site. In the areas having satisfactory level of renewable energy, it is possible without support of diesel generator to use standalone or hybrid power supply system for continuous powering of BS site during whole year. Also, it is shown that hybrid or standalone power supply systems based on renewable energy sources can significantly reduce operators' OPEX and CO₂ emissions in comparison with power supply systems based solely on a diesel generator. Hence, in rural and remote areas it is expected that further trends will transform off-grid diesel powered BS sites into green and sustainable ones powered by renewable energy sources. In order to increase the reliability of hybrid power supply systems, our future research activity will be focused on the investigation of interdependence among different renewable energy sources.

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