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Modeling and control strategy of a hybrid PV/Wind/Engine/Battery system to provide electricity and drinkable water for remote applications

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Abstract

In this paper a small-scale energy system called emergency container is presented. This container has lots of applications and can be designed as stationary solution in remote areas such as rural electrification and a mobile solution for disaster situation, military purposes and exploration teams. In this study the container is a hybrid PV/wind/engine energy system that is designed to provide electricity and drinkable water for 1000 person in disaster situations. A transient model implemented in Transient Simulation System (TRNSYS) program is developed and performance of the system during one-year operation for two locations (Nairobi in Kenya and Nyala in Sudan) with relatively high solar insolation is analyzed. The result of the model is significantly important in order to choose the right size of the different components. Due to the fluctuations of solar and wind energy as well as the importance of the battery life cycle, there is a need to have a smart power management and an appropriate fast response control system. In order to achieve it and to fulfill the energy demand as much as possible through renewable energies, a dispatch strategy is introduced and a control algorithm is applied to the model. This control algorithm has increased system reliability and power availability. The transient simulation shows that the share of power generation by solar energy is 63% and 80% and the share of wind power is 27% and 12% in Nairobi and Nyala respectively. It means that most of the energy demand (around 90%) can be covered by renewable energy. This results in significant mitigation of environmental issues compared to using only diesel engine that is a common solution in disaster situations.

Keywords: Solar Building;Solar Energy;Thermal Energy Storage;System Analysis;Solar Panel

1. Introduction

Small-scale renewable energy systems are becoming more popular due to the recent development of small-scale energy technologies and global increasing of the energy demand. Integration of these different technologies forming a hybrid system can be a realistic alternative to conventional fossil fuel powered engines to provide energy in small communities. Among these energy systems the renewable ones, such as wind, solar and biomass are even more attractive due to rising fossil fuel prices and environmental impacts [1, 2].

The combinations of different types of renewable energy such as wind, solar and biomass coupled with energy storage units, such as batteries and gas/diesel engines as backup, provide a stand-alone energy system usually called Remote Hybrid Power System (RHPS) [3, 4, 5].

The focus of this work is on small hybrid solar/PV/engine/battery systems to provide electricity and drinkable water. This small-scale energy production system can be used as a temporary or long-term solution for rural areas [6],

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natural or human-made disaster situations [7], mobile exploration teams or military purposes. The intermittent nature of wind and solar energy in combination with battery cycling and gas/diesel engine operation emphasizes on importance of control strategy. A comprehensive control strategy needs to be defined according to the source of energy production and energy flow consumption. Without having a good control strategy, the system will not operate efficiently and premature failures in different components lead to increasing costs and related emissions. In this work a RHPS called "mobile container" is proposed with a focus on providing emergency needs in disaster situations [7]. The results of the transient simulation demonstrate system operation in a specific period of time and a specific geographical location, which is necessary in localization of energy system.

Nomenclature

RHPS	Remote hybrid power system
SOC_B	State of charge of battery
FSOC	Fractional state of charge of battery
GPD	Gallon per day
AC	Alternating current
DC	Direct current
SOC_{max}	Maximum state of charge of battery
SOC_{min}	Minimum state of charge of battery
P_{pv}	PV panel power output (kW)
P_{wd}	Wind turbine power output (kW)
P_{load}	Load demand (kW)
RO	Reverse osmosis

2. System Overview

2.1. System configuration

The main objective of this study is to evaluate system operation based on desired criteria and to define a proper control algorithm and a dispatch strategy to extract the maximum available energy from the solar and wind sources. In order to achieve this goal, a model has been developed to evaluate the system operation during one year. Energy demand is predicted for an emergency situation and a load profile is determined. The model is considered as the first phase of the project. An experimental setup has been built at the Energy department of KTH to validate the model as the second step [8].

As described in the introduction, small-scale RHPS have several different applications. The most important amongst them, in the present application, is to provide power and clean water in disaster situations. The emergency module is composed of a wind turbine, PV panels, an engine generator set (as back-up), a battery bank and a water purification system.

In a typical hybrid system composed of solar PVs, wind turbine and an engine generator set, integration between different components can be configured in several ways. They can be connected in series, parallel and with AC or DC coupling. In this work a parallel configuration with an AC coupling has been chosen. Parallel configurations have several advantages over series ones but they need a well-designed energy management and a more sophisticated control system [9]. The overall configuration of the system is shown in Fig.1.

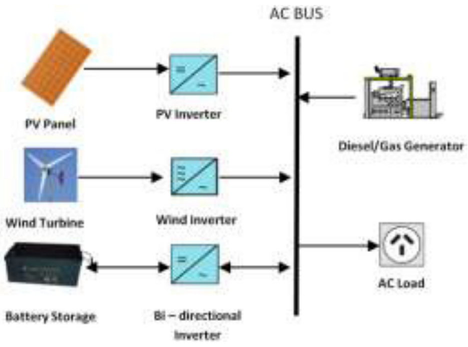

Fig.1.Overall configuration of the system [9]

2.2. Experimental Setup

The experimental setup [8] is shown in Fig. 2 and is composed of the following components:

- A horizontal wind turbine with a capacity of 1kW, 8m tower height and 3m turbine diameter. (FD-1000)
- Solar PV panels composed of 22 mono-crystalline PV modules altogether 5 kW rated power. The efficiency of a PV module is around 15% and the maximum power of each module at standard test conditions is around 230 W.
- Diesel engine generator set rated at 1 kW to 10 kW can be chosen according to the renewable energy sources availability and demand the load.*
- Gas an engine generator set coupled with a gasifier; the gasifier system is an integrated unit composed of a gasifier part and engine generator set. The electric power output can vary between 2 kW to 10 kW depending on the system needs. The fuel to the system is wood chips. The available gasifier is a 10 kW Power Pallet from All Power Labs. *
- Battery bank composed of 6 batteries with a capacity of 200 Ah at 12 V each. The battery storage plays an important role in the system and should be coupled with a charge controller to control battery operation.
- Water purification system; a reverse osmosis system RO -200 acquired from Pure Aqua Inc.
- Other components such as inverter/converter, power router and other communication systems to monitor and control the system operation.

Fig. 2.Prototype Emergency Container at KTH Campus [8]

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* Depends on the available local energy sources and the energy demand, diesel engine, gas engine or both of them can be used but it is desired to eliminate diesel engine due to the environmental impacts and substitute a renewable driven backup system such as biomass gas engine.

3. Model Description

3.1. Model overview

The model is implemented in TRNSYS software [10]. Standard TRNSYS components are used to simulate different parts of the model. However, a control algorithm is developed using user-defined equation modules. This model includes the following components:

- Weather data processor (Type109)
- Wind turbine (Type 90)
- PV panel (Type 94a)
- Engine generator set (Type 120a)
- Battery (Type 47a)
- Regulator/Inverter (Type 48b)
- Forcing function (Type 14h)

Hourly solar irradiation and wind speed data are extracted from the TRNSYS database for a complete year. Using the transient model, the variation in operation throughout the year is taken into account and the performance of the system is analyzed. The wind turbine model is based on an analytical solution and the mathematic behind it are presented in TRNSYS [10]. Power curve from manufacture is used as an input to the model. The impact of tower height and air density is considered in turbine power output [10].

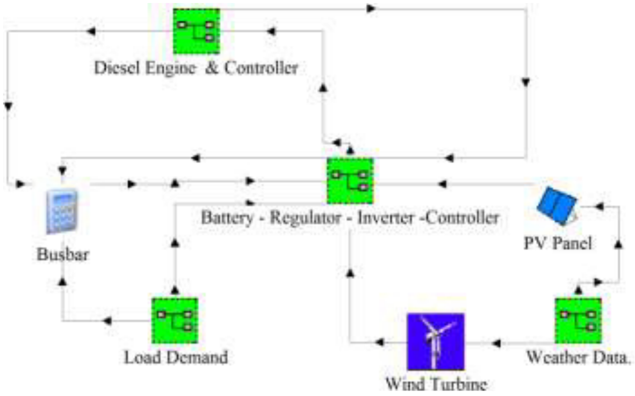

Fig.3. Model illustration in TRNSYS

The solar PV component is based on a “four-parameter” equivalent circuit for a mono-crystalline PV [10]. In this model the slope of the IV curve (A current-voltage curve) is assumed to be zero at short circuit condition based on TRNSYS mathematical reference [10]. The battery in the model is a lead-acid battery storage and the mathematical description is based on the equation devised by Shepherd [10]. Battery state of charge (SOC) can be specified based on the given charge and discharge rate. Fractional state of charge of the battery (FSOC) is used in battery charge controller as an important parameter to protect the battery from over charging and over discharging situations that may decrease battery capacity and cause premature battery failure [11, 12]. In the engine generator set model, fuel consumption is calculated as a function of the electrical output and is based on 1st order polynomial empirical relation [10]. Regulator/Inverter component plays an important role in system operation. The regulator distributes generated power to and from the battery and the inverter converts DC power to AC and sends it to the AC Bus. The chosen component for the model (Type 48b) provides a” parallel maximum power tracker system” [10].

Weather data in various standard formats available in TRNSYS are imported from the weather data processor model [10]. Load data are imported to the model through a forcing function to determine load profile over a specific period of time.

3.2. Component specification in the model

A transient simulation of the emergency module having the following components has been done:

- Solar PV composed of 22 PV modules with 5 kW power output
- Wind turbine with 1 kW rated capacity
- Diesel generator set with 1.5 kW rated capacity
- 6 batteries with a capacity of 200 Ah at 12 V each. The maximum and minimum fractional states of charge (FSOC) are assumed to be 85% and 20% respectively [11].

3.3. Load Characteristics and meteorological data

The energy demand is defined based on the standard needs of human in disaster situations [7]. Since clean water and medicine protection are the most critical issues in such situations, the main target is to produce enough electricity to cover these needs specifically for 1000 people in this model. It is assumed that basic water is provided locally. The drinkable water need is assumed to be 3.5 liter/person/day but in case of excess electricity more water will be produced occasionally.

The total electricity demand for a typical emergency situation is shown in Table.1 and the daily demand profile is also shown in Fig.4.The system should meet the energy demand that is shown in this figure. The load pattern remains the same throughout the year.

Table 1. Daily electricity demand for emergency needs for 1000 persons

Equipment	Electricity demand (kWh/day)
Water Purification	11
Lightning	3.35
Cooler	5
Mobile + computer	2.1
Satellite Mobile & Other equipment	10
Water Pumping	0.14
Total ≈	32

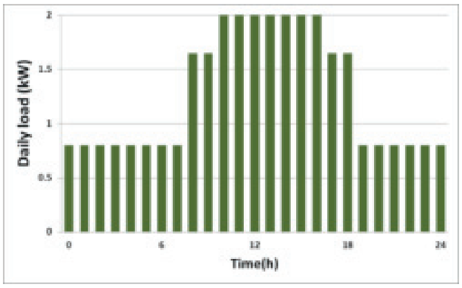

Fig.4. Daily load profile

4. Control Strategy

The control strategy has an important role in system operation [13]. A proper control system increases the power availability, system efficiency, battery life and the amount of power generation [14]. It also decreases the number of deficit hours, the engine operating hours and the amount of dumped power. Some other issues which must be considered in the control system are battery management, engine on/off cycling, maximum power point tracking of the available solar and wind energy, load management, quality of power during power generation and operation of different components [15].

In this paper, a rule-based algorithm is proposed and a block diagram of the control strategy is shown in Fig.5. The decision is based on the generated power, the load demand and the state of charge of the battery. Two parameters $\Delta E1$ and $\Delta E2$ are introduced in control strategy.

- $\Delta E1$= (PV power output + Wind power output – Load)
- $\Delta E2$= (PV power output + Wind power output + Engine generator power output– Load)

The first step is to determine whether the generated power by the wind turbine and the solar PV panels can cover the load or not ($\Delta E1>0$). If $\Delta E1> 0$ and the battery is not fully charged a command will send to the system in order to charge the battery. If the surplus power is more than the energy demand of a second water purification system (RO2) and the battery is fully charged, first the RO2 will be turned on and then the remaining excess power will be dumped. If $\Delta E1<0$ and the SOC_B is less than SOC_{min} two scenarios will be applied to the system:

a) If the deficit is less than 400 W, in order to decrease the load, the less necessary components will be turned off in three steps as it is shown in control strategy block diagram, Fig.5.
b) If the deficit is more than 400 W the engine starts to generate power. In this case if the surplus power ($\Delta E2$) is more than the energy demand of the RO2, it will be turned on and the remaining excess power will be dumped.

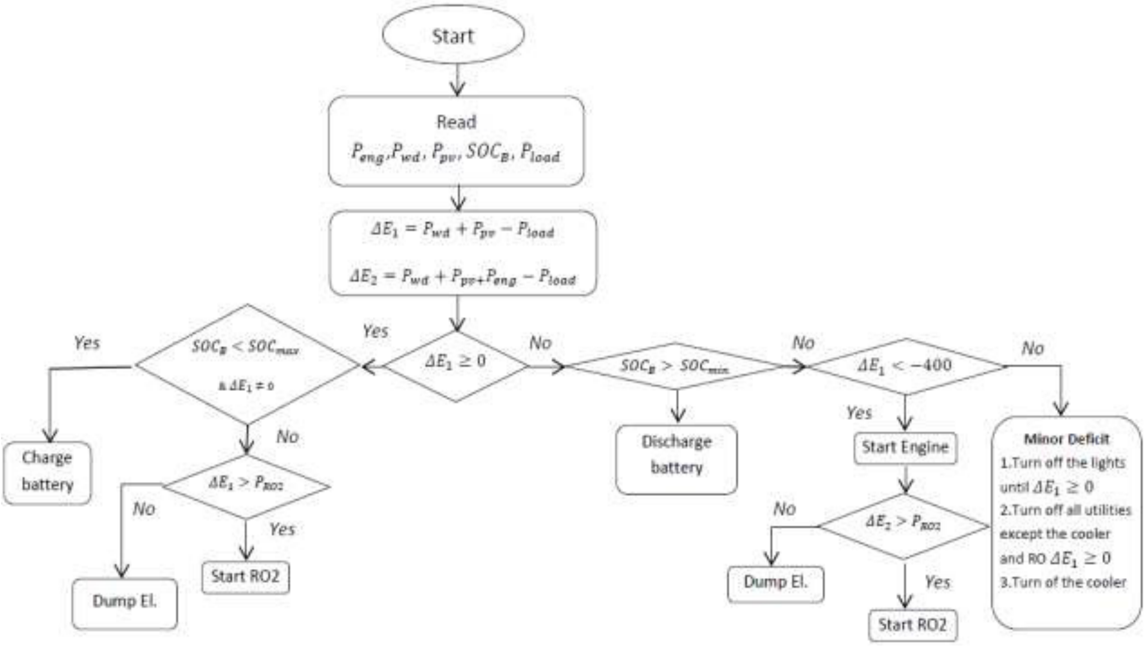

Fig.5.Control strategy block diagram

5. Model Result

In order to understand the system behavior, the operation of the system in two different cities is studied. Hourly solar irradiation and wind speed extracted from TRNSYS database are used for the model implementation during one-year operation. Nyala located in Sudan with solar irradiation (2330 kWh/m^2/year) and Nairobi located in Kenya with solar irradiation (1850 kWh/m^2/year) are selected as case studies. The reason of choosing these two locations is to provide a temporarily solution in case of human-made disaster situations such as war or natural disaster situations and the model does not provide a long term solution for normal daily life needs such as refugee camps. The average wind speed value is slightly higher in Nairobi. Hourly solar radiations and wind speed for these two cities are shown in Fig.6 and Fig.7 respectively.

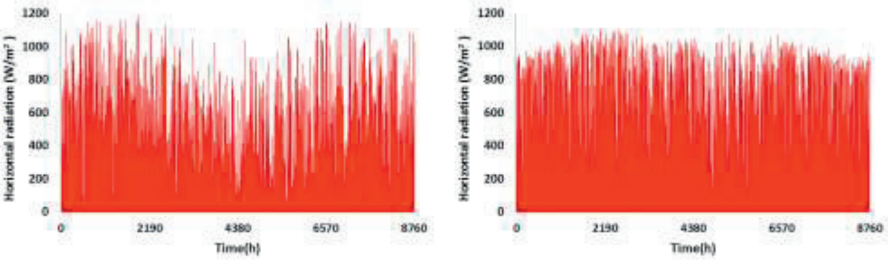

Fig.6.Global solar radiation on horizontal surface, Nairobi (left) and Nyala (right)

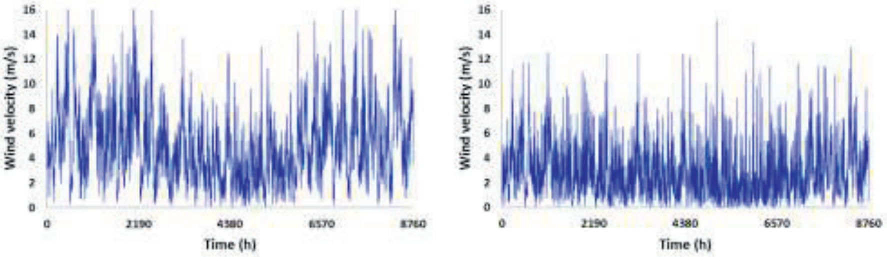

Fig.7.Wind velocity variation, Nairobi (left) and Nyala (right)

The amount of predicted power generation is written in Table 2 for each city and the share of each component in power generation and the power consumption flow are shown in Fig.8

Table 2. Predicted power generation in Nyala and Nairobi

Power Generation (kW/year)	Wind power output	Solar power output	Diesel generator set	Total
Nyala	1800	12300	1300	15400
Nairobi	4200	9600	1500	15200

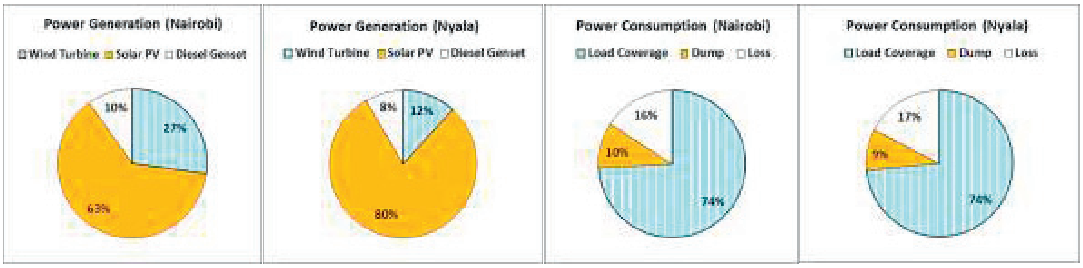

Fig.8. Share of each components in power generation (left); Power consumption flow (right)

As it is shown in Fig.8, the solar PV has the highest share (63% in Nairobi and 80% in Nyala) and the diesel engine has the lowest share in power generation (10% in Nairobi and 8% in Nyala). The share of the wind turbine is 27% and 12% in Nairobi and Nyala respectively. Due to the high solar insolation in both areas, the share of renewable energies in power generation is around 90% and diesel engine is only used for emergency situations. In both locations 74% of power generation is used, 9-10% is dumped due to excess power and 16% to 17% is lost through the different components especially in the battery bank.

These results show that for a geographical location with high solar insolation and an average wind speed, the share of the engine in power generation is relatively low. In this case, despite of using renewable fuel in the pellet-fired gas/engine, it should be considered as the second option for backup unit because of its complexity to run and control, safety issues and being a slow response system compared to the diesel engine. But in order to find the best system for backup and evaluate the system operation, a techno-economic optimization in combination with environmental issues and the share of the engine in power generation should be taken into account [16].

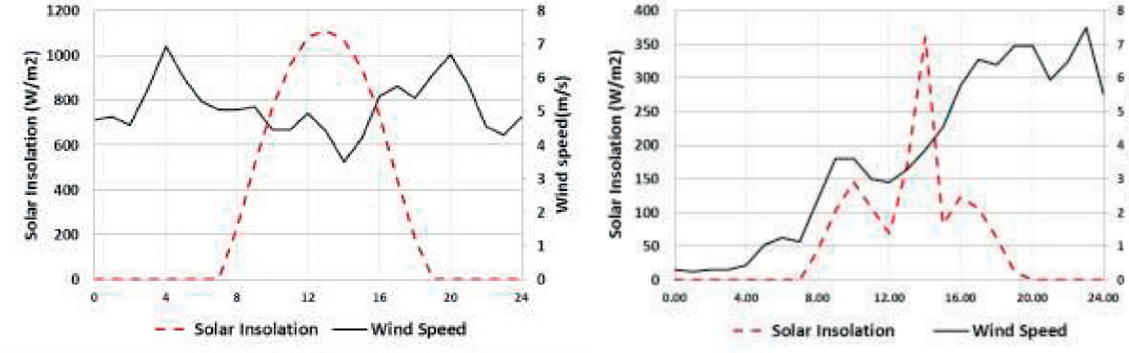

Fig.9. Solar insolation and wind speed for two selected days, September 22 (left) and July 21 (right) in Nairobi

To achieve better understanding of the system operation, two different days in Nairobi are chosen; July 21 with low solar insolation (1400 Wh/m^2/day) and an average wind speed (3.6 m/s) and September 22 with normal solar insolation (8100 Wh/m^2/day) and an average wind speed (5.2 m/s). It should be mentioned that the solar and wind energy availability, which are quiet low on July 21, is the extreme case scenario with low probability during the year. This condition is just investigated in order to analyze and improve the dispatch strategy and the system is not designed based on it.

The weather data are extracted from TRNSYS database for 24 hours and shown in Fig.9. Generated power by each component and the deficit or surplus power for these two days are illustrated in Fig.10 and Fig.11.

On September 22, the solar and wind energy are enough to cover the load demand and the diesel generator is off. There is a surplus power ($\Delta E1>0$) and the battery is in the charging mode during the day until SOC reaches SOC$_{max}$ as it is shown in Fig.12. The results show that the current system operates properly and the battery can cover the deficit of the power during the system operation.

On July 21, in contrast, there is a lack of energy ($\Delta E1<0$) and the battery discharges until it reaches the SOC$_{min.}$ As it is shown in Fig.11, the diesel generator is started to cover the demand load in this situation. Since the battery state of charge is low and the amount of deficit power is high, the share of power generation by diesel generator is high. In the first hours of the day when the demand is relatively low, the engine operates at partial load and by increasing the demand around 8:00 am in the morning it operates at rated power for some hours. Since the efficiency of the engine changes at different loads, this parameter should be considered in the control algorithm and the component design.

The battery status should be monitored and controlled during the system operation. Fig.12 demonstrates some valuable data regarding the battery operation. These data are necessary in order to spot the weakness of the system design or any mismatch in the system operation. The model results can be used for design evaluation and modification of the system which result in higher power availability, system reliability, better battery operation, lower amount of dumped electricity and higher amount of clean water production.

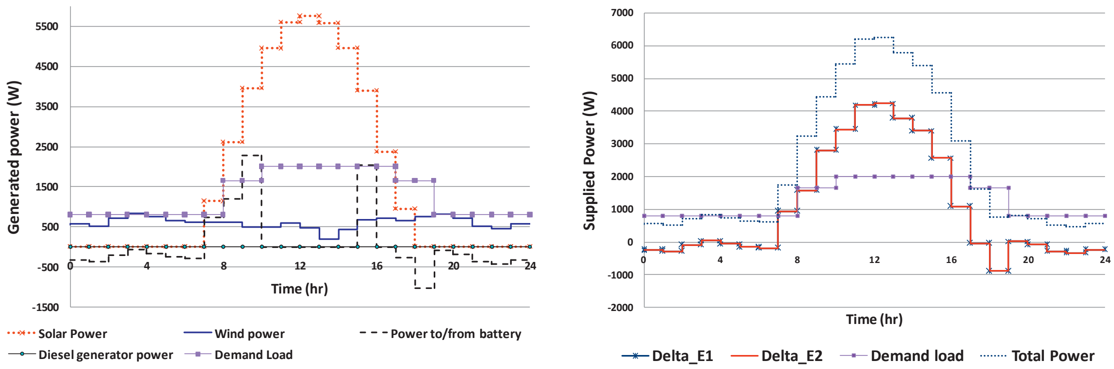

Fig.10. Generate power by solar PV, wind turbine, diesel generator and battery power (left) and supplied power (right) on September 22 in Nairobi

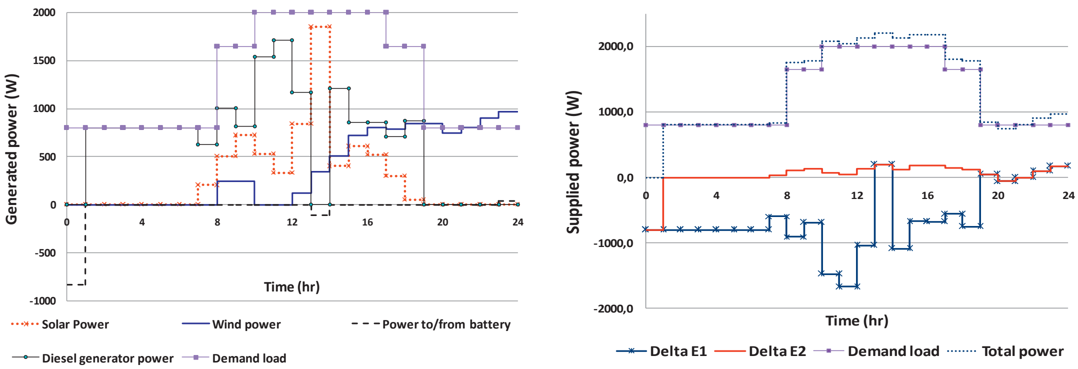

Fig.11. Generate power by solar PV, wind turbine, diesel generator and battery power (left) and supplied power (right) on July 21 in Nairobi

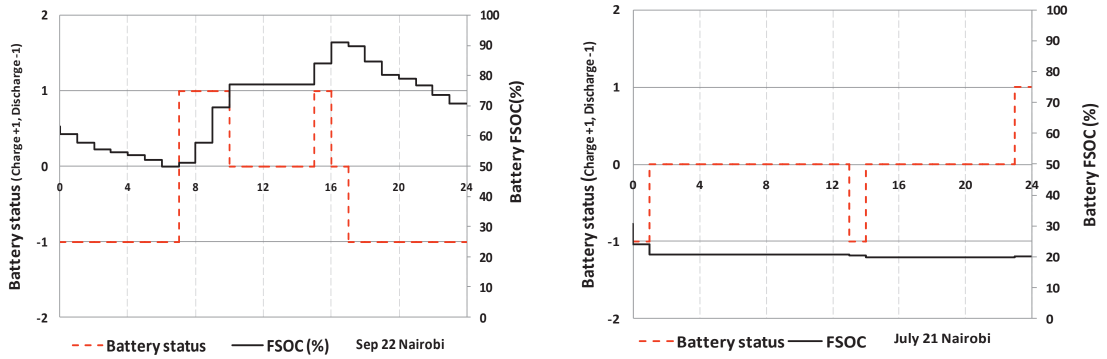

Fig.12. Fractional state of charge of the battery (FSOC) and battery status on September 22 (left) and July 21(right) in Nairobi

6. Conclusion and future work

In this study a hybrid system including wind/PV/engine with battery bank storage is presented as an energy solution for remote area. The focus of this work is on an emergency module which is a transportable container to provide drinkable water and electricity for disaster situations. The system is modeled with TRNSYS and its operation during one year for two geographical locations with relatively high solar insolation is analyzed.

The share of power generation by solar energy is 63% and 80% and the share of wind power is 27% and 12% in Nairobi and Nyala respectively during one year operation. It could be concluded that the share of the renewable energies is sufficiently high; therefore the diesel engine operating time is relatively low, result in lower environmental issues related to using only diesel engine which is a common solution in emergency situations.

The focus of the control strategy is to maximize the energy extraction from the wind and solar energy, to improve the battery performance and to use the surplus power in producing more clean water rather than dumping it.

System operation during 24 hours for two different weather conditions in Nairobi has been studied. The result emphasizes the importance of the power management in increasing the power availability, the amount of generated power without dumping the surplus power and protecting the battery from being over charged or discharged.

This work is considered as the first step of an ongoing project. The next step will be running the experimental setup to validate and modify the current model and techno-economic-environmental optimization for different geographical locations with different renewable local energy sources.

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