Optimal Design of Renewable Hybrid Power Supply Systems

Krzysztof Puczko
Delta Energy Systems (Poland) Ltd
Poleczki 23
PL-02-822 Warsaw
krzysztof.puczko@delta-es.com

Abstract— **A global climate warm up, rising costs of traditional fuels and constrains regarding nuclear power plants make renewable energy sources more and more interesting not only in regions with low grid availability but also in well developed countries. Renewable Hybrid Power Supply systems offer a possibility of optimized power generation for telecom networks as well as for local communities. This paper presents various architectures of hybrid power systems, related dimensioning methods and smart control logics. Experimental results from test hybrid site are presented and discussed.**

I. INTRODUCTION

In recent years telecommunication networks were built in well developed countries, in which electricity was available all around. Mobile base stations, repeaters as well as transmission nodes were usually powered form grid using rectifier systems with a battery backup. Depending on the location the backup time was in a range of 10 – 720 minutes. Today the networks are expanding to regions with low grid availability. In many areas more than 70% of mobile base stations are powered from local generators burning oil, gasoline or gas. Fig.1 shows a picture that represents a global electrification map.

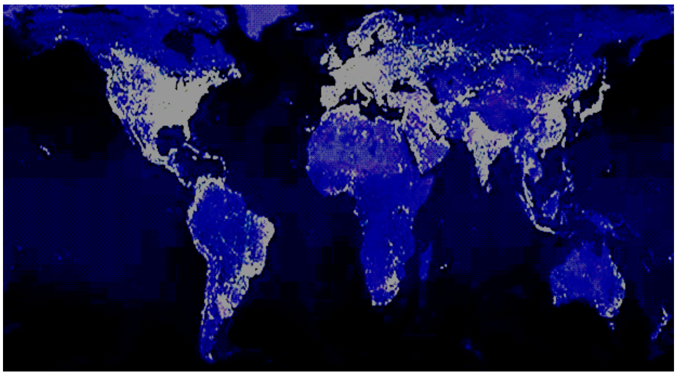


Fig.1 World electrification map (source NASA).

One can imagine what kind of challenges appear in front of telecom service providers, which want to deliver services to off-grid regions. Local communities with limited grid availability have difficult life, education and development conditions. Delivering electricity is essential for their civilization perspectives.

II. POWERING OFF-GRID SITES

A. Continous use of generators

Usually in off-grid regions electricity is delivered by generators which run all the time providing power to telecom installations. In many cases, the generators run at partial load level, which brings to low efficiency and high fuel consumption. Fuel delivery to remote sites and their maintenance services are often difficult and expensive. Typical gen-set efficiency curves [6] are shown in Fig.2. Nowadays, variable-speed generators are offered by vendors. They present better efficiency at low load level. Such generators, however, are not very popular yet. They are more expensive than standard (constant speed) generators and require more maintenance activities.

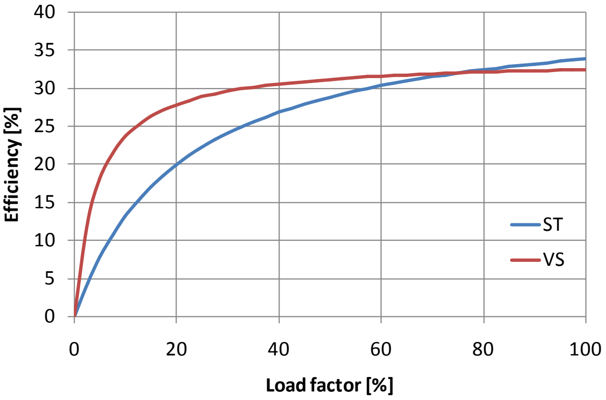
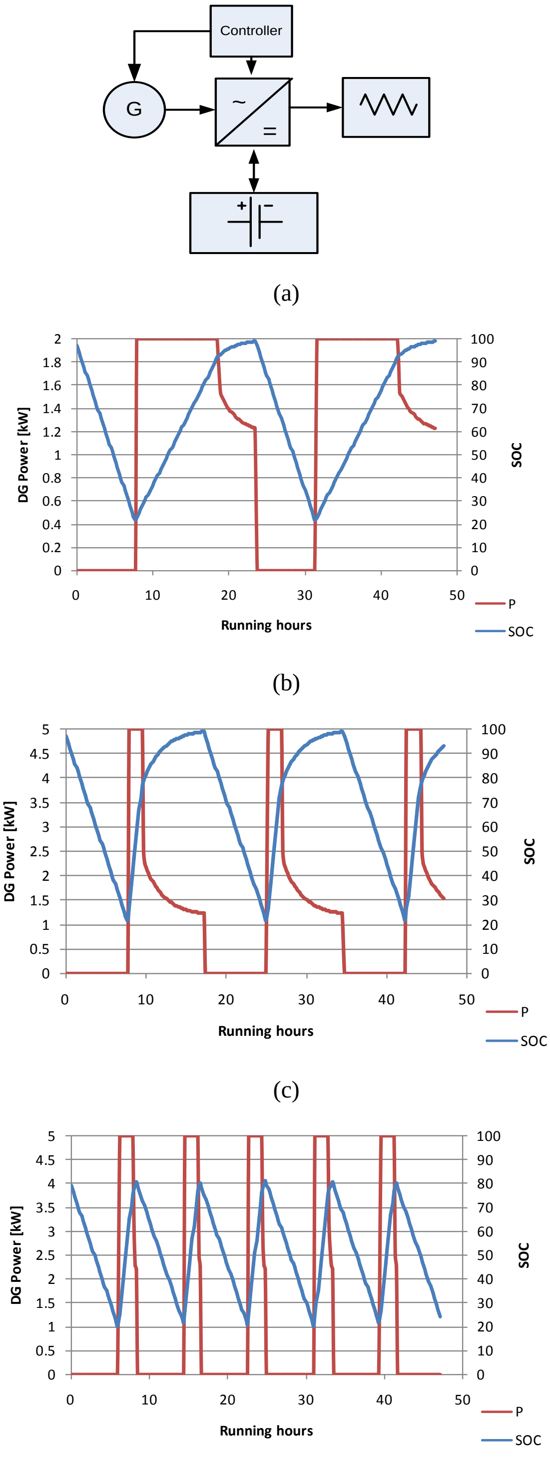


Fig.2. Typical diesel generator efficiency curves:
standard generator (ST) versus variable speed generator (VS).

B. Systems with battery cycling

The simplest way to improve generator efficiency is so called battery cycling system. This kind of system consists of a power generator, a rectifier system and a battery (See Fig.3a) The generator is runs at optimal load factor, charging the battery. As soon as the battery is full, the generator turns OFF and the battery is discharged by a load. Once the battery is discharged (to certain level) the generator is ON again. There are several parameters determining battery cycles in such systems: Depending on the relationship between generator power, load power, battery capacity it's assumed Depth of Discharge (DOD) and charge set point level the battery cycles may look different.

Exemplary cycling curves are shown in Fig. 3b, 3c and 3d. If the generator and rectifier system power (P_G) versus load power (P_L) is low, and the battery charge set point is close to 100%, the number of generator running hours is high. In addition, if the battery state of charge level (SOC) reaches 80%, the battery current is limited by the battery, resulting with lower generator load factor, lower efficiency and higher fuel consumption. (see Fig. 3b).



(a)

(b)

(c)

(d)

Fig.3. Simulations of cycles in hybrid system with gen-set and battery at different settings (load power = 1kW, battery 190 Ah):

(a) - block diagram; (b) – P_G=2kW, SOC_{MAX} =100%; (c) – P_G=5kW, SOC_{MAX} =100%; (d) - P_G=5kW, SOC_{MAX} =80%;

Increasing generator power to 5 kW results with shorter operating hours in the first phase of battery re-charging. (see Fig 3c). The situation may improve if the battery charge set point is reduced to 80% (see Fig. 3d). In that case, however, only part of the battery capacity is used.

Table I shows generator running hours, its fuel consumption, expected battery life time and generated electricity cost at different system configurations. Assumed system load was 1 kW and the battery capacity and its DOD level were 190 Ah and 80%, respectively. Two generator power levels were compared: 2 kW and 5 kW. The figures were calculated assuming fuel cost of 1USD/liter.

It is shown, that lower generator power brings to higher number of running hours but generated electricity is much cheaper. Unfortunately, low power generators are not popular yet in telecom applications. Using, 5 kW generator in cycling mode and adjusting the battery SOC set point to 80% may reduce fuel consumption by 32% and generated cost of electricity (COE) by almost 40%. To prolong the battery life time (which is quite short at 80% of DOD) it is recommended to boost the battery to full level periodically (e.g. once a week).

TABLE I. HYBRID SYSTEM PARAMETERS AT DIFFERENT SETTINGS

Genset power 2 kW				
SOC	Annual genset running hours	Annual fuel consumption [l]	COE [$/kWh]	Battery lifetime [years]
100 (*)	8,760	3,477	0.722	15
100	5,859	3,224	0.672	2.15
90	5,281	3,174	0.665	1.8
80	5,282	3,174	0.665	1.8
70	5,282	3,174	0.665	1.8
Genset power 5 kW				
SOC	Annual genset running hours	Annual fuel consumption [l]	COE [$/kWh]	Battery lifetime [years]
100 (*)	8,760	4,857	1.32	15
100	4,798	3,888	1.01	1.57
90	3,184	3493	0.882	1.12
80	2,394	3,302	0.819	0.99
70	2,159	3,243	0.901	0.94

(*) – Continuous generator running

C. *Batteries in hybrid applications.*

Telecom power supplies use batteries as backup energy sources. Usually the batteries work in “stand by” mode. When grid AC voltage is present, the battery remains fully charged and it is discharged only occasionally, during mains failures. Battery lifetime depends on the operating temperature and it may be as long as 10-15 years. Batteries in hybrid systems are used in cycling mode. Operating temperature is still a key factor but in that case the battery lifetime is determined by number of cycles and a depth of discharge (DOD). Battery vendors offer batteries, which are optimized for cycling operation. Exemplary data of Cycles to Failure (CTF) versus DOD level are shown in Fig.4.

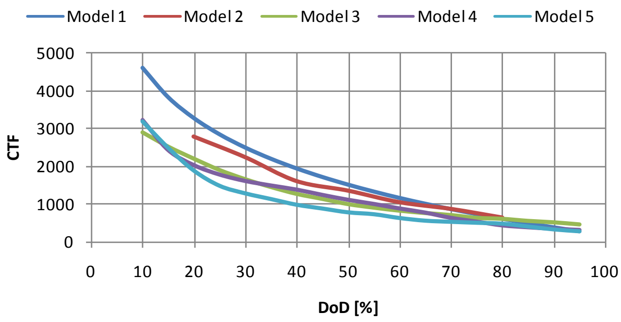


Fig.4. Cycles to Failure (CTF) versus Depth of Discharge (DOD) for different models of lead-acid batteries.

Deep discharge levels lead to shorter battery lifetime. Standard lead-acid batteries can survive for less than 300 cycles only. Batteries optimized for cycling operation may handle up to 1500 cycles. (at DoD =50%). Battery cycles in hybrid systems can be irregular. That is why it is not easy to predict real battery lifetime. Quite helpful in that case is so called *Lifetime Throughput* that represents a total amount of energy that can be cycled through the battery before it needs replacement. The DOD level can be optimized for each battery model in order to maximize amount of the energy taken from the battery over its lifetime, (see Fig5).

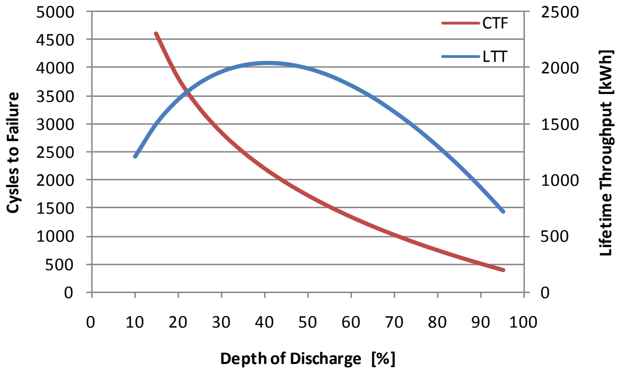


Fig.5. Cycles to Failure (CTF) and Lifetime Throughput (LTT) versus Depth of Discharge (Battery: SBS190F)

D. Solar and wind energy sources

Renewable energy sources are time, region and season-dependent. Solar energy resources are well documented. The solar irradiation statistics are available, e.g. from NASA and from Joint Research Centre of European Commission. Fig.6 shows daily solar irradiation in kWh/m^2 on optimally tilted surfaces in several locations. The closer to the equator, the lower seasonal changes of solar irradiation are observed. The highest daily values as well as annual average are observed in the Southern Pole (!). There is, however, a polar night for six months there and only few people remain in that region. Please note that the irradiation is not only an effect of sun position but also the weather. In Equator areas there is an overlaying effect with rainy season, which influences the irradiation. From sun position logic point of view, peak insulation is expected in +/- March and September, which is not the case for the Aug - Oct period.

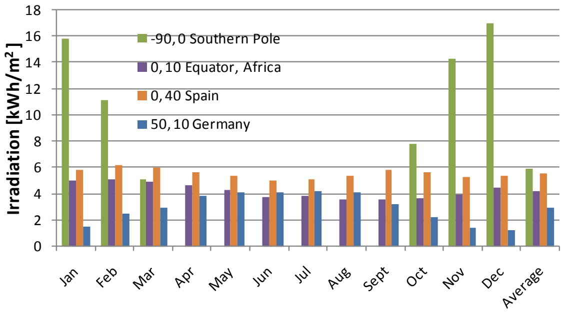


Fig. 6. Average daily sun irradiation in kWh/m^2 on optimally tilted surfaces.

Wind resources are documented not as good as solar resources. In principle, best wind conditions occur at sea coasts and in middle of oceans (see Fig 7). Regional wind maps are published by different organizations but long-term measurements are necessary to determine real wind conditions at dedicated location. Moreover, one can observe “good wind years” and “bad wind years”. That is why wind energy is less useful than solar energy in off grind locations.

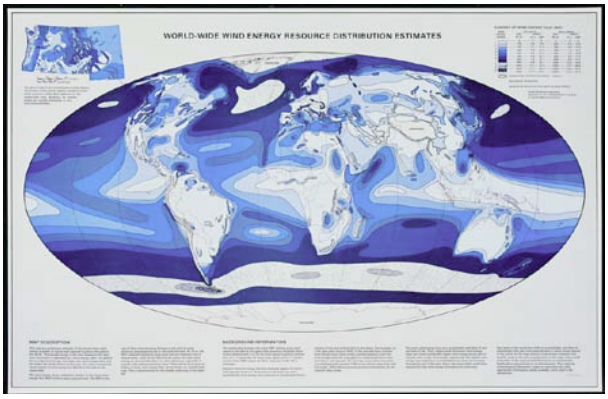


Fig. 7 World wind map (by US Department of Energy)

III. ENERGY SAVING – A KEY SUCCESS FACTOR

Electricity generated in off-grid hybrid systems is expensive. It is necessary to check all system components as well as loads, including: lighting, and all user equipment to look for possible energy savings before system final dimensioning is completed. Remote sites which are 24h guarded by humans may often need even 800W of additional power to feed lights and auxiliary equipment (see Table 2). Assuming that telecom equipment consumes 2 kW, a total power requirement would be 2,8 kW. In that case 28% of power is used for non-telecom loads (Case 1). By replacing standard devices by energy-saving products the total power can be reduced to 2.3 kW providing 18% of energy savings (Case 2). Such approach may have significant influence on power system dimensioning.

TABLE II. POWER CONSUMPTION ON AN EXEMPLARY SITE

Equipment	Power consumption [W]	Qty Case 1	Qty Case 2
Table fan	25	1	1
TV set LCD	200	1	
TV set LED	70		1
100 watt incandescent lamp	100	2	
100 Watt equivalent compact fluorescent lamp	30	3	
100 Watt equivalent LED lamp	12		5
Warning light standard	50	1	
Warning light LED	6		1
Refrigerater	60	1	1
PC	200	1	
Laptop	50		1
Telecom equipment	2000	1	1
TOTAL POWER		**2825**	**2271**

IV. THERMAL MANAGEMENT

Hybrid cooling is a combination of an Air Conditioner and a ventilation unit (see Fig.8). Depending on the geographical location and the system design, hybrid cooling may reduce the cooling power consumption by 30-85% in comparison to air conditioning because in such system the air conditioner operates only if the ambient temperature rises above the limit.

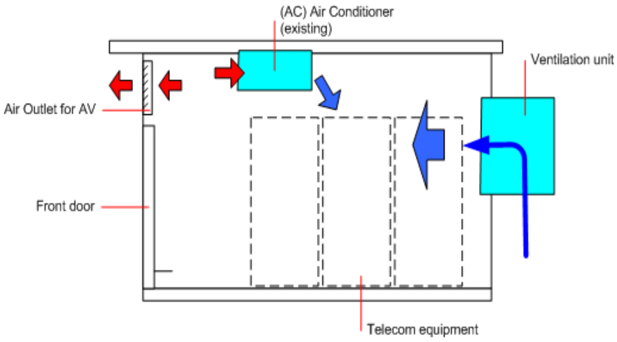


Fig.8. Telecom shelter with hybrid cooling.

Table 3 shows power consumption figures in typical telecom shelter with the size of 2000x1900x1900 mm, heat transfer coefficient of 13.5 W/K and 2 kW heat power generated inside located in two regions. It is shown that in Frankfurt, Germany cooling power consumption can be reduced by 85% and total power consumption by 14% while using hybrid cooling instead of air-conditioner. The same figures in the shelter located in Nairobi, Kenya are equal to 33% and 7%, respectively.

TABLE III. ANNUAL ENERGY CONSUMPTION IN SHELTERS WITH AIR-CONDITIONING AND HYBRID COOLING AT THE LOAD POWER OF 2 KW.

Description	Annual energy consumption [kWh]				
	Equipment	AirCon	Ventilation	Total cooling	Total All
Frankfurt, Germany					
Shelter with AirCon	17 520	3 402	0	3 402	20 922
Shelter with hybrid cooling	17 520	22	489	511	18 031
			Energy savings [kWh]	**2 891**	**2 891**
			Energy savings [%]	**85.0%**	**13.8%**
Nairobi, Kenya					
Shelter with AirCon	17 520	4 543	0	4 543	22 063
Shelter with hybrid cooling	17 520	1 948	1 088	3 036	20 556
			Energy savings [kWh]	**1 507**	**1 507**
			Energy savings [%]	**33.2%**	**6.8%**

V. RENEWABLE HYBRID SYSTEM – DESIGN EXAMPLE

A. *Assumptions*

As a design example a hybrid systems consisting of: Diesel Generator, Rectifier System, PV array and a Battery was taken into considerations. The system was placed in telecom shelter, located in Cyprus (N35^{o}41'; E34^{o}34'). The system block diagram is shown in Fig. 9.

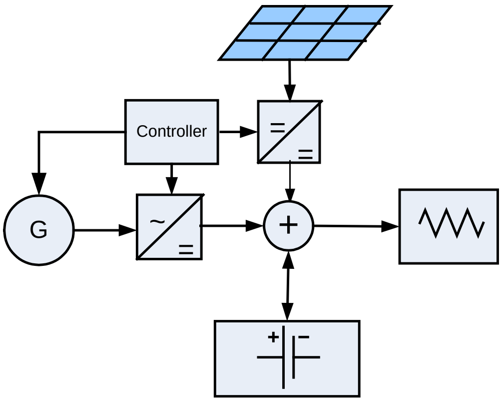


Fig. 9. Exemplary renewable hybrid system layout.

System dimensioning was done at the following assumptions:

(1) Load power: $P_L = 2\ kW$
(2) Heat power inside the shelter: $P_H = 2\ kW$;
(3) Shelter heat transfer coefficient : $U = 13\ W/K$
(4) Efficiency of an Air Conditioner (35/35): $\eta_{AC} = 4$;
(5) Gen-set power: $P_{DG} = 5\ kW$
(6) Required renewable energy fraction: $\zeta_R = 0{,}8$
(7) Efficiency of PV modules: $\eta_{PVM} = 0{,}14$
(8) Battery round trip efficiency: $\eta_{BAT} = 0{,}94$
(9) Solar charger efficiency: $\eta_{PVC} = 0{,}96$

The assumption (6) means that 80% of energy should be delivered from solar source.

B. *System dimensioning steps*

1. *Calculating total average load power*

Taking into account geographical location the following figures can be found in NASA database:

TABLE IV. CLIMATE DATA IN THE CONSIDERED LOCATION (CYPRUS)

Month	Air temperature [C]	Irradiation [kWh/m2]	Daylight hours
Jan	7.6	3.77	10.02
Feb	8.0	4.53	10.92
Mar	11.1	5.48	11.97
Apr	15.7	5.79	13.08
May	20.2	6.28	14.07
Jun	24.7	6.73	14.57
Jul	28.5	6.83	14.35
Aug	28.4	6.77	13.52
Sep	25.1	6.49	12.43
Oct	20.2	5.64	11.32
Nov	13.9	4.05	10.30
Dec	9.3	3.40	9.77
Ann	17.7	5.48	12.19

Using thermal simulations of the given system, the following energy consumption figures were obtained:

TABLE V. MONTHLY ENERGY CONSUMPTION OF THE GIVEN SYSTEM

Energy consumption [kWh]	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
Load	1 488	1 344	1 488	1 440	1 488	1 440	1 488	1 488	1 440	1 488	1 440	1 488	**17 520**
AirCon	281	255	298	314	353	373	416	415	376	355	305	290	**4 030**
Total	1 769	1 599	1 786	1 754	1 841	1 813	1 904	1 903	1 816	1 843	1 745	1 778	**21 550**

Average daily energy consumption of the system is: $E_d=59kWh$ that represents total average load power of:

$$P_{Ltot}= E_d /24h=2.46\ kW. \qquad (1)$$

2. Calculating required PV area

Taking into account required renewable energy fraction: $\zeta_R= 0.8$ daily energy production from PV plant is given as:

$$E_{DPV}=E_D*\zeta_R=47.2\ [kWh] \qquad (2)$$

In the given location, average daily irradiation is: $I_D= 5.48\ kWh/m^2$ Therefore, required PV plant is given by the equation:

$$A_{PV}= E_{DPV}/ (I_D* \eta_{PVM} * \eta_{PVC} * \eta_{BAT}) = 68.2\ [m^2] \quad (3)$$

3. Calculating optimal battery capacity.

In order to utilize all renewable energy from PV plant, the battery must be able to store the renewable energy, which is not directly consumed by the load during daylight hours. Assuming that generator does not recharge the battery but it is just feeding the loads during the night (so called *"load following strategy"*), generator running hours can be calculated as:

$$t_{DG}=E_D*(1- \zeta_R)/ P_{Ltot}=4.8[h] \qquad (4)$$

Average daylight in the given location is: $t_{DL}= 12.2h$ (see Table 4). Modeling sun irradiation as a part of sine wave a time when battery delivers energy to the load is estimated as:

$$t_{BAT}=24- t_{DL}- t_{DG}*\pi/2=11[h] \qquad (5)$$

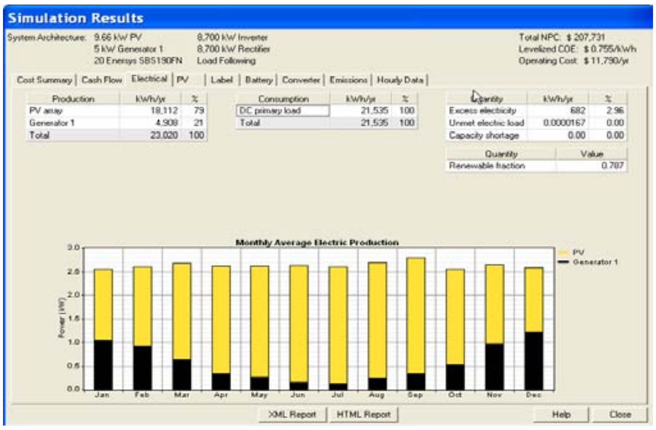
which is equivalent to the energy of:

$$E_{BAT}= P_{Ltot*}\ t_{BAT}/ \eta_{BAT} =28.8\ [kWh] \qquad (6)$$

Assuming that the battery DOD level is 80%, and average backup voltage is 48V, the required battery capacity is 750 [Ah]. That capacity should be increased by the coefficient of 1.25 to assure enough space for PV energy during best moths (July), when the sun irradiation is 25% higher than annual average.

C. Modeling of the system operation

The operation of the given system was simulated using a HOMER tool [3]. A solar array with 9.66 kW peak power (42 modules, 230W, 1.62 m^2 each) was taken into considerations. Five strings of SBS190F batteries (950 Ah total capacity) were considered as a battery bank. The simulation results were in line with the above calculations (see Fig. 10). In practice, different design criteria can be taken into account such as: CAPEX limitations, space limitations, desired OPEX reduction, etc. In many cases the most important criteria for system dimensioning is so called *Total Cost of Ownership* (TCO) over the project lifetime. Minimizing TCO indicator brings to best investment structure and determines the system dimensioning.



System Architecture: 9.66 kW PV
5 kW Generator 1
20 Enersys SBS190FN
8,700 kW Inverter
8,700 kW Rectifier
Load Following

Total NPC: $ 207,731
Levelized COE: $ 0.755/kWh
Operating Cost: $ 11,790/yr

Production	kWh/yr	%
PV array	18,112	79
Generator 1	4,908	21
Total	23,020	100

Consumption	kWh/yr	%
DC primary load	21,535	100
Total	21,535	100

Quantity	kWh/yr	%
Excess electricity	682	2.96
Unmet electric load	0.0000167	0.00
Capacity shortage	0.00	0.00

Quantity	Value
Renewable fraction	0.787

Fig.10. Simulation results of the considered system.

VI. SMART SYSTEM CONTROL

Smart system control logic is required in hybrid systems for battery management and best utilization of all energy sources. Different control strategies are possible in hybrid systems:

A. Load Following

Under the *Load-Following* strategy, a generator produces only enough power to serve the load, and does not charge the battery bank. The battery is charged from solar or wind charger only (or grid, if available). This kind of strategy is used mostly in grid-tied systems. In off-grid systems variable-speed generators are recommended while using load following strategy.

B. Cycle-Charging

Under the *Cycle-Charging* strategy, whenever a generator operates, it runs at its maximum rated capacity (or as close as possible without incurring excess electricity) and charges the battery bank with the excess. Applying this kind of strategy may require optimization of State of Charge set point to reduce fuel consumption. Charging the battery to its full capacity is applied periodically, but not at every cycle.

C. .Micro Cycling

This strategy is similar to *Load Following* one. The generator starts if the battery State of Charge (SOC) crosses minimal level but it runs for in short intervals, keeping the SOC at the same level. The battery is re-charged from solar or wind charger only. Charging the battery to its full capacity is applied periodically if there are not enough renewable sources available for longer periods.

VII. EXPERIMENTAL RESULTS

An experimental hybrid system was established and tested over several months. A photo of the test system is shown in Fig 11. The system consists of: high-efficiency rectifier shelf, 4,6 kW$_{pp}$ solar plant, solar chargers, 1kW wind turbine, wind charger and 380 Ah battery bank. System components are placed in two outdoor cabinets. The first cabinet contains rectifier system, solar chargers and battery bank. The cabinet is cooled by fans and TEC module. The second cabinet is dedicated for a dummy load of 3,6Ω/1kW. That cabinet is equipped with fans and air conditioner (hybrid cooling).

Fig.11 Test hybrid system in Bern

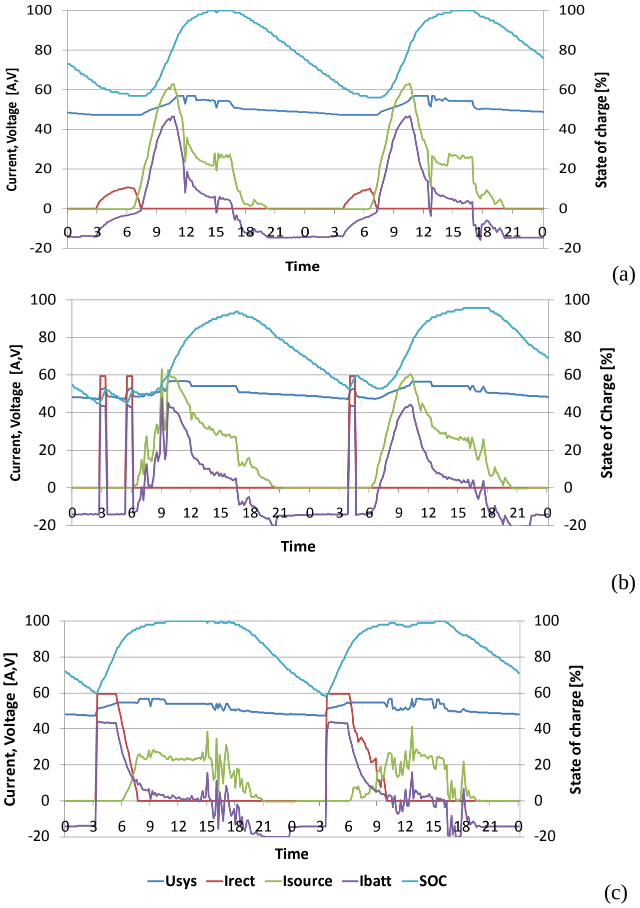


Fig.12. Test system waveforms at different control strategies.
(a) - load following; (b) - micro cycling; (c) - cycle charging

All important data coming from continuous measurements were recorded and analyzed. Different system control strategies were tested. Corresponding waveforms are shown in Fig. 12. Table VI compares energy delivered to the load from rectifier system, renewable sources and the battery at different control strategies.

The *Load Following* strategy (Fig.12a) gives best utilization of solar energy, while *Cycle Charging* strategy (Fig 12c) limits solar power because the battery can’t absorb proper amount of solar energy during daylight hours.

Micro Cycling strategy (Fig.12b) gives results, which are comparable to *Load Following* strategy.

TABLE VI. COMPARISION OF DIFFERENT CONTROL STRATEGIES

Control Strategy	Eload [kWh]	Erect [kWh]	Ebatt [kWh]	Esource [kWh]
Load following	100%	9%	47%	91%
Cycle charging	100%	52%	35%	48%
Micro cycling	100%	17%	51%	83%

VIII. CONCLUSIONS

The experimental results were in a good agreement with theoretical calculations and brought to interesting conclusions. In the period of January to June 2011 renewable sources delivered 61% of total energy consumed by the load in comparison to the value of 66% that was assumed. Wind power was below expectations due to weak wind conditions in the test location. It was shown that *Load Following* strategy gives best utilization of renewable energy sources. That kind of control logic can be used in grid-tied systems. In systems, which are not connected to grid but they use local generators, the *Micro-Cycling* strategy is recommended.

The tests are running continuously and all data are recorded with the site management controller PSC 3 with its integrated high performance energy log functionality. The convenient extraction of large amount of record data with XML file transfer via LAN or GPRS from the site to the office, allows accurate benchmark of the results to enhance the operating modes of the hybrid systems.

REFERENCES

[1] Wang, D. H.; Nayar, C. V.; Wang, C. “Modeling of stand-alone variable speed diesel generator using doubly-fed induction generator”, Power Electronics for Distributed Generation Systems (PEDG), 2010 2nd IEEE International Symposium.
[2] C. D. Barley and C. B.Winn, “Optimal dispatch strategy in remote hybrid power systems” Solar Energy, Vol. 58, pp. 165–179, 1996.
[3] Lambert, T; Gilman, P; Lilienthal, P. “Micropower System Modeling with Homer” U.S. National Renewable Energy Laboratory.
[4] http://eosweb.larc.nasa.gov
[5] http://re.jrc.ec.europa.eu/pvgis/
[6] Johannes Hübner Giessen, BR Energie Systeme v1.5, p.10