Evaluation of the environmental aspects to operate off-grid, stand-alone telecommunication systems

A comparison of greenhouse gas emissions of autonomous hybrid systems compared with a conventional diesel generating set

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Abstract— **The production of electricity through renewable energies has gained importance in the last years. Especially the incidence of Fukushima shows that mankind has to fight its dependence on fossil fuels in order to save the environment. Also smaller energy generation systems have to be considered.**

I. INTRODUCTION

Through the deployment of telecommunication infrastructure into emerging markets with only limited access to public grid, stand-alone off-grid power supply systems play a major role for powering the telecom sites.

So far, the installations of stand-alone power solutions have been done by usage of diesel generators. Because of rising fuel costs and significant operating costs for refilling of fuel as well as price erosions of solar panels, more and more photovoltaic supported telecom sites are being installed. Due to significant savings in the operating cost and an attractive payback time, these solutions became very beneficial recently.

But we have to ask ourselves, if regenerative power supply systems are really such environmental friendly as they look like. What is the environmental impact of using the semiconductor elements; silicon based PV modules with high-energy expenditure and the application of additional batteries and reduced lifetime due to cycling of them?

This paper assesses and compares the environmental impact of a photovoltaic hybrid powered and a diesel generator powered site. The aim is to inspect and compare the released environmental emissions of both powering concepts over a life cycle of 25 years. The purpose of this paper is to answer the questions "How green are photovoltaic power solutions in telecommunication industry?" and "How many years it takes until a photovoltaic power solutions will operate greener than traditional power solutions?".

For this reason the greenhouse- and acidification potential will be taken into the inventory and the cumulated energy consumption for the production of both power concepts will be calculated. For the assessment of the environmental impacts the factors raw material extraction, resource availability and recycling will be evaluated. The final part of this paper will compare both powering concepts and their ecologically aspects. For this case a real project in Togo/Africa has been selected to compare the results.

The paper is structured according to following topics

- Description and definition of the two power systems architectures
- Environmental emission life cycle analysis of both powering concepts
  a) through manufacturing of the components
  b) through installation and operations
  c) through recycling after EOL
- Comparison and evaluation of the results
- Discussion of the results
- Conclusion

II. DEFINITION OF THE TWO POWER SYSTEM ARCHITECTURES

For the study, traditional power system architecture has been selected for the benchmark of the environmental aspects in comparison with photovoltaic hybrid power system architecture. In this paper we use the following abbreviations:

- "Diesel PS" stands for the traditional power architecture with a diesel generator.
- "PV-hybrid PS" stands for the photovoltaic hybrid power architecture with diesel generator support.

A. *Introduction of the "Diesel PS"*

Currently, the majority of stand-alone off-grid telecommunication systems are supplied by diesel or gasoline generators. To achieve an optimum efficiency the sizing of the diesel generator should be selected to achieve around 75% of loading of its nominal rating during continuous operation. Sometimes the generator is not selected carefully and results in an oversized solution, which makes the diesel generator to operate at an even more poor efficiency. In such installations the power architecture is typically operating in a cycling mode by combining the alternative supply from diesel generator and from batteries. This has a direct impact on battery capacity, reduced battery lifetime and additional energy losses in the battery cycling process.

The Diesel PS power architecture (Figure 1.) consist of the following building blocks:

- Diesel generator
- Telecom power system containing rectifiers, controller, power distribution
- Batteries

Typically the power system and batteries are installed in outdoor cabinets, small shelters or small buildings.

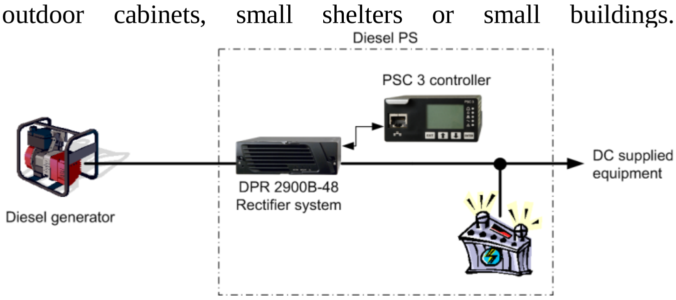

Figure 1. Diesel PS architecture

B. Introduction of the “PV-hybrid PS”

This power architecture combines different power sources, which leads to the terminology “hybrid”. In this case, the combination of photovoltaic power source and diesel generator power source are combined. As telecommunication infrastructure require a high availability of the telecommunication services, the combination of various energy sources brings a great value, because it is not necessary to over dimension the photovoltaic installation and the batteries to cover all extreme weather conditions which are hard to predict and which happen relative seldom. In such case the diesel generator takes the role to supply the energy to cover the lack of photovoltaic energy during extreme conditions of consecutively following cloudy days.

The PV-hybrid PS power architecture (Figure 2.) consist of the following building blocks:

- PV (Photovoltaic) panels
- Installation frames for photovoltaic installation
- Junction box to combine supply cables from PV panels and host lightning protection elements
- Diesel generator
- Telecom power system containing rectifiers, photovoltaic chargers, controller, power distribution
- Batteries

Typically the power system and batteries are installed in outdoor cabinets, small shelters or small buildings.

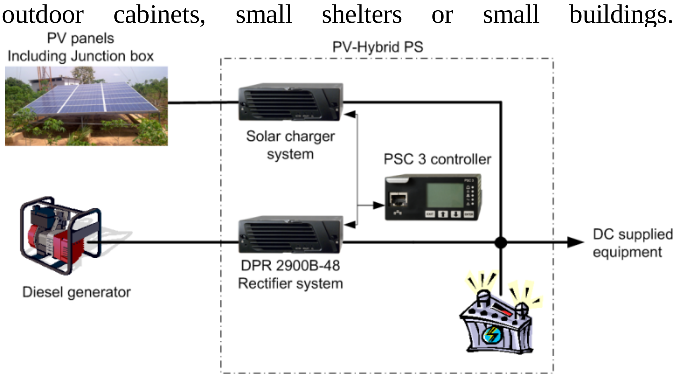

Figure 2. PV-hybrid PS architecture

C. Difference between both power architectures

The PV-hybrid PS (section A) contains just additional elements compared to the Diesel PS (section B). The additional components are the PV (Photovoltaic) panels, open area installation kit for photovoltaic installation, junction box to combine supply cables from PV panels and host lightning protection elements and the PV chargers. The common elements for both powering architecture are the diesel generator, telecom power system containing rectifiers, controller, power distribution and the batteries.

D. Introduction into the Togo / Africa case

The selected telecommunication site (Figure 3.) for this study is located in Togo / Africa. This site has a daily energy consumption of 40.8 kWh, which represents an average load of 1.7 kW. From the available statistic data [11], the annual horizontal average solar irradiation in this location is 5.1 kWh/m^2/day. Due to the seasonal variations the month with least expected average solar irradiation is 4.05 kWh/m^2/day.

Month	kWh/m^{2}d	no sun days
Jan	5,48	1,35
Feb	5,78	1,59
Mrz	5,73	1,83
Apr	5,58	1,77
Mai	5,3	3,86
Jun	4,74	2,53
Jul	4,28	3,18
Aug	4,05	3,58
Sep	4,37	2,88
Okt	4,97	3,43
Nov	5,24	1,83
Dez	5,34	1,16

TABLE I. MONTHLY SOLAR IRRADIATION IN TOGO

The battery backup system is 48 V based and equipped with 1000 Ah battery capacity. The photovoltaic system is equipped with 53 panels with a total peak power capacity of 12.2 kWp.

This case result in a significant contribution of solar energy and result in an expected OPEX (operating expense) reduction of 60% compared to the traditional Diesel PS architecture described in section II / A.

At night, the site is powered by the batteries. If the batteries reach a specified low charge level, the generator starts to power the site and only maintains (keeping) the battery charge level. The next day with good weather condition, the photovoltaic system will recharges the batteries and powers the telecommunication infrastructure.

Figure 3. PV-hybrid PS installation in Togo

III. LIFECYCLE ANALYSIS

A. *Introduction*

For this case study, a lifetime of 25 years has been defined for analyzing the environmental aspects. Typically telecommunication sites are long term investments and the basic infrastructure provides long lifetime. This value is selected equal to the performance guarantee for photovoltaic modules. All other components in the system are designed accordingly except the lifetime of the batteries which is limited to 3 years only due to cycling and thermal conditions. Also the involved electronics lifetime is limited to 15 years life only (rectifiers, controller, ..). This means batteries will be replaced every 3 years and electronics will be replaced every 15 years for this case study and will contribute to the environmental factors accordingly. The accounting of emissions and energy consumption includes all processes of production and operation. The accounting of production is calculated by using the cumulated energy consumption (section III/B). Finally, the recycling and reprocessing is considered. Not included in the study is the transport from the production of the components to the place of application and the installation process.

B. *Environmental relevant substances*

Two categories of substances are relevant to quantify the environmental aspects:

- "SO_2 equivalents": The quantitative expression of the acidification potential is expressed in the SO_2 equivalents. In addition to SO_2 other air pollutants are also included in the "SO_2 equivalents" like nitrogen oxide (NO_x), hydrogen chloride (HCl), hydrogen fluoride (HF), ammonia (NH_3) and hydrogen sulfide (H_2S).
- "CO_2 equivalents": The quantitative expression of the global warming potential is expressed in CO_2 equivalents. In addition to CO_2 other air pollutants are also included in the CO_2 equivalents like methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbon (CFC), haloalkane, sulfur hexafluoride (SF_6), nitrogen trifluoride (NF_3) and tetrafluoroethane.

Those substances are emitted during the manufacturing and recycling process due to the need of energy. The emissions during operation are reflected in the usage of energy from the diesel.

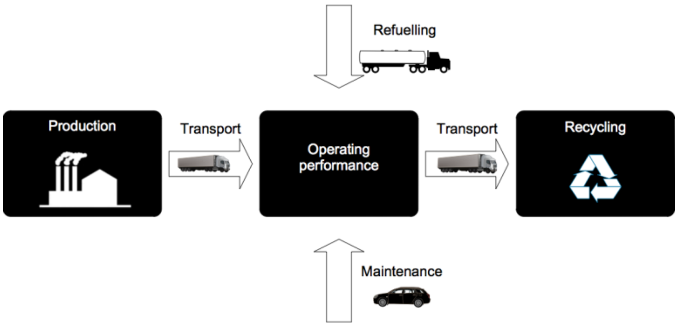

Figure 4. Process stages at the life cycle

Figure 4. shows the split of the individual steps for analysis based on the life cycle scenario.

C. *Production*

1) *Cumulated energy consumption (CEC)*

The cumulated energy consumption CEC summarizes all of the primary energy of upstream process chain to manufacture the components used for the related power architecture. The energy for disposal is not included in the cumulated energy consumption.

To calculate the CEC in this study, the material balance analysis method is applied. In this method all components are split into their ingredients (primary material) and then multiplying with the specific CEC of the individual material. The equation, constitutes the facts for the calculation of the production

$$CEC_P = \sum_{materials} (cec_{material} \cdot m_{material}) \cdot M_F$$

CEC_P: Cumulated energy consumptions for the production in kWh

$cec_{material}$: Specific cumulated energy consumptions for a certain material in kWh

$m_{material}$: Mass of material in kg

M_F: Factor for the manufacturing process

For each material, the specific cumulated energy consumption $cec_{material}$ and the factor for the manufacturing process M_F are taken from the GEMIS database [1]. By using the database GEMIS [1] and the deposit material balances, the specific energy consumption and specific CO_2 and SO_2 equivalents of the individual components can be calculated.

The CEC is summed up for each region of origin of the components individually, to be able to further calculate the emissions for the production process.

2) Production location

The location of production of the individual components has a direct relation with the emissions in the production process, because the energy mix for the electricity is different for each region. The energy mix for the different origin of the components has been taken from [19], [20], [21]

	Greenhouse gas				Airborne pollutants			
Country	SO_2-eq. g/kWh	SO2 g/kWh	NO_x g/kWh	Dust g/kWh	CO_2-eq. g/kWh	CO_2 g/kWh	CH_4 g/kWh	N_2O g/kWh
EU-27	1,5	0,8	1	0,09	465	440	0,8	0,02
China	8,2	6,1	3,02	1,17	813	697	4,68	0,03
German	0,9	0,4	0,6	0,04	644	618	0,8	0,02

TABLE II. OVERVIEW OF EMISSIONS BASED ON DIFFERENT ENERGY MIX

The origin of the electronic components such as rectifiers, PV charger, controller and in addition the PV chargers and the PV panels is China. The origin of the power system cabinet, the open area installation frames and cables origin is Slovakia and therefore the EU-27 energy mix model has been applied. The origin of the heavy diesel generator is Germany.

3) Lifetime model

Some components in the power system have limited operating lifetime, because of its usage in the application and the ambient conditions. The batteries have a limited operating lifetime due to the cycling usage. Typically the cycling of the batteries in PV-Hybrid PS is more than in the Diesel PS and therefore this has been taken in account in this study with different lifetime models for each of the powering concepts. Electronic components such as rectifier, PV charger and controller are also not intended to remain in operation more than 15 years. Those components need to be exchanged over the expected operating time of the installation. TABLE III. list the components that need to be exchanged over the life cycle of the hybrid system. Those components will be taken in account in the CEC calculation described in section III / C / 1).

Components	Estimated lifetime	Exchange over operating time
Batteries in Diesel PS	5 Years	5 times
Batteries in PV-Hybrid PS	3 Years	8 times
PV-charger	15 Years	1 time
Rectifiers	15 Years	1 time
Controller	15 Years	1 time

TABLE III. OVERVIEW COMPONENTS WITH LIMITED LIFETIME

4) Results of the environmental emissions for the production

By summarizing the individual energy consumptions and the related total emissions it is possible to rate the entire emissions for the production of the system components.

TABLE IV. gives an overview for the Diesel PS about the calculated CEC and the related CO2 and SO2 equivalents for the individual components. TABLE V. gives an overview for the Diesel PS about the calculated CEC and the related CO2 and SO2 equivalents for the individual components

Components	CEC in kWh_{PRIM}	SO_2-equivalents in g	CO_2-equivalents in g
Generator	5564	4327	1321210
Batteries	14010	291417	6439578
Rectifier	176	1717	66076
Controller	17	157	6039
Cable materials	973	1366	327220
Total	20740	298984	8160123

TABLE IV. SUMMARY OF EMISSIONS FOR THE DIESEL PS

Components	CEC in kWh_{prim}	SO_2-equivalents in g	CO_2-equivalents in g
Photovoltaic	64864	538371	11350310
Generator	5564	4327	1321210
Batteries	22416	466267	10303324
PV-charger	847	915	245916
Rectifiers	176	1717	66076
Controller	17	157	6039
Cable material	10038	13888	2767343
Open area installation	18226	14118	4247561
Total	122149	1039760	30307780

TABLE V. SUMMARY OF EMISSIONS FOR THE PV-HYBRID PS

These emissions from production are treated as bias in the overall break even calculation in section IV.E

D. Operation

The operation of both powering concepts is structured into following individual categories for the analysis of the environmental emissions:

- Direct diesel generator operation
- Maintenance trips to service the components
- Fuel refilling process

1) Operation of the Diesel PS

In the Diesel PS powering concept, the diesel generator is operating with a 24 h / 365 days powering concept, which provides the best energy efficiency in case the optimum diesel generator size is selected. In this operating mode, the battery lifetime is better compared to a cycling operating model. Due to that this operating model has been chosen for this study.

Consumption diesel generator		
Power rating	6,8	kW
Fuel Consumption 25% loading	1,4	l/h
Diesel fuel specific gravity	0,85	kg/m3
Operating hours a year	8760	h
Annual consumption prime	13490	l
Resulting annual CO2 equivalent	41073,6	kg
Resulting annual SO2 equivalent	460,9	kg

TABLE VI. GENERATOR OPERATING DATA FOR THE DIESEL PS

2) *Operation of the PV-Hybrid PS*

The hybrid system has been designed that the diesel generator is used as a backup to cover exceptional conditions only. Also in August, the month with the lowest solar radiation in Togo, the PV generator delivers enough energy to guarantee the supply of the load. Excluded are days on which are not expected any solar radiation or only very low radiation. To minimize the investment cost, these days must be supplied with energy by a generator. TABLE VII. provide an overview about the operating data of the generator for the PV-Hybrid PS.

Consumption of the diesel generator		
Power rating	6,8	kW
Fuel Consumption 25% loading	1,4	l/h
Diesel fuel specific gravity	0,85	kg/m^3
Operating hours a year	956	h
Annual diesel consumption	1472	l
Resulting annual CO2 equivalent	4501,2	kg
Resulting annual SO2 equivalent	50,5	kg

TABLE VII. GENERATOR OPERATING DATA FOR THE PV-HYBRID PS

3) *Maintenance*

To guarantee a long-term operation for the period of 25 years, regular service and fuel delivery are essential. Through the distance of 100 km to the nearest service center in Lomé / Togo, the operating hours of the generator has been minimized in the PV-Hybrid PS, which results in a minimized need for service of the diesel generator.

Diesel generator requires service after 500 operating hours. Referring to annual operating hours from TABLE VI. 18 trips are required annually for the Diesel PS. Referring to annual operating hours from TABLE VII. 3 trips are required annually for the PV-Hybrid PS.

For the diesel refill process, the base of a 3500 liter fuel tank has been considered in the study, which results in 4 times site access for the fuel refilling of the Diesel PS and in 1 time refill process for the PV-Hybrid PS.

The resulting annual emissions through service intervals and refueling are summarized in TABLE VIII. to TABLE XI.

Emissions passenger car (maintenance)	CO g	$HC+NO_X$ g	NO_X g	Particulate mass g	CO_2-eq. g	SO_2-eq. in g
Round trip	100	60	50	5	68000	42
Per year	1800	1080	900	90	1224000	752
Over 25 years	45000	27000	22500	2250	30600000	18792

TABLE VIII. EMISSIONS FOR THE DIESEL PS FOR SERVICE

Emissions passenger car (maintenance)	CO g	$HC+NO_X$ g	NO_X g	Particulate mass g	CO_2-eq. g	SO_2-eq. g
Round trip	100	60	50	5	68000	41,76
Per year	300	180	150	15	204000	125,28
Over 25 years	7500	4500	3750	375	5100000	3132

TABLE IX. EMISSIONS FOR THE PV-HYBRID PS FOR SERVICE

Emissions truck (refueling)	CO g	HC g	NO_X g	Methane g	Particulate mass g	CO_2-eq. g	SO_2-eq. g
Round trip	640	88	320	104	3,2	105600	284
Per year	2560	352	1280	416	12,8	422400	1136
Over 25 years	64000	8800	32000	10400	320	10560000	28397

TABLE X. EMISSIONS FOR THE DIESEL PS FOR FUEL REFILLING

Emissions truck (refueling)	CO g	HC g	NO_X g	Methane g	Particulate mass g	CO_2-eq. g	SO_2-eq. g
Round trip	640	88	320	104	3,2	105600	284
Per year	640	88	320	104	3,2	105600	284
Over 25 years	16000	2200	8000	2600	80	2640000	7099

TABLE XI. EMISSIONS FOR THE PV-HYBRID PS FOR FUEL REFILLING

E. *Recycling*

Most of the materials such as steel, copper, aluminum, plastics from both power architectures can be recycled, which means the material can be reused and less primary energy and natural resources are needed to create new products with the recycled material. The energy needed and the related emissions are much smaller than producing primary materials. Due to that fact, the energy and emissions for the recycling process are neglected in this study. Most of the materials such as steel, aluminum, plastics can be typically re-used locally as a secondary material and the return transport would consume much more energy and create more emissions than the recycling process itself.

IV. THE COMPARISION AND EVALUATION OF THE RESULTS

The aim of this chapter is to present the results and the comparison of the two system concepts. The results are evaluated individually for each process (resource availability, production, operation and recycling). The focus is on the emissions caused during the whole life cycle.

A. *Comparison of resource availability*

In general all resources are very valuable and finally all elements are exhaustible. The lower the deposits of resources, the more complex is the mining or harbesting. This results in negative environmental aspects and side effects, such as rising costs and sustainability. Therefore, resources should be sparingly used.

In comparison, the PV-hybrid PS requires more resources for manufacturing due to the photovoltaic components and material required for the open area installation. The biggest difference between both powering architecture from raw material point of view, is the significantly greater usage of silicon in the PV-Hybrid PS due to the solar cells in the panels. The additional use of silicon is unproblematic, because of huge deposits of raw materials on our planet. However the use of aluminum is critically assessed due to its high primary energy input, and high impact on CO2 equivalent emissions . Through the additional use of copper in the PV-Hybrid PS for the long connecting cables, the impact on the ecological balance is negative. Connecting photovoltaic panels in series to increase the voltage, reducing the currents will support solutions with better ecological balance.

B. *Comparision of the cumulated energy consumption CEC*

GEMIS database [1] does not list all specific data from the material inventory. To avoid gaps in the CEC calculation, data from similar substitutes have been chosen to minimize the effect of accuracy and to maintain the quality of the result.

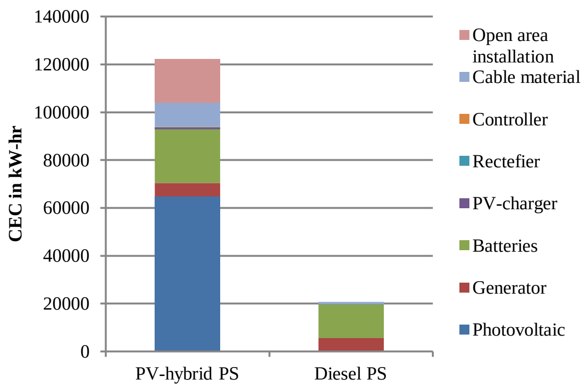

Figure 5. Comparison of the CEC

In Figure 5. it is evident that the additional PV-components of the PV-Hybrid PS is significant bigger compared to the traditional Diesel PS architecture. In particular, the energy consumption for production of solar modules, installation frames including the concrete with its big mass to fix the photovoltaic installation has a large impact on the overall result. This difference represents a bias, which needs to be compensated during the operating lifetime to become “greener” compared to traditional Diesel PS. Figure 6. and Figure 7. Show the comparison of the SO_2- and the CO_2- equivalents.

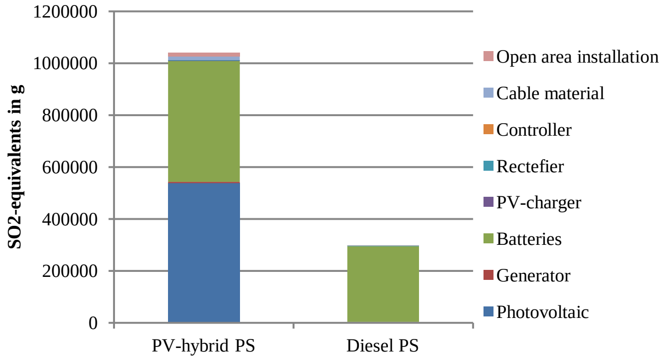

Figure 6. Comparison of the SO_2 equivalents for production

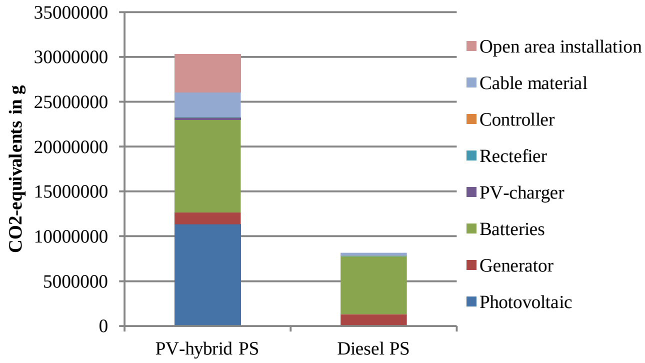

Figure 7. Comparison of the CO_2 equivalents for production

C. *Comparison of the releases emissions during operation*

The comparison of the releases emissions during 25 years between the PV-Hybrid PS and Diesel PS are shown in Figure 8. and Figure 9. Over 25 years of operation the SO2 equivalents (acidification) are reduced by 89% and the CO2 equivalents (global warming factor) are reduced by 74% compared to the Diesel PS supply concept.

D. *Comparison of the total emissions over the operating lifetime*

The comparison of the PV-Hybrid PS and the Diesel PS is presented in Figure 8. and Figure 9. is based on the selected case in Togo. The results show clearly the significant saving on emissions over the life cycle. Although the energy expenditure during the production and thereby the SO_2 and CO_2 equivalent emissions of the PV-Hybrid PS are seven times as high as the Diesel PS. The released emissions during the operation compensates those emissions and result in a significant overall saving. The released SO_2 and the CO2 equivalents are nine times higher when operating such site with a Diesel PS compared by a PV-Hybrid PS using photovoltaic power source.

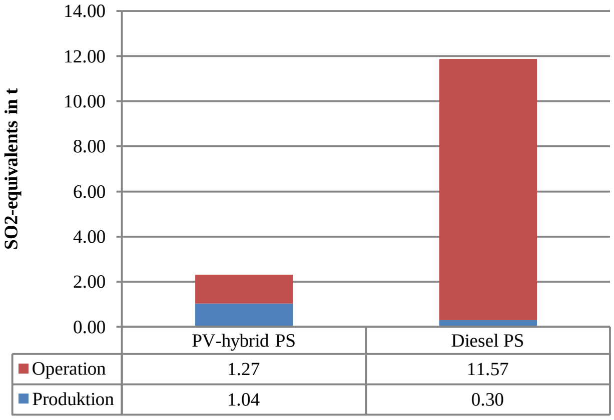

Figure 8. Comparison of the SO2 equivalents emissions during lifetime

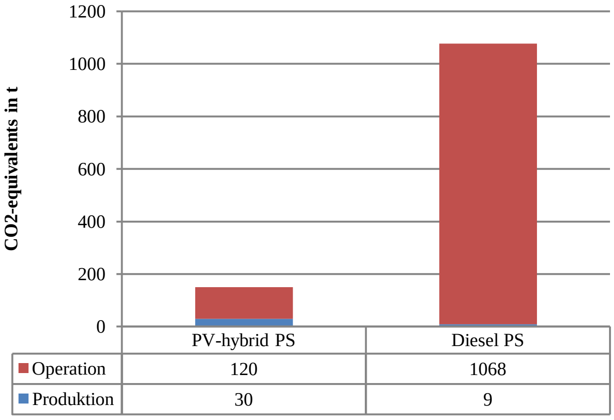

Figure 9. Comparison of the CO2 equivalents emissions during lifetime

E. Break even point from emission point of view

PV-Hybrid PS has to be considered from long term investment point of view. Figure 10. and Figure 11. show the evolution of emissions over the operating lifetime. The conclusion is that this regenerative hybrid system will become more environmental friendly during 2nd year of operation.

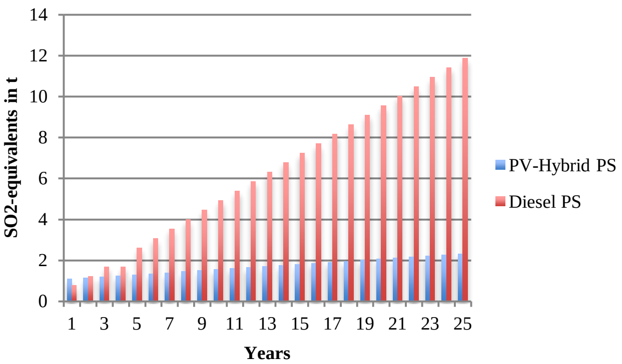

Figure 10. Comparison of the SO_2 equivalents over the operating lifetime

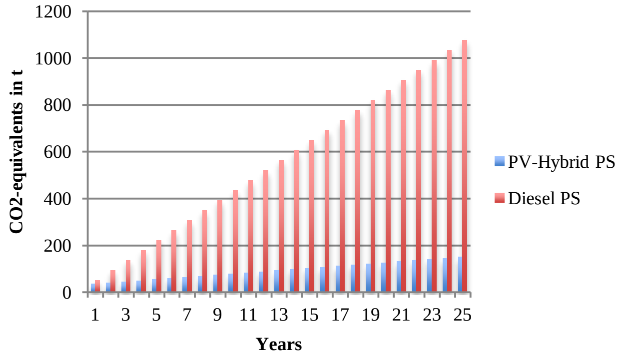

Figure 11. Comparison of the CO_2 equivalents over the operating lifetime

V. DISCUSSION OF THE RESULTS

The accuracy of the CEC data suffers from incompleteness of all the materials and their specific record for the production process. Therefore substitute materials with similar substances have been selected for the modeling to avoid a gap in the modeling. Because of the low contribution of the production energy in the overall result, the accuracy of this data has negligible impact.

The operating hours for the diesel generator is based on the average energy consumed by the telecommunication infrastructure and the average statistics of the local solar energy [11]. The real operating hours may vary due to annual deviations from the statistics. Due to the 25 years operating lifetime applied for this study, the usage of the statistical data can be considered as very accurate.

This study is based on data of a specific wireless base station in Togo / Africa. Different configurations in the telecom infrastructure in different locations of the world impact on differences in terms of load power and system configurations. Usually, telecommunication power systems consist of standard building blocks (components) that only differ in their arrangement to provide the necessary scalability. Consequently, the results of this work and the released specific emissions can be applied also for other telecommunication systems in case the role of the diesel generator remains the same as described in this paper.

VI. CONCLUSIONS

This study show the clear environmental benefit by using photovoltaic technology for powering off-grid and bad-grid installations in emerging markets instead of a diesel generator based powering concept.

Initially, for manufacturing of the components, the traditional solution is much more environmental friendly than the renewable solution. The renewable solution consumes much more energy during manufacturing (silicon, copper, steel, & concrete, …). It is clearly visible that the emissions during the operation make a big difference. The difference on emissions over the operating time of the different powering concept is so significant, that variations from case to case can be neglected.

Today the gap of “commercial break even” and “emissions break even” points are quite different, which result in a typical typical difference in the range of 3-5 years. The reason for this difference is that the manufacturing process of new technologies is not as mature, which is reflected in the market price of Photovoltaic panels. The higher demand for this technology will lead also to mature manufacturing technologies which will finally result that the break even points will merge closer together.

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