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Energy-Self-Sufficiency for Health Facilities in Ghana

Final Report

Working Package 3.1 and 3.3 by Cologne Institute for Renewable Energy, TH Köln

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Authors:	Prof. Thorsten Schneiders, Paul Bohn (MSc))
	Cologne Institute for Renewable Energy, TH Köln

Inhalt

1. Final report

1.1. Contributions to WP3: Country and sector specified optimization

1.1.1. Work package lead

- Hochschule Bonn-Rhein-Sieg (H-BRS)

1.1.2. Work package contributors

- Cologne Institute for Renewable Energy, TH Köln (CIRE)
- Kwame Nkrumah University of Science and Technology (KNUST)
- University of Augsburg (UniA)
- West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL)
- Reiner Lemoine Institut (RLI)

1.1.3. Goal of work package

This work package aims at improving the country and sector specific database. In order to establish a well-founded design and optimized, forecast-based operation, relying on a sector specific electricity demand model (WP3.1), a well-founded validation, and an improved forecasting of the local solar radiation and temperature for Ghana (WP3.2). The new data will be considered (a) for the system design and (b) for the system operation (WP3.3). Furthermore, the project provides a data-based electrification- and market introduction strategy for PV-Hybrid systems for the health sector in Ghana and for surrounding rural (WP3.4).

1.1.4. WP3.1: Electricity demand of the Ghanaian health sector

Literature research

During the development of the load modelling tool Load Profile Creator a literature research was conducted. The research was mainly aimed at data sets and individual load profiles of electrical consumers. The report “*Hospital Engineering – Teilbericht Energieeffizienz*” published by *Fraunhofer UMSICHT* and the releated dissertation ‘*Messdatengestützte dynamische Simulation zur Analyse des Energieverbrauchs in Krankenhäusern*‘ served as sources for the database of the LPC.

Data acquisition and load measurement

Two measurement systems have been implemented in the *St. Dominic Hospital* (SDH) in Akwatia. The systems will be split up by their usage and described briefly.

Grid analysis

The grid analysis is performed at two points in the power grid of the hospital. Therefore, two UMD 98 from PQ PLUS are installed at the generator and transformer house as shown in Figure 1. Initially, the data transfer was to take place via a remote access through a VPN tunnel.

Figure 1 Grid analyzers PQ PLUS UMD 98 generator house (left); transformer house (right)

The data remote data transfer proved to be a challenge and was not fixed during the project. In order to gain access to the measurement data, the workers on site were tasked with the data transfer. The data should be transferred on a weekly basis since the internal storage of the measuring devices overwrites itself after 8 days. However, setting up the laptop of the local workers to connect to the measuring devices appeared to be challenging. Instructions were written and desktop videos were created for the installation of the software. In addition, the process had to be followed and monitored step by step. This process could be simplified by using Remote Desktop Applications. Since no remote desktop software is pre-installed on the laptop of the local workers, the installation of the *ENVIS.Daq* software from *PQPlus* was done with the help of several video calls.

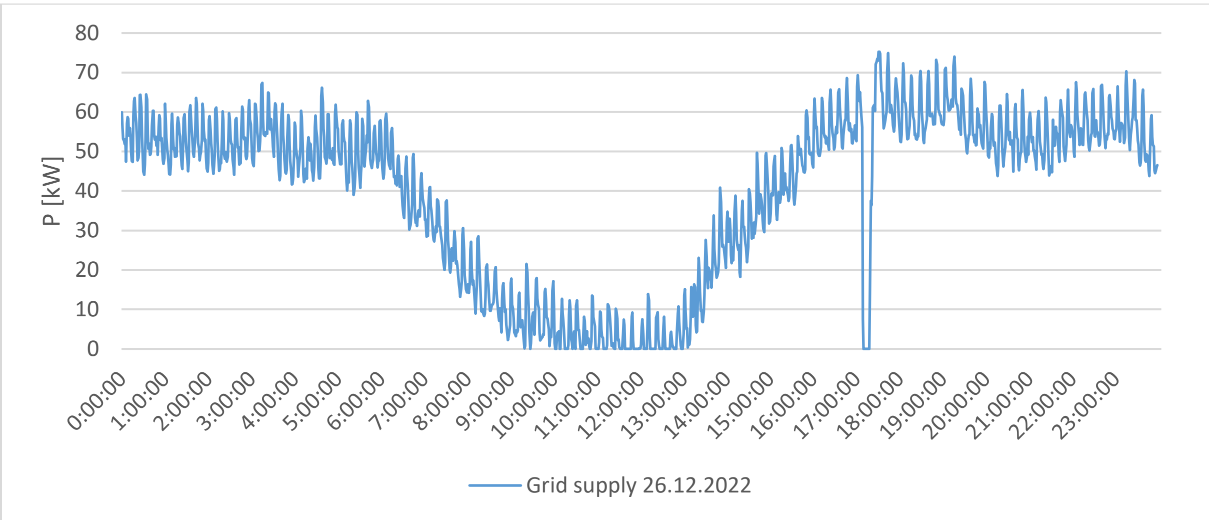

Figure 2 Grid supply 26th of December 2022

Due to these challenges data gaps in the data sets could not be avoided. Nevertheless, valuable conclusions can be drawn from the available data sets. Figure 2 shows the grid supply of the SDH on the 26.12.2022. Contrary to the expectation of a midday peak, grid power consumption drops sharply over the midday hours. This can be explained by the self-consumption of the PV electricity (90 kWpeak). In addition, the grid supply drops to 0 W between 17:10 and 17:18. This indicates a blackout in the power grid.

The measuring device also logs voltage events. It is noticeable that immediately before the blackout the voltage events ‘Voltage Interruption’ and ‘Voltage Dip occur’ simultaneously. The voltage events are defined as follows:

- Voltage interruption: Reduction of the voltage at a point in the electrical system below the interruption threshold
- Voltage dip: Temporary reduction of the voltage magnitude at a point in the electrical system below a threshold

Regarding the blackout from 17:10-17:18 on 12/26/2022, it can be observed in the data sets that the voltage on all phases drops from 250.7 V to 0 V at 17:09. Due to the minute-by-minute resolution of the data sets, the exact time cannot be verified. Nevertheless, a clear connection between the voltage dip and the blackout is recognizable. The same behavior can be observed in several other examples. However, in order to make a more precise statement about the behavior, more data sets in higher resolution are needed.

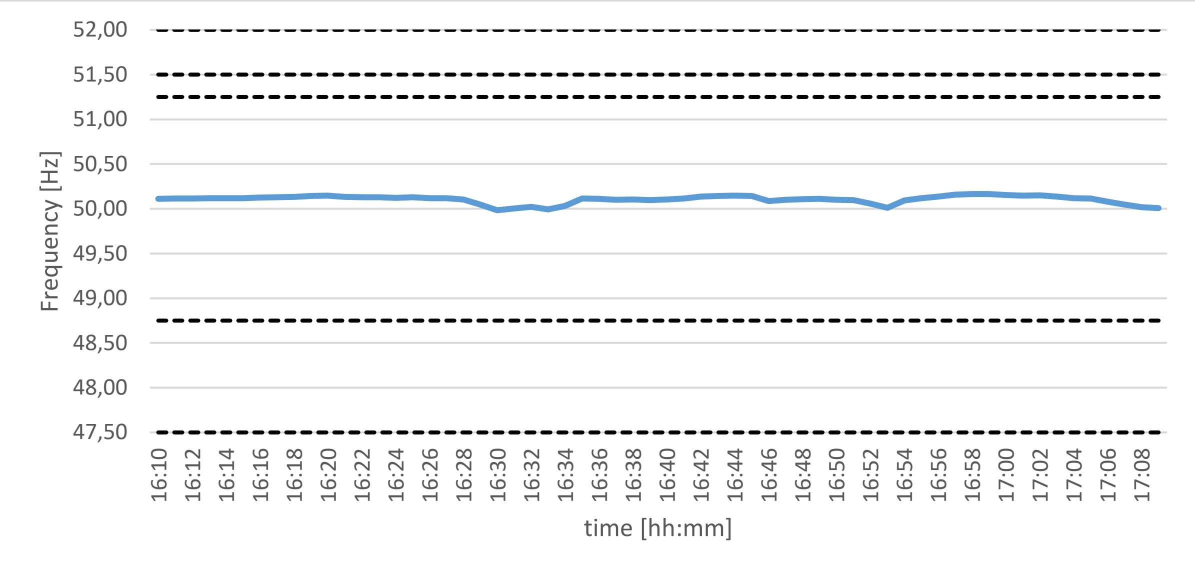

Figure 3 Frequency one hour before blackout event

Figure 3 displays the frequency on the 26/12/2022, one hour before the blackout event. The black dashed lines mark different frequency ranges. Table 1 shows the frequency ranges and the allowed consecutive time of operation.

Table 1 Frequency ranges of operation

Frequency [Hz]	Operation [1]
47.5-48.75	90 min
48.75-51.25	Unlimited
51.25-51.4	90 min
51.5-52	15 min

It is clear that the grid frequency one hour before the blackout event is within the range of 48.75 Hz to 51.25 Hz. In this range, operation is possible without further restrictions. This behavior was observed in all studied cases of blackout.

Load measurement

The load measurement is carried out with SmartCost transmitters. Sensors are connected to the electrical subdistribution and transmit the data to the SmartCost Hubs. The SmartCost hubs are connected to a mobile router. The logged data is transferred directly to the *energomonitor* dashboard. From there, the data can be retrieved. Figure 2 show the installation of one of three *SmartCost* hubs in the hospital.

Figure 4 SmartCost Hub connected to mobile router

The three *SmartCost* hubs collect data from the following departments (Table 1). The number of sensors connected to each hub varies because of the physical distance between the sensors and the hubs.

Table 2 SmartCost hubs and connected departments

Hub 1				Hub 2	Hub 3
Administration	Theater	Pump station	Children ward	Laundry	Eye clinic

The *SmartCost hubs* have been collecting data for the entire year 2021. The data is exported from the *energomonitor* dashboard for every month. To process the data a python tool was programmed. The tool splits up the monthly sensor data in daily-department data. The tool also differentiates between weekdays and weekends. Figure 3 shows the processed data for the departments Administration, Theater, Pump Station and Children Ward on October 1st, 2021. It can be stated that the sensors of the Administration, Pump station and Theater work reliably. Load data has been collected over the whole period. The data collection of the Children ward is unreliable. This can be attributed to the large distance between the sensor and the hub. The sensor was repositioned in July 2022, yet the data transfer connection remained inadequate.

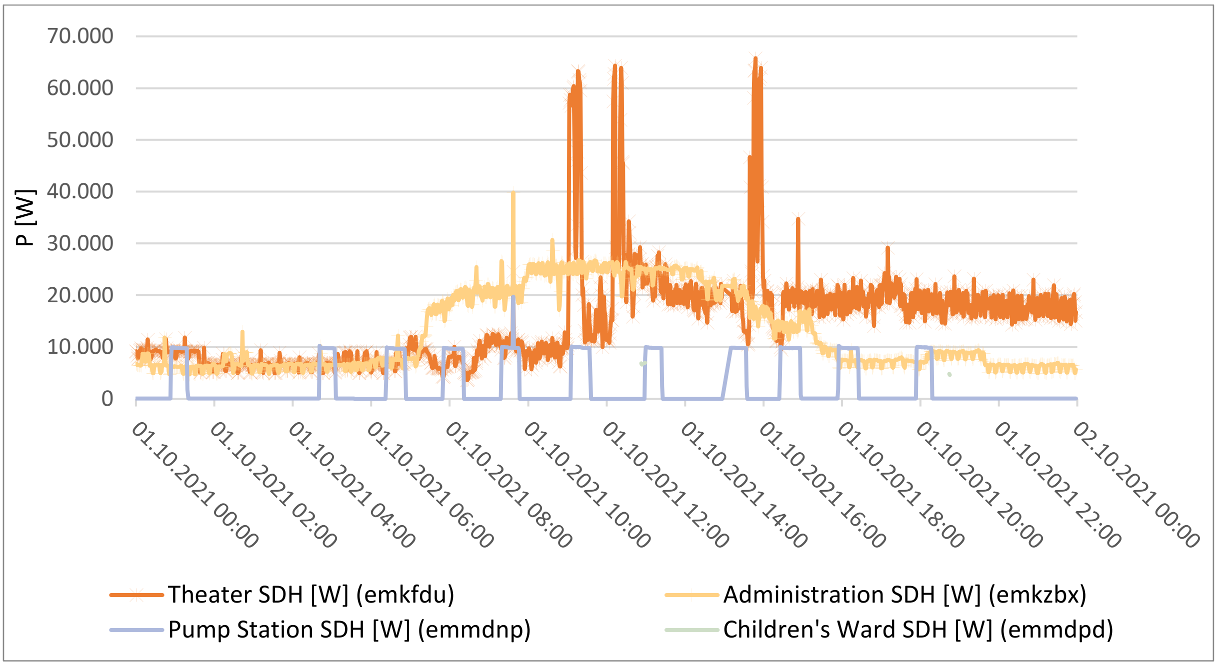

Figure 5 Energy consumption Hub 1 01/10/2021

Data analysis

The data sets were analysed in depth. Therefore, datasets from the Sankt Michaels Hospital (SMH) in Kumasi were used as for comparison. Altogether, the SDH and SMH administration provided the most reliable data sets and cover part of the hospital´s wards. As a main finding, the administration datasets can be used representatively for smaller healthcare facilities. Figure 7 displays the average load profiles of both Administration departments and compares them to the VDEW reference load profiles G0 (business general), G1 (business 8:00-18:00) and G3 (business continuous) [2].

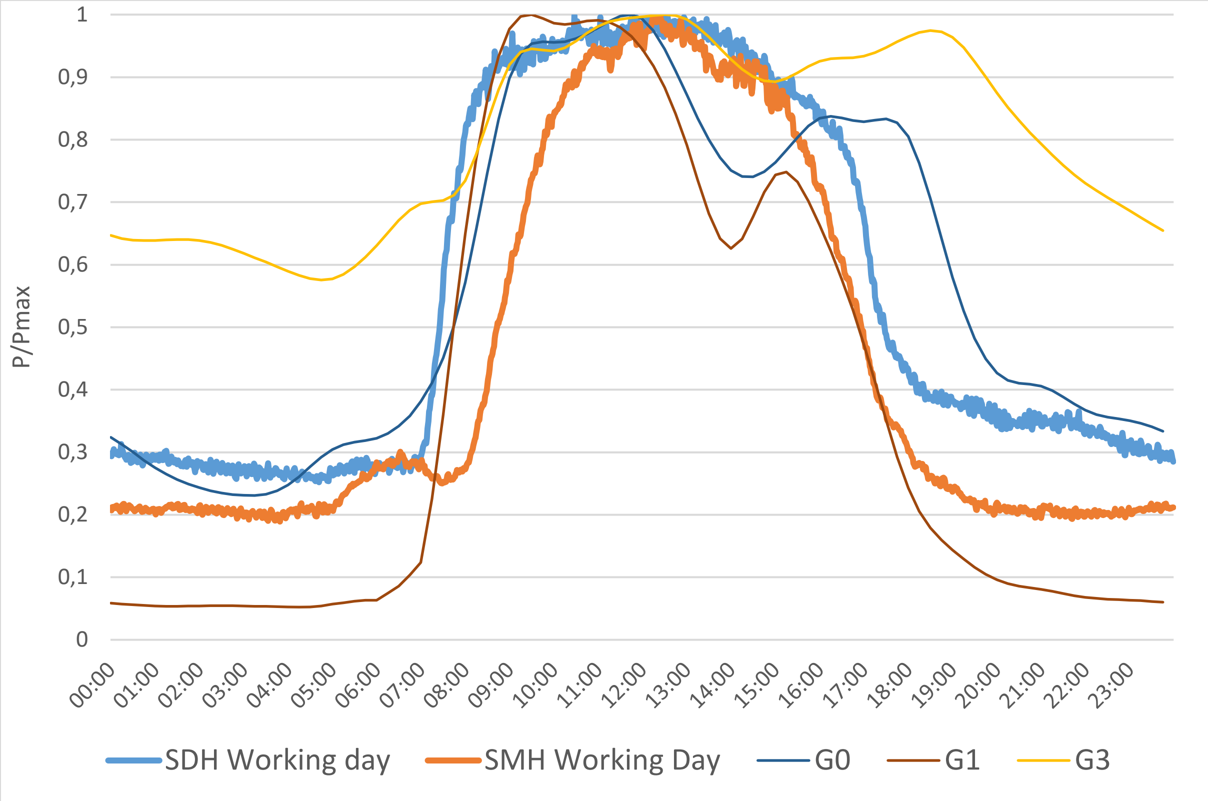

Figure 6 Comparison Administration SDH and SMH with German standard load profiles (G0, G1, G3)

Due to comparability, the load profiles are plotted as a percentage of the maximum power. The load profiles of both Administration departments reveal the same characteristics. During non-operating hours the base load stays roughly the same. The opening and closing-hours are marked by a sudden increase and decrease of the load. The highest load is present around midday.

The G3 load profile represents hospitals in the German power grid. It is clear that the G3 load profile differs from the Administration load profiles. The base load is significantly higher. Additionally, another load peak occurs in the evening hours. During the midday hours, the behavior is similar. However, the Administrations´ load characteristics from the morning hours until midday are represented quite well in the G0 load profile. During the afternoon a low sink appears in the G0 profile which significantly deviates from the Administrations load profile. Even though the base load in the evening hours is about 15% lower than the Administration, the late afternoon and evening hours are best represented in the G1 profile. Both the Go and G3 profile have another load peak around 18:00. The G1 profile has a sudden power decrease at around 15:00 h (3 pm).

[2] BDEW Bundesverband der Energie- und Wasserwirtschaft e.V., Standardlastprofile Strom, 01.01.2017, online: https://www.bdew.de/energie/standardlastprofile-strom/

Figure 5 displays both Administrations´ load profiles and the sliced reference load profiles (G013).

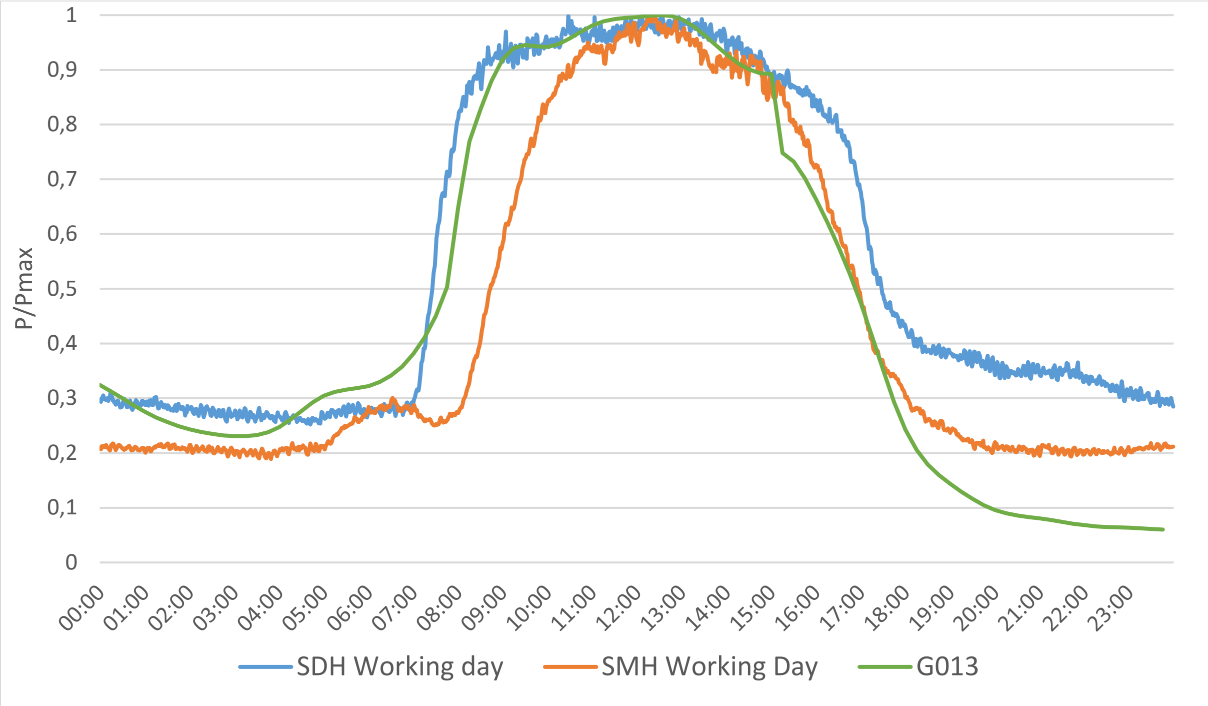

Figure 7 Load profile comparison SDH, SMH and sliced reference load profile

Each of the three reference load profiles represents a significant part in the G013 curve:

- G0: 00:00-8:15
- G3: 8:30-15:00
- G1: 15:15-23:45

The G013 curve resembles the Administrations load profiles. Only the base load behavior in the evening hours is lower compared to the SDH and SMH load profile. It deviates from the real base load by approx. 15%.

Load model development

Over the course of the reviewed period the open source python tool *Load Profile Creator* (LPC) was developed and published open source. The LPC is graphical user interface (GUI)-based library to create load profiles from a database. Within the tool, the object for which a profile is created is spatially divided. The four hierarchy levels are displayed in Figure 3.

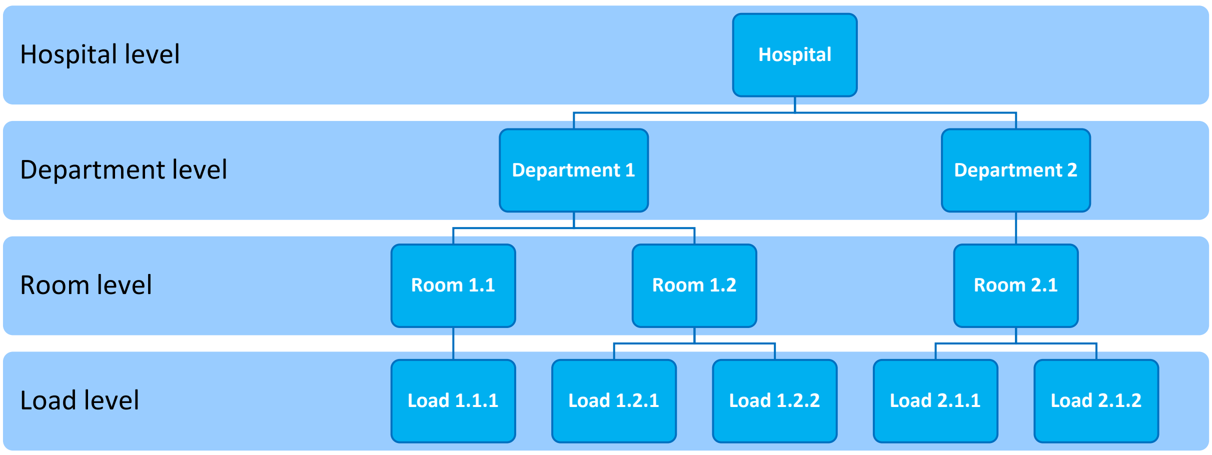

Figure 8 Hierarchy levels

The load profile for a hierarchy level is the sum of the load profiles from the next lower hierarchy level. The load level consists of individual load profiles of every consumer. These individual load profiles are built up from a database. The program uses three different load types to describe all loads:

- Constant
- Sequential
- Cycle

Constant loads are influenced by the opening hours of the respective higher-level spatial unit. During operating hours, constant loads are assumed to operate at rated load. During non-operating times, constant loads operate at standby power or are completely switched off. Constant loads include lighting, computers, monitors. Sequential loads have a regularly repeating load cycle with a fixed interval between the load cycles. The interval can vary between operating and non-operating hours. Typical loads for sequential loads are air conditioning, pumps and fridges. Cycle loads have a non-regularly repeating load cycle. The loads follow a schedule which is not predictable and can vary from day to day. In most cases medical equipment is considered a cycle load. Figure 4 shows the three different load types and their characteristic load profile behavior.

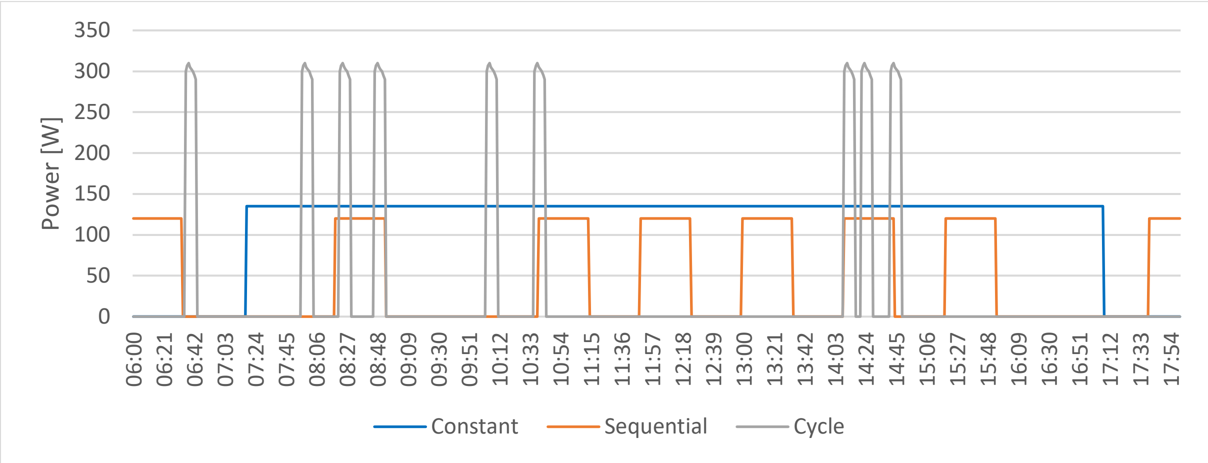

Figure 9 Load types

The workflow of the LPC is displayed in Figure 5. The blue bordered steps represent the steps of the modeling process. The green bordered steps describe the results of the modeling process. To grant an easier handling of the tool, a GUI (Graphical User Interface) was implemented. This guides the user through the modeling process. Basic knowledge in common office applications is necessary for the modeling process.

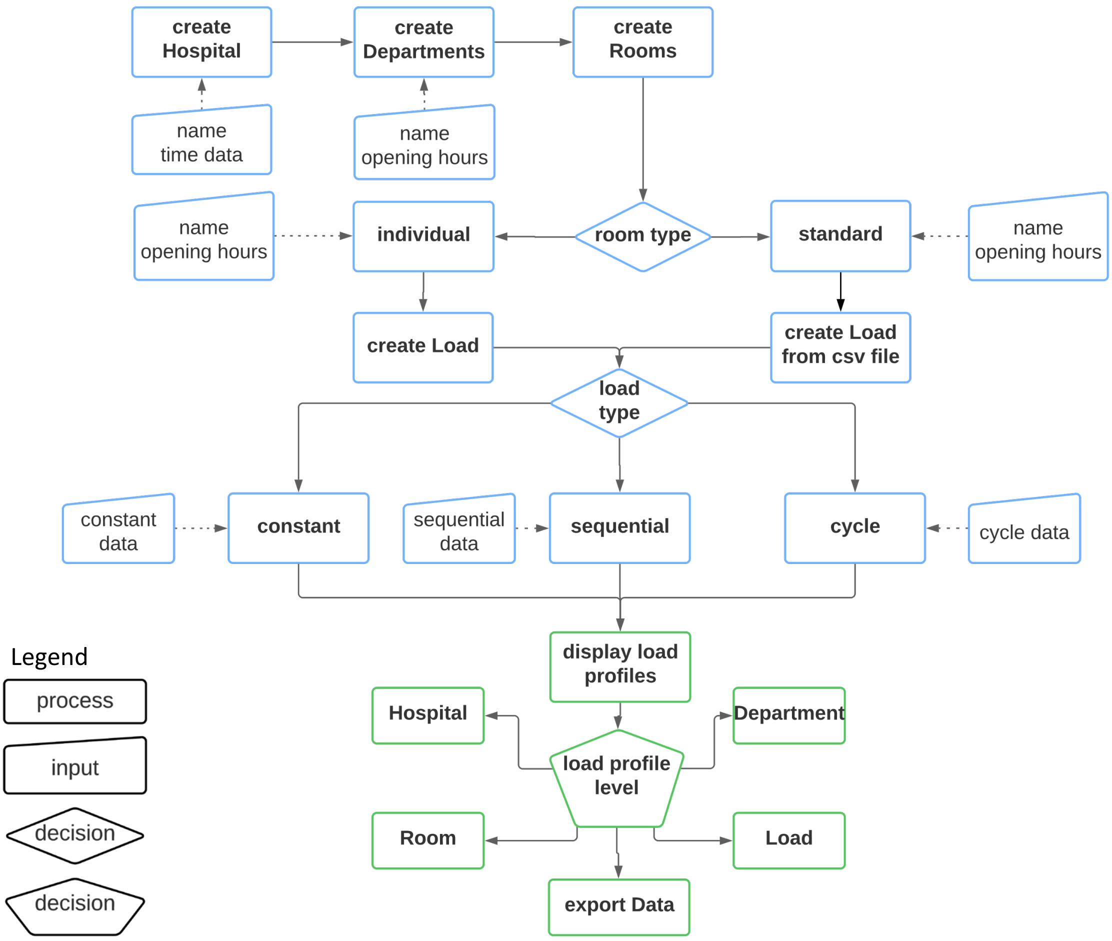

Figure 10 LPC program schedule

The modeling results are exported as csv profiles for every hierarchy level. Figure 6 displays the measured load profile of the Administration department of the SDH and the modeled load profile using the LPC.

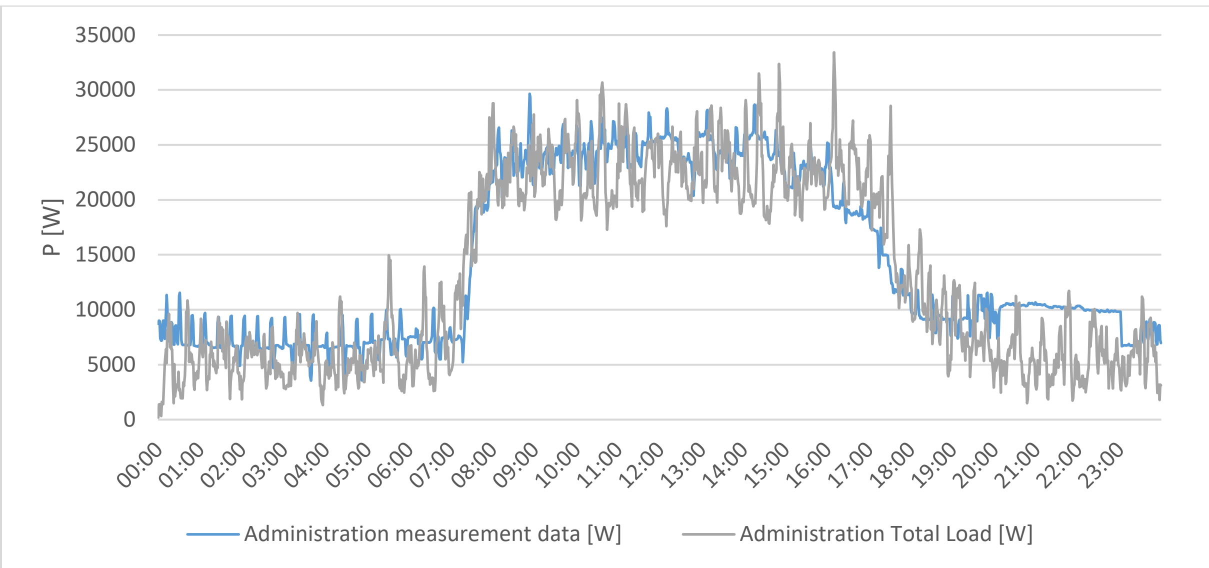

Figure 11 Measured load profile and modeled load profile in comparison

The modeled load profile resembles the measured load profile. The shape follows the same characteristics and the number of load peaks are similar. However, the load peaks are more pronounced in the modeled load profile. The quality of the underlying database influences the quality of the generated load profiles. The measurement concepts in the SDH only provide for a departmental resolution. Due to the large number of consumers in the departments and the overlapping of the individual load profiles, no individual load profiles can be read out.

From these findings, it is concluded that good preparation can produce higher quality load profiles. **The following steps are recommended to create an accurate database:**

(1) Definition of hierarchy levels

As a first step, the institution should be divided into several hierarchical levels. When defining the departments and rooms, care should be taken to ensure that they form logical groups. Thus, for example, demand response potentials can be assigned in more detail. In addition, the opening hours of the rooms and departments must be recorded.

(2) Detection of electrical loads

First, all electrical consumers are recorded and assigned to the respective room. The electrical consumers should be classified according to their load type. Basic parameters such as manufacturer, model and nominal power can be read directly from the electrical consumer.

(3) Load measurements

The focus of the load measurements should be on consumers with high nominal power and consumers with repetitive load cycles. Ideally the load measurements are carried out for at least one consumer of every consumer group. By measuring the consumers, the standby power, the load cycles and the interval between the cycles of the consumers can be recorded accurately. In order to be less dependent on measurement equipment, it is possible to document schedules and the length of load cycles as well as the intervals between load cycles. With this method, the load cycles are mapped as a rectangular load.

(4) Creation of the database

In the last preparation step the gathered data from the steps above are put together as a database. Depending on the load type csv-files containing the load data, cycle and profile have to be created.

Demand response potential

Work package 3.1 also explored strategies for harnessing demand response potential (DRP) in Ghanaian healthcare facilities. Two main strategies were examined:

- Peak shaving (decrease the peak load)
- Increasing RE self-consumption

Identifying relevant consumers

As mentioned above monitoring the electric consumers inside the hospital is an important step in the preparation process of modelling the load profiles. This also applies for harnessing DRP. A list of all electric consumers and ideally individual load profiles of larger consumers are helpful to identify consumers with DRP. Not every consumer is suitable for DRP. Shifting the load cycle must not affect the workflow and must be technically feasible. Medical devices, for example, which are subject to scheduled user behavior, are suitable for this. Depending on the DRP strategy the approach of selecting the consumers with DRP varies from another.

To identify consumers for peak shaving the time with the maximum peak(s) needs to be identified from the overall load profile. All consumers with high nominal power running at this time need to be considered. In order to further limit the consumers, further measurements can be carried out on the respective consumers if possible. To identify the new time to run the consumer the load profile has to be examined for load sinks. Since the consumer's use must normally proceed within a certain time frame, a maximum displacement period can be specified. Thus, the range in the load profile that is examined is limited.

Possible consumers for increasing the RE self-consumption typically consume a lot of energy over a certain time. This can vary from short load cycles with a higher power or longer load cycles with lesser power. In order to increase the RE self-consumption, the load cycles must lie outside the period of the previously used RE. In order to identify the consumers, the RE generation profile is required in addition to the load profile and the consumer list. Figure 10 displays the laundry and the production profile of the PV system. The blue curve is the curtailed PV power which is not used for RE self-consumption.

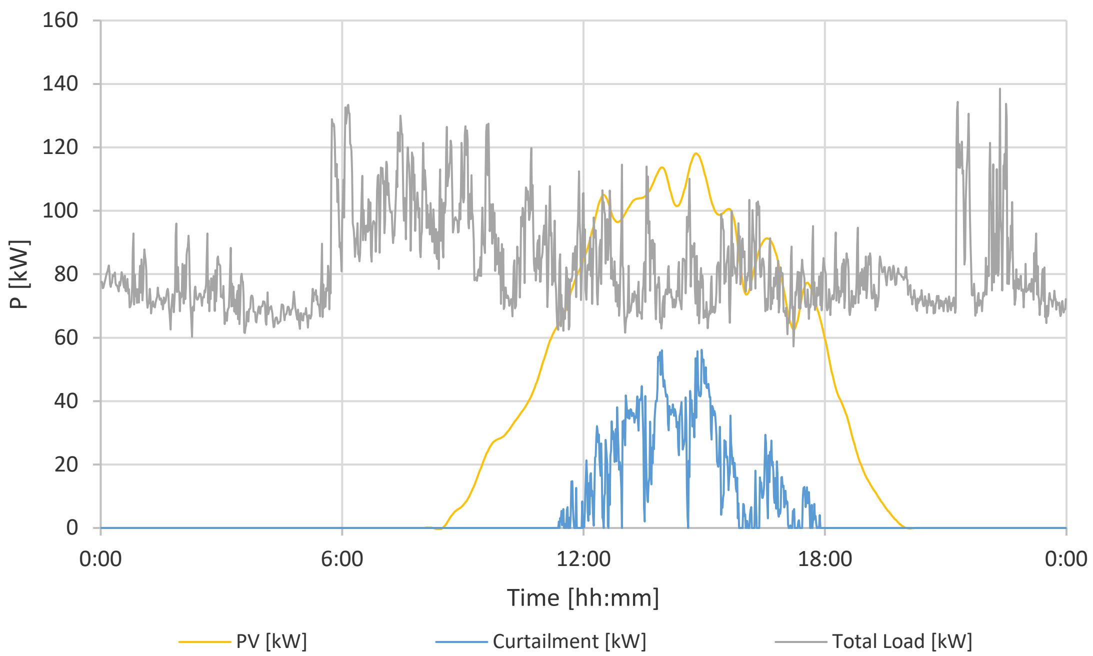

Figure 12 Laundry and PV production profile

To identify the optimal new starting time for maximum increase of the renewable energy (RE) self-consumption a python tool was created. The tool compares the decrease of RE curtailment in a predetermined time period. As an output the tool delivers the new starting time, the new load profile and the increase of RE self-consumption. The tool is published open source on the software development platform GitHub. Figure 11 shows the laundry and the RE curtailment before and after the curtailment.

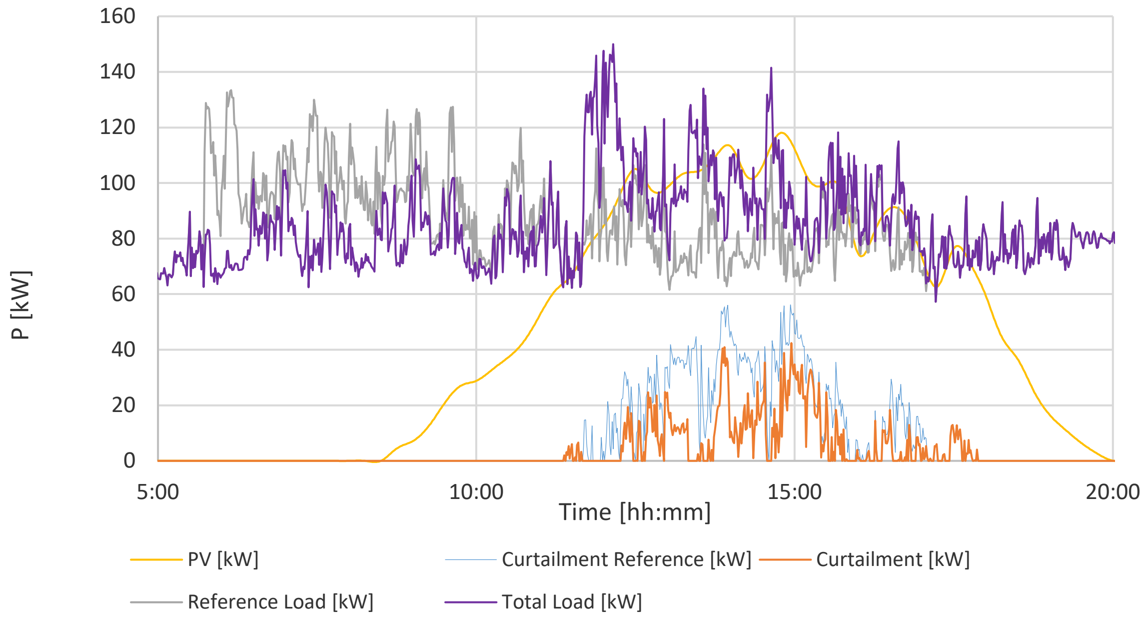

Figure 13 Laundry and curtailment before and after load shifting

To illustrate the increase in self-consumption, the optimum time during the day was chosen in the example. The curtailment could be reduced by 57% and the self-consumption increased by approx. 53 kWh. Even with a maximum displacement of 90 min. the curtailment is reduced by 4.33 %.

1.1.5. WP3.3: Tools for the country- and sector specific system planning and plant optimization

Literature research

In the course of the literature research, characteristic values for analysis parameters such as specific investment costs, maintenance costs and CO2 emissions were identified.

Development and validation of the planning tool

The goal of work package 3.3 is developing and validating a planning tool for PV-diesel hybrid systems. The developed tool is named with the acronym *MiGUEL* which stands for *Micro Grid User Energy Planning Tool Library*. *MiGUEL* is a python-based tool and will be published on the software development platform *GitHub*. During the development process, emphasis was placed on a low barrier to entry and comprehensible simulation results. The following passages briefly describe the basic functions of *MiGUEL* further details are documented on *GitHub* and in the programs docstrings.

Model structure

The following system components are featured in *MiGUEL*:

- PV-systems
- Wind turbines
- Power grid
- Diesel generators
- Energy storages
- Load

The system components are simulated in their own class. The Environment class represents the energy system as a whole. The operator carries out the system simulation and evaluation. Figure 10 displays the model structure of MiGUEL. The upcoming paragraphs will give a brief overview of every system component.

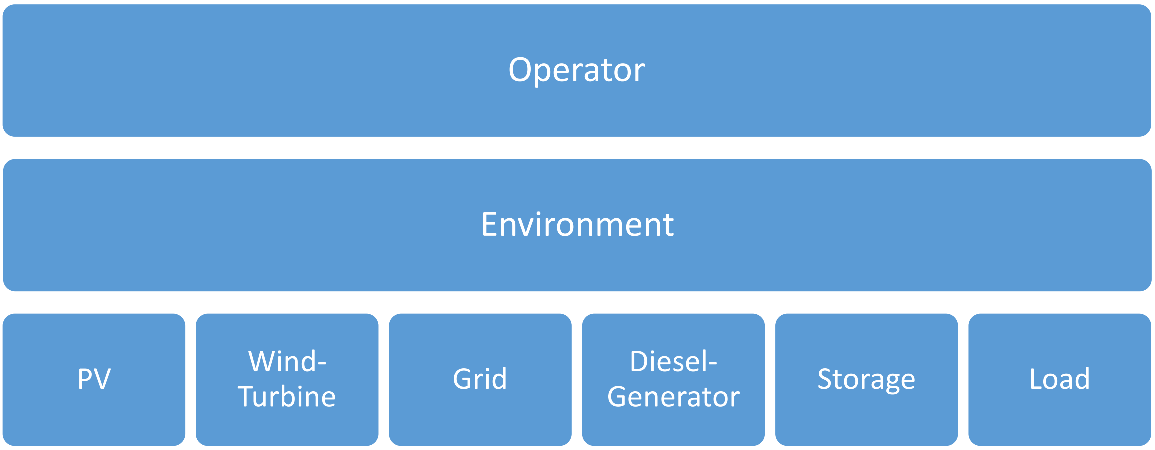

Figure 14 MiGUEL model structure

Environment

The environment is the base-modelling class. It includes all the time frames, location, information system parameters and components, economic and ecologic parameters. These parameters are necessary to simulate and evaluate the system. The time frame determines the period under consideration. The time resolution can be selected in 1 minute or 15 minutes steps. It is recommended to carry out an annual simulation and a system lifetime of 20 years. The environment represents the overall energy system. The system components are added to the environment. Each system component will be described separately.

Load

The **system component** load represents the load profile of the subject under review. The load profile can be generated in two different ways.

1) **Standard load profile** for African hospitals: During the project standard load profiles for Ghanaian hospitals were created (Figure 7). This daily standard load profile is implemented in the program. To create a load profile from the standard load profile, the annual electricity consumption needs to be returned to the function (annual_consumption). The standard load profile has a 15min-time resolution.
2) **Input via csv-file**: If actual measurement data from the subject is available, the data can be returned to the program as a csv-file (load_profile).

The input parameters are listed in Table 3.

Table 3 Input parameters class Load

Parameter	**Description**	**dtype**	**Default**	**Unit**	**Comment**
annual_consumption	Annual electricity consumption	float	-	kWh	Only for method 1
load_profile	File path to load profile data	str	-	-	csv-file with load profile, Only for method 2

The accuracy of the simulation results increases with the quality of the input data. Using the adjusted standard load profile will provide less accurate results compared to measured data. The library *Load*

Profile Creator (chapter: Load model development) can be used to create load profiles based on the electric inventory of the subject.

If the resolution of the load profile does not match the environment time resolution, the resolution of the load profile will be adjusted by summarizing or filling in the values. If no annual load profile is provided, the load profile will be repeated to create an annual load profile.

PV-system

The class *Photovoltaic* (*PV*) is based on the library *pvlib* 3]. There are three methods implemented to **create PV systems**:

1) Adding basic system parameters: Simplest way to create PV system with only basic parameters such as nominal power, surface tilt and azimuth, module and inverter power range. The class Photovoltaic will randomly choose a PV module, number of modules and an inverter that matches the parameters
2) Selecting your modules and inverter: All system parameters such as module, number of modules, inverter, strings per inverter, modules per string, surface tilt and azimuth, ... need to be returned to the function.
3) Provide measured PV data: Input of measured PV as a csv-file

The input parameters are displayed in Table 4.

Table 4 Input parameters class Photovoltaic

Parameter	Description	dtype	Default	Unit	Comment
p_n	Nominal power	float	-	W	
pv_profile	File path to pv porduction data	str	-	-	Measured pv data in csv file, Only for method 3
pv_data	PV system parameters	dict	-	-	
pv_module	PV module	str	-	-	PV module from pvlib database, Only for method 2
inverter	Inverter	str	-	-	Inverter from pvlib database, Only for method 2
modules_per_string	Modules per string	int	-	-	Only for method 2
strings_per_inverter	Strings per inverster	int	-	-	Only for method 2
surface_tilt	PV system tilt angle	float	-	-	
surface_azimuth	PV system orientation	float	-	-	North=0°, East=90°, South=180°, West=270°
min_module_power	Minimum module power	float	-	W	Only for method 1
max_module_power	Maximum module power	float	-	W	Only for method 1
inverter_power_range	Inverter power range	float	-	W	Only for method 1

pvlib will run the *PV* simulation based on the selected system parameters. The weather data for the project location is retrieved by the Environment. The data source is ***PVGIS*** hosted by the *European Commission*.

[3] Holmgren et al., (2018). pvlib python: a python package for modeling solar energy systems. Journal of Open Source Software, 3(29), 884, https://doi.org/10.21105/joss.00884

Wind turbine

The class ***WindTurbine*** is based on the library ***windpowerlib*** [4]. To add wind turbines to the Environment the turbine type and the turbine height need to be returned. The input parameters for the class *WindTurbine* are listed in Table 5.

Table 5 Input parameters class WindTurbine

Parameter	Description	dtype	Default	Unit	Comment
turbine_data	Turbine data	dict	-	-	
turbin_type	Turbine type	str	-	-	Turbine name and manufacturer from windpowerlib register
tubine_height	Hub height	float	-	m	

As in the *PV* model, *PVGIS* is also used as a weather data server. This data is processed in the class *WindTurbine* so it can be used for the simulation.

[4] Sabine Haas, Uwe Krien, Birgit Schachler, Stickler Bot, kyri-petrou, Velibor Zeli, Kumar Shivam, & Stephen Bosch. (2021). wind-python/windpowerlib: Silent Improvements (v0.2.1). Zenodo. https://doi.org/10.5281/zenodo.4591809

Grid

The class ***Grid*** represents the power grid. The power grid provides electricity to the energy system. Depending on the input of blackout data, a stable or unstable power grid is simulated. The possibility of feed-in is determined in the Environment. To add a power grid to the Environment, no specific parameters are needed.

Diesel generator

The class ***DieselGenerator*** is based on a simplified, self-created generator model. The model assumes that in the future generators with low-load capability are used in PV-diesel hybrid systems. In comparison to conventional diesel generators, low-load diesel generators are more fuel efficient and therefore reduce CO2-emissions [5]. The input parameters for diesel generators are displayed in Table 6.

Table 6 Input parameters class DieselGenerator

Parameter	Description	dtype	Default	Unit	Comment
p_n	Nominal power	float	-	W	
fuel_consumption	Fuel consumption at nominal power	float	-	l	
fuel_price	Fuel price	float	-	US$/l	

The fuel consumption for the generator is calculated every time step using Equation 1. The equation was derived using characteristic values of a 150-kW diesel generator at loads of 0%, 25%, 50%, 75% and 100% [6].

Equation 1 Dynamic calculation fuel consumption

$$fc(l) = -1.66360855\ x\ l\ 4 + 3.96330272\ x\ l\ 3 - 3.19877674\ x\ l\ 2 + 1.8990825\ x\ l + 0$$

$fc = relative\ fuel\ consumption$ [%]

$l = relative\ load$ [%]

[5] PV Magazine, "Low-load generators make photovoltaic diesel applications cleaner and more efficient", 06. October 2015, online: Niedrig-Last-Generatoren machen Photovoltaik-Diesel-Anwendungen sauberer und effizienter

[6] Generator Source, LLC 1999-2023; Approximate Diesel Fuel Consumption Chart; online available: https://www.generatorsource.com/Diesel_Fuel_Consumption.aspx

Storage

The class ***Storage*** is used to simulate battery storage systems. A simplified model is used to simulate the battery storage. Every time step the storage can be charge and discharged. Both operations are subject to the following restrictions: The minimum and maximum state of charge cannot be undercut or exceeded; the maximum charging and discharging power corresponds to the nominal power multiplied with the respective efficiency. The input parameters for storage systems are displayed in Table 7.

Table 7 Input parameters class Storage

Parameter	Description	dtype	Default	Unit	Comment
p_n	Nominal power	float	-	W	
c	capacity	float	-	Wh	
soc	Initial state of charge	float	0.5	-	
soc_max	Maximum state of charge	float	0.95	-	
soc_min	Minimum state of charge	float	0.05	-	
n_discharge	Discharge efficiency	float	0.8	-	
n_charge	Charge efficiency	float	0.8	-	

Operator

The ***Operator*** functions as the top-level class of *MiGUEL*. Here the system simulation and evaluation are carried out. The operator uses different dispatch strategies depending on the type of system. The following systems can be modelled with *MiGUEL*:

1) Systems with stable grid connection
2) Systems with unstable grid connection
3) Off grid systems

Depending on the system types the dispatch priorities vary from another. Figure 15 displays the different dispatch strategies for all system types.

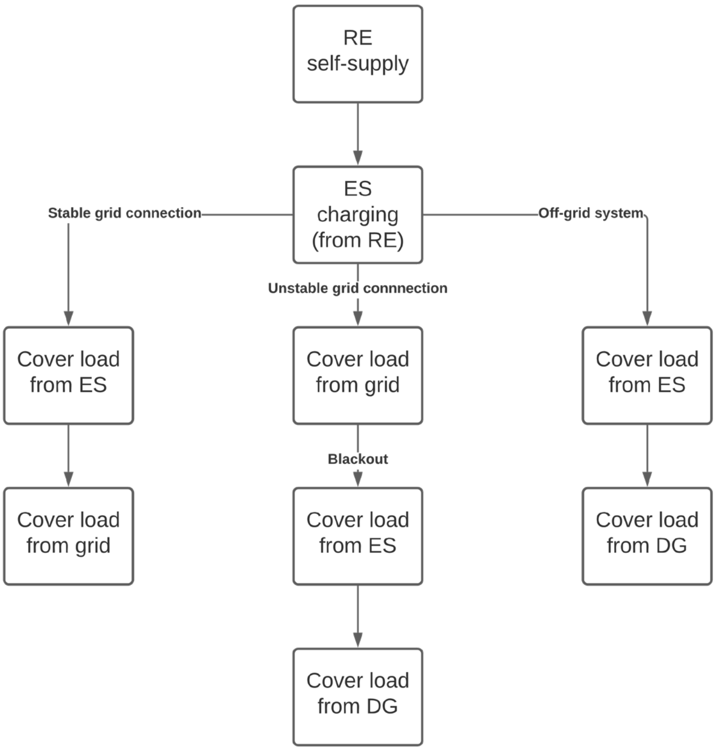

Figure 15 Dispatch strategies

The first priority is the self-supply from renewable energy sources (RE). Afterwards, the battery storage (ES) is charged from the remaining renewable energy (RE) production. Depending on the system type the priorities vary. Off grid systems and systems with a stable grid connection cover the remaining load from the battery storage and afterwards from the diesel generator (DG) eand grid. System with an unstable grid connection cover the load from the grid. In case of a blackout the load is covered from the storage afterwards the diesel generator covers the remaining load. After the operator has run the dispatch. The operator checks if the current system configuration covers the load in the annual simulation.

System evaluation

The system is evaluated with the key parameters *levelized cost of energy* (LCOE) and *CO_2-emissions*. The LCOE are calculated as shown in Equation 1 [7].

Equation 2 levelized cost of energy

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + O_t + R_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

$LCOE = Levelized\ cost\ of\ energy$ $n = system\ lifetime$

$t = time\ step$ $I = Investment\ cost$

$O = Operating\ cost$ $R = Revenues$

$E = Energy\ supply$ $r = discount\ rate$

The CO_2-emissions include the CO_2-emissions during the system lifetime as well as the CO_2-emissions during the manufacturing and installation process. The total CO_2-emissions are the sum of the CO_2-emissions of every component.

Every system component includes specific values for investment cost, operation and maintenance cost and CO2-emissions during the manufacturing and installation process. These specific values are scaled up by the nominal power or capacity of each system component.

[7] Michael Papapetrou, George Kosmadakis, Chapter 9 - Resource, environmental, and economic aspects of SGHE, Editor(s): Alessandro Tamburini, Andrea Cipollina, Giorgio Micale, In Woodhead Publishing Series in Energy, Salinity Gradient Heat Engines, Woodhead Publishing, 2022, Pages 319-353, ISBN 9780081028476, https://doi.org/10.1016/B978-0-08-102847-6.00006-1

Simulation Outputs

MiGUEL provides **two outputs** for the user. One being a csv-file with all the simulation time steps. The csv-files are meant for in depth analysis of the energy systems behaviour. The file can be used for further scientific research. The system evaluation is not included in the csv-files.

The second output is a pdf-report. The report is automatically created by *MiGUEL* and can be used as a project brochure. It contains a summary of the most important findings, an overview of the input parameter, climate data from the PVGIS server at the selected location, the load profile, system configuration, dispatch and the system evaluation. The report gives the opportunity to compare different system configurations based on the LCOE and CO_2-emissions. Appendix 1 shows an example report.

Sensitivity analysis (with reference to the input data)

In the following chapter, different system configurations are created with *MiGUEL* and compared with each other using the parameters LCOE and CO_2-emissions. Variants for systems with grid connection and off-grid systems are created. For comparability between the systems the base parameters and load profile will be the same. Between each simulation only one parameter will be changed to analyse the impact on the overall system. The system will be evaluated based on the LCOE and the annual CO_2-emissions.

Base parameters and load profile

The basic parameters are displayed in Table 8. For all simulations the load profile of the administration from *St. Dominic Hospital* in Akwatia is used (Figure 6).

Table 8 Basic simulation parameters

Parameter	**Value**	
Longitude		-0.7983°
Latitude		6.0442°
Start time		00:00 – 01.01.2022
End time		23:59 – 31.12.2022
Time resolution		00:15
Currency	US$	
Electricity price [US$/kWh]		0.14 [8]
Diesel price [US$/l]		1.385 [9]
CO_2-price [US$/t]	No CO_2-pricing	
Feed-in tariff [US$/kWh]	No feed-in	
System lifetime [a]		20

Discount rate	0.03
CO_2-factor grid [kg/kWh]	0.1350 [10]
CO_2-factor diesel [kg/kWh]	0.2665 [11]

[8] Public Utilities Regulatory Commission (PURC), Publication of Electric Tariffs, 2023

[9] GlobalPetrolPrices.com, Ghana Diesel prices, 13-Feb-2023, 2023, online: https://www.globalpetrolprices.com/Ghana/diesel_prices/

[10] International Energy Agency (IEA), CO2 intensity of energy mix (CO2/TES), Ghana 1990-2020, 2023online: https://www.iea.org/countries/ghana

[11] Umweltbundesamt, Kohlendioxid-Emissionsfaktoren für die deutsche Berichterstattung atmosphärischer Emissionen, 2022, online: https://www.umweltbundesamt.de/sites/default/files/medien/361/dokumente/co2_ef_liste_2022_brennstoffe_und_industrie_final.xlsx

Comparison of off-grid systems variations

Table 9 displays the system configurations, the investment cost, LCOE and the CO_2-emissions of the seven simulations carried out for off grid systems. The LCOE and CO2-emissions are displayed in Figure 16.

Table 9 Off-grid system simulation parameters

	Diesel Generator	**PV40 DG30**	**PV60 DG30**	**PV80 DG30**	**PV60 DG30 ES10**	**PV60 DG30 ES20**	**PV60 DG30 ES30**
Diesel generator power [kW]	35	30	30	30	30	30	30
PV power [kWp]	-	40	60	80	60	60	60
Energy storage capacity [kWh]	-	-	-	-	10	20	30
Demand covered	True	True	True	True	True	True	True
Investment cost [US$]	16380	33880	43800	53720	55800	67800	79800
System LCOE [US$/kWh]	0.55	0.44	0.39	0.31	0.33	0.33	0.36
CO_2-emissions [t]	827.721	555.479	484.643	382.206	400.598	384.566	414.225

Figure 16 illustrates the LCOE and the CO_2-emissions of the seven off-grid system simulation. The simulation *DG35* is used as a reference. Even though the investment for this energy system are the lowest, the system LCOE (0.55 US$/kWh) is the highest of all simulations. The same applies for the annual CO_2-emissions. As PV power increases, both LCOE and CO_2-emissions decrease. By adding an energy storage with a capacity of 10 kWh to the 60 kWp PV system the LCOE and the CO_2-emissions decrease even further. If the storage size increases the LCOE and the CO_2-emissions start increasing again. By observing this behaviour, the implementation of a PV-system to an off-grid energy system is highly recommended. It appears that at this stage it is better to invest into a larger PV plant compared to a smaller PV plant and an energy storage.

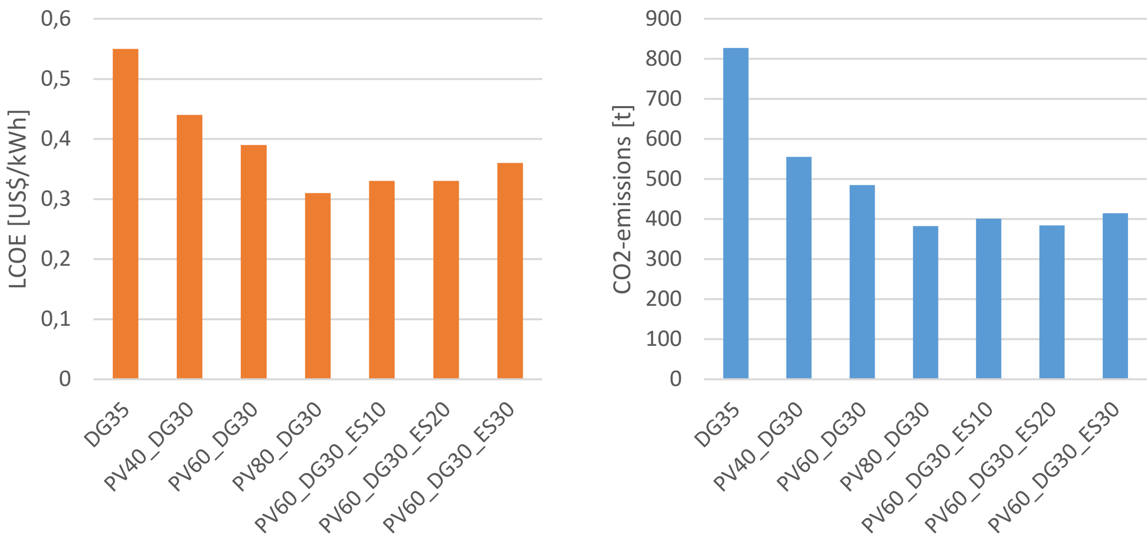

Figure 16 LCOE and CO2-emissions for off-grid system configurations

Comparison of grid-connected systems variations

Table 10 displays the system configurations, the investment cost, LCOE and the CO_2-emissions of the seven simulations carried out for off grid systems. The LCOE and CO2-emissions are displayed in Figure 16.

Table 10 Grid connected system simulation parameters

	Grid	PV40	PV60	PV80	PV60 ES10	PV60 ES20	PV60 ES30
Grid	True	True	True	True	True	True	True
PV power [kWp]	0	40	60	80	60	60	60
Energy storage capacity [kWh]	0	-	-	-	10	20	30
Demand covered	True	True	True	True	True	True	True
Investment cost [US$]	0	19840	29760	39680	41760	53760	65760
System LCOE [US$/kWh]	0.14	0.10	0.08	0.09	0.10	0.09	0.09
CO_2-emissions [t]	414.648	277.918	230.298	252.41	256.188	212.253	198.831

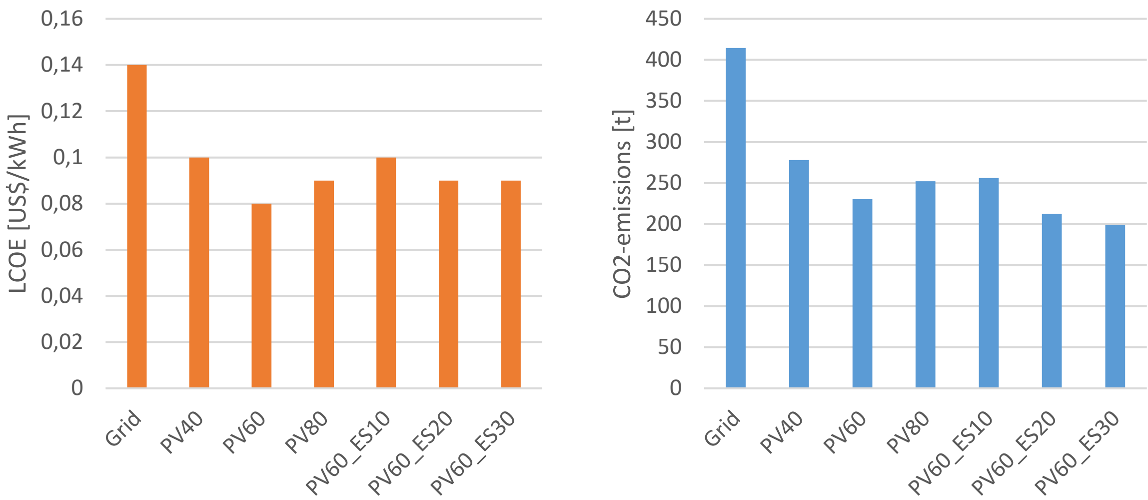

Figure 17 LCOE and CO2-emissions for grid connected system configurations

Figure 17 illustrate the LCOE and the CO_2-emissions of the seven grid-connected system simulation. The simulation *Grid* is used as a reference. Although no additional investment is required when sourcing from the grid, both LCOE (0.14 US$/kWh) and CO2 emissions (414 t) are significantly higher compared to the other simulations. In contrast to the simulations of the off-grid systems, the energy system with the 60 kWp PV system has the lowest LCOE. Since the electricity to be substituted from the grid is significantly cheaper than the electricity provided by the diesel generator, the additional investment cost of a larger PV system outweighs the revenues. The use of larger storage systems (20 kWh/30 kWh) reduces LCOE and CO2 emissions compared to smaller storage systems (10 kWh). The implementation of PV systems into grid-connected energy systems has a positive impact on the LCOE and the CO_2-emissions. From an economical point of view adding energy storages to the system is not feasible at this time. However, from an ecological standpoint adding larger storage systems to the systems is reasonable.

Summary

MiGUEL is able to simulate both off-grid and grid-connected energy systems. It provides comprehensible results to the user that can be used for further research and in-depth analysis and gives an overview over the most important findings as well as the system evaluation. Furthermore, *MiGUEL* has a low entry barrier since the program can run simulations with little, basic parameters. It must be said that the quality of the input parameters influences the accuracy of the simulation result. The tool offers the possibility to the user to provide data sets to the simulation. This extends the spectrum of the tool from simpler simulations, without data sets, to more accurate simulations based on measurement data.

MiGUEL is capable to simulate the following system components:

- Load
- PV systems
- Wind turbines
- Diesel generators
- Power grid
- Energy storages

These system components give a wide variety off different system configurations. By using weather data from the PVGIS server systems can be modeled all over the world by entering the respective coordinates. The components PV and wind turbine use existing libraries. The model for diesel generators, energy storages and power grids are developed in the course of the *EnerSHelF* project. These models are simplified in comparison to the existing libraries *pvlib* or *windpowerlib*. This is due to the given time frame. However, this does not affect the goal of developing a modeling tool for PV-diesel hybrid systems. In the future more accurate models for diesel generators and energy storages can be added to MiGUEL to provide even more accurate simulations-

Depending on the system configuration the tool runs the dispatch with different system priorities. The system is evaluated based on the LCOE and CO_2-emissions. Both evaluations use specific literature values. The values are implemented in the program due to the focus on an easy entry barrier. The values might vary at different locations and in the future. This issue is solved by manually entering the specific values or real plant values. Nevertheless, the specific values are necessary to keep the entry barrier for the tool low.

The report gives a consistent output of the most important findings. This creates easy comparability of the individual system variations. The influence of a single system component on the energy system can be easily tracked by comparing the LCOE and the CO_2-emissions of the system variations.

1.1.6. Summary of results and conclusions under WP3

Within work package 3.1, minute-by-minute load data could be collected for various departments in Saint Dominic Hospital. The data sets for network analysis are partially incomplete. Nevertheless, knowledge about the blackout behaviour could be gained from the available data sets. The load data was used to create standard load profiles for Ghanaian healthcare facilities. An open-source tool (*Load Profile Creator*) was created and published on *GitHub* to create load profiles for objects based on the electrical inventory in the facility. The *Load Profile Creator* can be used to model a more accurate load profile compared to standard load profile.

MiGUEL was developed in work package 3.3. *MiGUEL* focuses on having a low entry barrier for users. No data sets are required for use. The simulation can be carried out with a few simple parameters. Furthermore, the user only requires basic programming skills. The second focus of *MiGUEL* is to deliver comprehensible results. The simulation results are output in the form of a csv-file and a pdf-report. The csv-file is meant for scientific use and further research. The report can be used as a project brochure. It contains an overview of the most important findings, input data, information about the energy system and evaluates the system with the LCOE and CO_2-emissions. The report gives the opportunity to compare system variations in a quick manner.

MiGUEL is capable of simulating off-grid and grid-connected energy systems. By providing blackout data to the tool, unstable grid-connected systems can be simulated as well. The following system components can be simulated: load, PV systems, wind turbines, diesel generators, power grid and energy storages. The models to simulate the system components are partially developed, partially use existing libraries e.g. *pvlib* partially self-developed models.

The sensitivity analysis proves that MiGUEL is capable of evaluating PV-diesel hybrid systems. The calculated LCOE is in line with the market. The system variations can be compared briefly by looking on the first page of the report. More details regarding the evaluation and system configuration are provided in the other chapters of the report.

2. Publications during period under review

2.1 Journal articles

Chaaraoui, S., Bebber, M., Meilinger, S., Rummeny, S., Schneiders, T., Sawadogo, W., Kunstmann, H., 2021. Day-Ahead Electric Load Forecast for a Ghanaian Health Facility Using Different Algorithms. MDPI energies, 14(2), 409. DOI: https://doi.org/10.3390/en14020409

2.2 Other types of publications

Bebber, M., Meilinger, S., Chaaraoui, S., Rummeny, S., Schneiders, T., Waffenschmidt, E., 2021. Modellierung und Evaluierung eines PV-Diesel-Hybrid-Systems für ein Krankenhaus in Ghana. Proceedings of the 36th PV-Symposim, 18.-26. May 2021, 348-349.

Bebber, M., Meilinger, S., Chaaraoui, S., Rummeny, S., Schneiders, T., Waffenschmidt, E., 2021. PV-Diesel-Hybrid-System für ein Krankenhaus in Ghana – Anbindung eines PV-Batteriespeichermodells an ein bestehendes Generatormodell/PV-diesel-hybrid system for a hospital in Ghana – Connection of a PV battery storage model to an existing generator model. IZNE Working Paper Series Nr. 21/3. DOI: https://doi.org/10.18418/978-3-96043-091-9

Ramde, E.W., Rummeny, S., Schneiders, T., Waffenschmidt, E., Chaaraoui, S., Bebber, M., Meilinger, S., 2020. "Planning of sustainable and stable micro grids for Ghanaian hospitals with photovoltaics". SDEWES Conference Paper

2.3 Poster presentations

Bebber, M., Meilinger, S., Chaaraoui, S., Rummeny, S., Schneiders, T., & Waffenschmidt, E. Modellierung und Evaluierung eines PV-Diesel-Hybrid-Systems für ein Krankenhaus in Ghana, PV-Symposium 2021, online.

Bebber, M., Meilinger, S., Chaaraoui, S., Rummeny, S., Schneiders, T., & Waffenschmidt, E. Modellierung and evaluation of a PV-diesel hybrid system for a hospital in Ghana, 3rd International Conference on Solar Technologies & Hybrid Mini Grids to improve energy acces, 2021, online.

Yousif, R., Kimiaie, N., Meilinger, S., Bender, K., Abagale, F. K., Ramde, E., Schneiders, T., Kunstmann, H., Diallo, B., Salack, S., Denk, S., Bliefernicht, J., Sawadogo, W., Guug, S., Rummeny, S., Bohn, P., Chaaraoui, S., Schiffer, S., Abass, M. & Amekah, E., 2022. Measurement data availability within EnerSHelF. EMS Annual Meeting Abstracts, Vol. 19, EMS2022-530, 2022. https://doi.org/10.5194/ems2022-530

2.4 Talks, speeches and lectures

T. Schneiders, P. Bohn; 2023; Analyzing load profiles and designing solar energy installations with the newly-created open-source tool MIGUEL; EnerShelf closing workshop, Accra/Ghana, 07.03.2023

T. Schneiders, P. Bohn; 2023; Electricity demand of the Ghanaian Health Sector (WP3.1); EnerSHelF Closing Symposium, Accra/Ghana, 14.02.2023

T. Schneiders, P. Bohn; 2023; Hybrid energy systems with photovoltaics, diesel generators and batteries - - offgrid and grid-connected; lecture at Accra Technical University, Accra/Ghana, 10.03.2023

T. Schneiders,; 2019; „Father Franz Kruse Solar Energy Project" Solar Energy for the St. Dominic's Hospital in Akwatia, Ghana and the follow-up research project „EnerShelf - Energy Self-sufficiency for Health Facilities in Ghana"; EnerShelf kick-off workshop, Accra, 21.08.2019

3. Milestones (M)

Number	Description	Due date (month)[1]
M3.1	Data collected for WP3.1	0
M3.7	System Design Tool developed and validated	0
M3.9	Sensitivity analysis performed	0

4. Deliverables (D)

Number	Description	Due date (month)[1]
D3.1	Validated set of measurement data from WP3.1	0
D3.7	System Design Tool and guideline	0
D3.9	Results of the sensitivity analysis documented	0

[1] Period under review: M32 – M43 (01.01.2022 – 31.12.2022)

Colour code:
- Not yet due during period under review
- Completed
- Delayed or cancelled

5. Exploitation plan

5.1 Economic prospects of success

The data and findings have been incorporated into the open source modelling tool MiGuel, which is publicly available free of charge via the GitHub web platform. This tool enables the design of local energy systems with photovoltaic battery storage, diesel generators with grid connection or as stand-alone systems. This tool is already being used by project partners in Ghana and has also been introduced in other countries (e.g. Brazil).

The advantages of MiGUEL compared to other tools (e.g. Homer, PV*Sol) is including its free availability, extensive functionality and the associated documentation, which allow the tool to be used and customised to individual specifications. It thus enables students and trained professionals to plan energy systems competently and comprehensively as part of their training or as a basis for their professional activities. This supports the integration of renewable energies into local energy systems especially in emerging and developing countries. It is also possible to apply the tool for the analysis of off-grid systems (e.g. sewage treatment plants, emergency power supply) in Germany.

5.2 Scientific and/or technical prospects of success

Partner	Exploitation	Time horizon (planned)	Implementation (%)
CIRE	Completion of a tool as planning basis for (hybrid) is-land-capable power grids	Towards the end of project	100
CIRE	Publication of the planning tool on Github	1-3 months after project end	100
CIRE	Use of the planning tool for the implementation of grid-capable power grids in other projects	From 3 months after project end	100

The tool was presented to university partners in Ghana and Brazil. Here, it will become part of vocational training in the field of energy technology at universities and further education institutions (e.g. SENAI). Users have the opportunity to supplement the Python-based tool with their own data and to further develop the content of the tool (e.g. inclusion of other renewable energies such as hydropower, biomass). MiGuel will also be used and further developed in teaching and research at TH Köln.

5.3 Scientific and economic connectivity

The investigations have shown that there is practically no reliable knowledge about the load behaviour of consumers (e.g. industry, stand-alone grids for municipalities) and the associated economic usability of photovoltaic hybrid systems. In addition, the interaction of photovoltaics with often existing diesel generators has not been sufficiently investigated in practice, which leads to insufficient coverage by photovoltaics. Further projects should investigate these load cases and analyse the interaction of photovoltaics and diesel generators using measurements and different setups (photovoltaics supplements diesel generators partially or completely as an off-grid system). This would provide further important insights into the increased market penetration of photovoltaics in previously fossil-fuelled generation systems with diesel generators (approx. 1,000,000 diesel generators worldwide).

5.4 Important items of numerical evidence

Most important budget items included staff, travelling and measuring equipment used in Ghana. Due to the restrictions by the CoVid pandemics, the project duration and budget was extended from originally three years (01/06/2019 – 31/05/2022) to the 31/12/2022. In addition, a cost-neutral extension of another three months was carried out with the project finally finishing at 31/03/2023.

5.5 Necessity and appropriateness of the project work carried out

The budget was spent as foreseen with some minor deviations. Most important budget items included staff, travelling and measuring equipment used in Ghana. No additional budget from other projects was spent in the project. Due to the CoVid pandemics and the travelling restrictions in the course of the project, some travelling budget was shifted to local workers´ payments.

5.6 Progress in the field of the project by other parties during the implementation of the project

The progress in the field of the project by other parties was monitored during the project. However, no progress in other projects or by other parties was made known to the grant recipient during the implementation of the project. Thus, no adjustment of project contents or goals was necessary.

6. Summary

1.	**Summary of the most important scientific and technical results and other significant events**
	Within work package 3.1, minute-by-minute load data could be collected for various departments in Saint Dominic Hospital. The data sets for network analysis are partially incomplete due to technical challenges. Nevertheless, knowledge about the blackout behaviour could be gained from the available data sets. The load data was used to create standard load profiles for Ghanaian healthcare facilities. An open-source tool (*Load Profile Creator*) was created and published on *GitHub* to create load profiles for objects based on the electrical inventory in the facility. The *Load Profile Creator* can be used to model a more accurate load profile compared to standard load profile. *MiGUEL* was developed in work package 3.3. *MiGUEL* focuses on having a low entry barrier for users. No data sets are required for use. The simulation can be carried out with a few simple parameters. Furthermore, the user only requires basic programming skills. The second focus of *MiGUEL* is to deliver comprehensible results. The simulation results are output in the form of a csv-file and a pdf-report. The csv-file is meant for scientific use and further research. The report can be used as a project brochure. It contains an overview of the most important findings, input data, information about the energy system and evaluates the system with the LCOE and CO_2-emissions. The report gives the opportunity to compare system variations in a quick manner. *MiGUEL* is capable of simulating off-grid and grid-connected energy systems. By providing blackout data to the tool, unstable grid-connected systems can be simulated as well. The following system components can be simulated: load, PV systems, wind turbines, diesel generators, power grid and energy storages. The models to simulate the system components are partially developed, partially use existing libraries e.g. *pvlib* partially self-developed models. The sensitivity analysis proves that MiGUEL is capable of evaluating PV-diesel hybrid systems. The calculated LCOE is in line with the market. The system variations can be compared briefly by looking on the first page of the report. More details regarding the evaluation and system configuration are provided in the other chapters of the report.
2.	**Current status of the project as compared to the originally granted (or as per changes approved by donor) work, time and expenditure plans (max. 4000 characters)**
	The project objectives of work packages 3.1 and 3.3 were achieved over the project duration. In addition to the objectives of work package 3.1, all measuring equipment was handed over to Ghanaian project partners who will continue the work in the future. MiGUEL (WP 3.3) will be further developed in the future by project member Paul Bohn. Progress and extensions will be updated in the GitHub repository.
3.	**Have the prospects for achieving the targets within the project term changed as compared to the original project proposal (motivation)? (max. 4000 characters)**
	Due to Corona pandemic, some delays occurred for the setup of the load measurements and local collaboration on-site in Ghana wasrestricted. However, this could be compensated by a stronger involvement of the local partners that lead to the successful installation of measuring equipment and collection of load data.
4.	**Have any original results or findings been published by third parties that may affect the project's implementation? (Presentation of current information research according to Nr. 2.1 BNBest-BMBF 98) (max. 4000 characters)**
	No
5.	**Is or will there be a need for adjusting the objectives? (max. 4000 characters)**

	No
6.	**Update of exploitation plan. This section should contain information on the following topics as far as applicable (company secrets of the grant recipient do not need to be disclosed):**
	X Pos. 6a to 6d: No changes as per project proposal
6a.	*Inventions, applications for industrial property rights and granted industrial property rights that were made or used by the grant recipient or by those involved in the project, as well as their location-based exploitation (licenses etc.) and recognizable exploitation options, (max. 4000 characters)*
	None, all results and the energy system modelling tool MiGUEL (Micro Grid User Energy Planning Tool Library)-were published as public source (https://github.com/topics/pv-diesel-hybrid-systems).
6b.	*Economic prospects of success after the end of the project (with time horizon) - e.g. also functional / economic advantages over competing solutions, benefits for different user groups / industries in Germany, implementation and transfer strategies (information and type of project allow this), (max. 4000 characters)*
	The data and findings have been incorporated into the open source modelling tool MiGuel, which is publicly available free of charge via the GitHub web platform. This tool enables the design of local energy systems with photovoltaic battery storage, diesel generators with grid connection or as stand-alone systems. This tool is already being used by project partners in Ghana and has also been introduced in other countries (e.g. Brazil). The advantages of MiGUEL compared to other tools (e.g. Homer, PV*Sol) is including its free availability, extensive functionality and the associated documentation, which allow the tool to be used and customised to individual specifications. It thus enables students and trained professionals to plan energy systems competently and comprehensively as part of their training or as a basis for their professional activities. This supports the integration of renewable energies into local energy systems especially in emerging and developing countries. It is also possible to apply the tool for the analysis of off-grid systems (e.g. sewage treatment plants, emergency power supply) in Germany.
6c.	*Scientific and economic connectivity for a possibly necessary next phase or the next innovative steps to successfully implement the results. (max. 4000 characters)*
	The investigations have shown that there is practically no reliable knowledge about the load behaviour of consumers (e.g. industry, stand-alone grids for municipalities) and the associated economic usability of photovoltaic hybrid systems. In addition, the interaction of photovoltaics with often existing diesel generators has not been sufficiently investigated in practice, which leads to insufficient coverage by photovoltaics. Further projects should investigate these load cases and analyse the interaction of photovoltaics and diesel generators using measurements and different setups (photovoltaics supplements diesel generators partially or completely as an off-grid system). This would provide further important insights into the increased market penetration of photovoltaics in previously fossil-fuelled generation systems with diesel generators (approx. 1,000,000 diesel generators worldwide).