Sizing and Optimization of Hybrid Mini-Grids with *micrOgridS* - an Open-Source Modelling Tool

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Abstract—**The transformation towards a sustainable, affordable and reliable energy system remains a challenging task for many island communities. The electric power supply through Hybrid Mini-Grids (HMG), containing RE technologies and energy storage systems in the mix, represent a cost-effective and fuel saving option. In the planning phase of HMG, software-based sizing tools have become necessary to map the complex interactions between the different sources of electricity. In this study we identify the requirements for such a software tool, and investigate on the advantages of open source modelling. Based on our findings, the open source model micrOgridS was developed by applying the Open Energy Modelling Framework (Oemof). As a result, we introduce the model in this paper and show its performance via a case study by comparing it with the software tool Homer® Pro 3.11. Drawing on the results, we conclude that with micrOgridS, we provide a valid basis for a open source HMG sizing tool.**

I. INTRODUCTION

In the Sustainable Development Goal # 7 (SDG7) the United Nations agreed to assure universal access to affordable, reliable and modern energy by 2030 [1]. Hence, a transformation of the existing, predominately fossil-based global energy system towards higher shares of renewable energy (RE) is required. Looking at the global electricity generation in 2015, fossil energy sources accounted for 66.3 % (39.3 % coal, 22.9 % natural gas and 4.1 % oil) of the 24,255 TWh of total generated electricity [2], whereas RE accounted for only 23.1 %. An even higher share of fossil-based electricity generation is widely obtained in remote regions with low economic capabilities, such as the Small Island Developing States (SIDS). Due to the fact that for many of island communities the conventional approach of grid extension is unprofitable, the energy supply on islands is widely realized through a set of diesel generation units that operate a decentralized and isolated distribution grid. For example, referring to the Pacific Islands Countries and Territories (PICT), as a subcategory of SIDS, these regions are marked by a strong dependency on imported petroleum goods, a costly energy infrastructure and a high threat towards effects of climate change [3].

The introduction of additional power generation sources, preferrably renewable based, into diesel powered grids is called hybridization. Hybridization is considered successful in case the specific fuel consumption of a mini-grid can be reduced [4]. Consequently, further advantages can be achieved including lower greenhouse gas emissions (GHG) as well as a decreasing dependency on oil price volatility, and a shift towards modern energy technologies. In addition to that, HMG are found the most cost effective option for many island power supply systems [5] due to the drastic decrease in mature RE technology cost, especially for PV, and storage capacity cost [6]. As a result, many PICT governments have defined ambitious RE targets within their Nationally Determined Contributions (NDCs). For example, the kingdom of Tonga, of which oil imports accounted for 18 % of the GDP in 2015 [7], agreed on the implementation of 50 % RE until 2020 and 70 % in 2030 [8].

One of the challenging aspect that arise with the integration of RE technology is an increased uncertainty associated with the planning and forecasting resulting from the interrupted temporal availability of the natural renewable resources. RE in combination with diesel generator sets and storage options lead to a complex system of interactions that has to be described and optimized (technically, economically and environmentally) within the planning phase of HMG. Consequently, software based sizing tools become crucial to deal with the increased complexity of interactions through RE technology, provide briefings for decision making by calculating a optimized set of solutions, and to develop scenarios to energy transition pathways that play a key role for policy making and project implementation [9].

As political decision making is mostly closely tight to public participation, Morrison points out to open source energy models as being notably valuable due to such models can increase transparency and public trust [10]. Following an argumentation on open source energy models in the context of scientific research by [11], it is stated that proprietary software tools are inapplicable as the scientific standards, such as transparency and reproducibility can only be met by open source software tools. Drawing on that, possible advantages that open source tools could impart in energy system planning and operation management of HMG are: an increased transparency in scientific electrification pathway studies, a reduction of barriers associated with bottom up planning resulting from high license cost, foster inclusive planning approaches though collaborative modelling and community-based model-development. This supports both public and private decision makers in convincing all involved stakeholders, for example the local community, financing institutions, and regulatory authorities, on the validity of the planned hybridization projects and strategies.

Currently, there is a lack of sufficient open-source software tools for mini-grid sizing in the global modelling community. The most commonly applied tool is Homer®

TABLE I
COMPONENT-SPECIFIC REQUIREMENTS FOR A SUFFICIENT SOFTWARE TOOL (STAKEHOLDER WORKSHOP FINDINGS)

high priority	**medium priority**	**low priority**
solar PV	wind turbine	geothermal component
generic energy source	biomass	tidal sources
	hydro-turbines	
Lead-Acid BSS	thermal storage	Redox-Flow BSS
Li-ion BSS	fuel cell	high temperature BSS
generic storage		pumped hydro storage
controller strategies	grid	
multiple DGs		
inverters		
AC- and DC coupling		

Pro but it is a commercial software and the code is not open. Thus we elaborate the requirements for a comprehensive open-source software tool for the purpose of optimized HMG system sizing and operation management in this work. On the basis of our findings the open-source tool micrOgridS was developed and validated. In this study the basic approach behind the tool is introduced and analyzed with respect to the defined requirements as well as a case study of a Pacific Island energy system is shown.

II. METHODS

A. Requirements for a comprehensive software tool

A stakeholder workshop was conducted to determine the requirements for a software sizing tool for the purpose of optimal HMG design. Together with nine micro-grid experts coming from academic institutions, as well as from private companies the requirements were elaborated. Results show that a comprehensive software tool for optimal HMG design, should be capable of:

- system sizing and identification of optimal operational strategies
- multi-objective optimization (cost of energy, emissions, capacity shortage, RE share)
- adjustable time resolution (15 minutes to hourly time increments)
- grid stability functions
- modelling different HMG components (high-, medium- and low priority)
- secondary functionality (couple with resource data and load profiles, update uncertain parameters over the course of optimization horizon).

In Table I the required component models are depicted and characterized according to the resulting prioritization, that is drawn from the workshop results. Following the discussion on requirements for a comprehensive tool, it is found that applicability of a tool would increase if the results are validated and if easy-to-use capabilities are integrated in the software tool. In addition to that, a modular structure is preferred by the stakeholder group, that incorporate the possibility to extend and link the tool to other use cases, modelling libraries and databases.

B. Tool design based on the Open Energy Modelling Framework (Oemof)

The Open Energy Modelling Framework is a generic, open-source toolbox that holds a range of useful functions to describe and optimize energy systems. By calling it generic, we mean that Oemof is not programmed for specific applications that follow one specific mathematical approach. Furthermore it can be utilized for various optimization tasks. Omeof's developer community is embedded in the Open Energy Modelling Initiative, which follows strict open-source, open-data and open-science policies. Oemof is programmed in the object-oriented programming language Python, and its development follows scientific standards.
To describe an energy system in Oemof, a graph based approach is used in which energy system components are, basically, represented by $Nodes$-objects that are connected via $Flow$-objects. Furthermore, the $Nodes$ are classified into subclasses, including *Source*s, *Sink*s *GenericStorage*. This structure allows to separate the energy system model from the mathematical parameterization and the solving process. Following the description in energy system modelling with Oemof, the paramterization of the system components is mainly done by adding attributes to the $Flow$-objects. Other aspects to considered Oemof as generic are represented by its generic objects (subclasses of the $Nodes$) that can be used to describe various system components as well as no units are associated within the energy system model. Drawing on that, we assume an increased modularity and flexibility in the modelling practise. Taking an example of describing a PV system that supplies direct current on the DC-bus, in that case both the PV system and the DC bus would be described as $Nodes$ that are connected via directed $Flow$s. The $Flow$ holds various attributes, such as actual_value (series, gen. specific power output) , nominal_capacity (gen. rated capacity) , variable_cost (gen. specific cost per rated capacity), fixed (True means that the output is determined by the actual_value and is not variable). In the given example the value of the flow would be interpreted as the power output of the PV plant, and could therefore be written as:

$$\text{flow.value}(t) = \text{flow.actual\_value}(t) \cdot \text{flow.nominal\_value} \tag{1}$$

$$P_{pv}(t) = p_{pv}(t) \cdot P_{pv,rated} \tag{2}$$

Following this approach, a set of equations is generated that represent the graph-based model of the energy system. The energy system model can than be transformation into an optimization problem by adding it to a *Model*-object and defining the optimization horizon (also referred to as *prediction horizon* PH). Throughout this step an objective function representing the sum of all attributed costs is generated, that has to be minimized, is initialized:

$$\min c^T \cdot x \tag{3}$$

where c describe the cost and x a set of decision variables.

Once the energy system model is described and the optimization task is set up by defining the *Model*, the problem then can be solved. To achieve this, four solvers

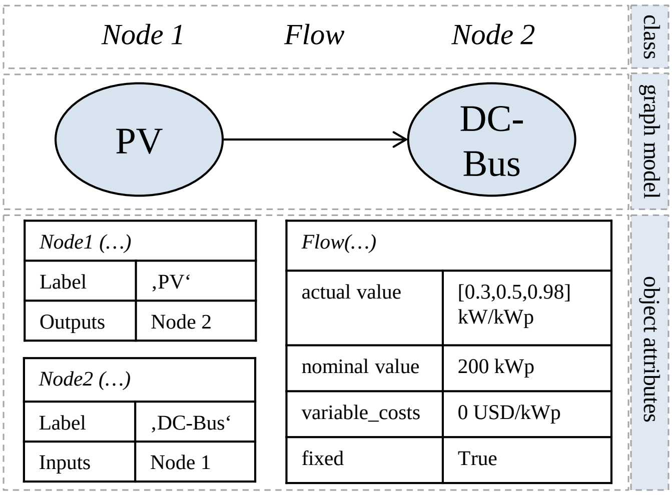

Fig. 1. Simplified schematic model of a PV system contributing to the DC-bus

are linked with Oemof, namely Coin-OR (CBC), Glpk, Gurobi®, Cplex that can be utilized [12].

III. RESULTS

Considering a set of simplifications and assumptions, the micrOgridS tool was developed to support the project development of a PV-diesel-battery HMG by providing both optimized sizing of system components and optimized dispatch of power flows. This is achieved by minimizing a single objective function representing the total cost of the system TC, as shown in (4),

$$\begin{aligned} {}_{min}TC = & \sum_{\mathrm{j}} (CC_{\mathrm{j}} + OPEX_{\mathrm{j}}) \\ & + AWC + \sum_{dg} FC_{\mathrm{dg}} \qquad \text{for } \forall \mathrm{j}, \forall \mathrm{dg} \end{aligned} \tag{4}$$

where CC_{j} are the component cost, and $OPEX_j$ represent the operation and maintenance cost for all system components j, respectively; AWC are wear costs associated with the BSS; and FC_{dg} represent fuel cost for all diesel generator components dg.

In Fig. 2 the schematic illustration of the energy system model is depicted as it is implemented in micrOgridS. It is shown that the energy system model is composed of the following components :

- a DG set including 3 units (DG1, DG2, DG3)
- a PV system
- a battery storage system
- an inverter unit
- an aggregation of loads
- a dump for excess energy
- a fuel source

Each component is connected to one of three *Bus*ses via *Flow*s. The *Bus*ses can be classified into a DC-, an AC- and a Fuel bus, respectively. Therefore, the following balance equations can be derived for each *Bus* that have to be met at every single time step of the optimization.

DC-bus balance:

$$0 = P_{\mathrm{pv}}(t) + P_{\mathrm{bss,out}}(t) - P_{\mathrm{bss,in}}(t) - P_{\mathrm{inv,in}}(t) \tag{5}$$

AC-bus balance:

$$0 = P_{\mathrm{inv,out}}(t) - P_{\mathrm{load}}(t) - P_{\mathrm{ex}}(t) + \sum_{0}^{\mathrm{dg}} P_{\mathrm{dg}}(t) \qquad \text{for } \forall \mathrm{dg} \tag{6}$$

Fuel bus balance:

$$0 = fuel_{\mathrm{source}}(t) - \sum^{\mathrm{dg}} fuel_{\mathrm{dg,in}}(t) \qquad \text{for } \forall \mathrm{dg} \tag{7}$$

Due to the generic character of Oemof, no units are assigned to the *Flow*s by default. Moreover, the user is requested to determine the units and to ascertain their consistency. For the micrOgridS model, all *Flow*s are regarded as power flows in kW, except the *Flow*s being connected to the *Bus*-object representing the Fuel bus. These *Flow*s represent actual fuel flows and are therefore given in Liters.

In analogy to Oemof, the model formulation is programmed in Python. At the moment the application of micrOgridS is suitable for sizing of PV and a BSS. Thus, sizing capabilities for DGs are not integrated due to their mathematical formulation result in nonconvex bound constraints (or integrality constraints), which can yet not be integrated in combination with sizing parameters of DG representing a decision variable. Further components such as loads (including aggregated appliances), inverters, AC and DC buses as well as a fuel commodity bus, and a dump for excess or surplus power flows, can also be modelled with micrOgridS.
The modelled power supply system is solved for an adjustable number of time steps, and with respect to a set of described constraints including:

- minimum and maximum power flow constraints associated with the dispatch of DGs
- spinning reserve provided by DGs or BSS
- rotating mass, which describes a defined share of load that has to be provided by accelerating power generation units (in this case referred to DG) and BSS
- a set that regulates generator order

Drawing on the possibility to calculate a optimized dispatch of power flows, comprehensive operational strategies can be identified by the practitioner. Calculation times for one reference year (of 8760 time increments) range from minutes to hours which opes up the debate upon the difficulty between describing the system's behaviour in a sufficient level of detail, and assuring applicability through acceptable computational times. However it has to be mentioned that the computational time achieved is strongly dependent on the hardware applied and the solver utilized. Hence, its quantification represents not always the global optimum but we found results within close range to this optimum.

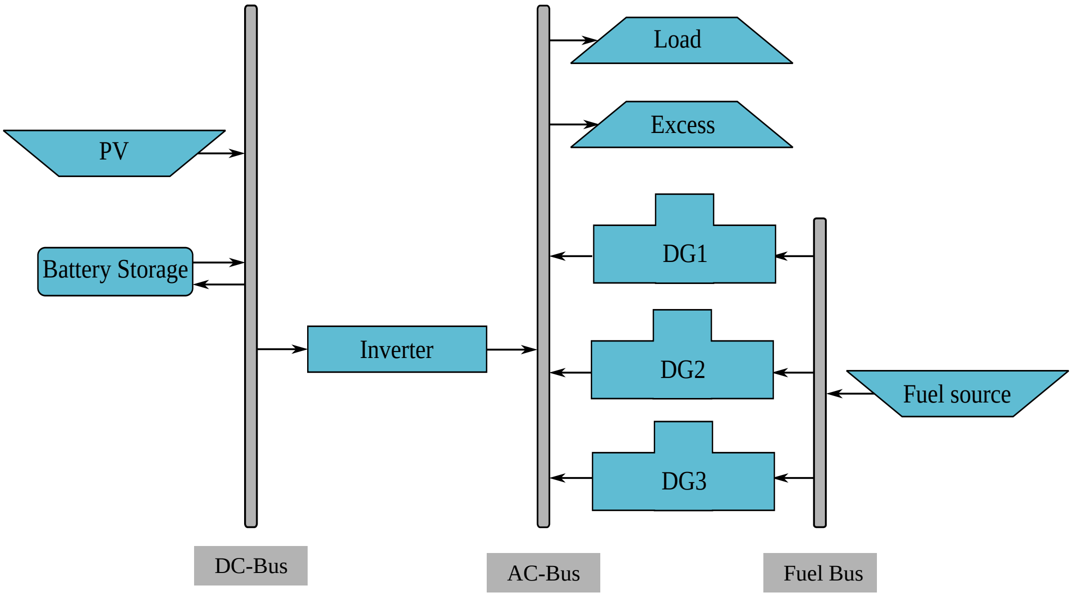

Fig. 2. Schematic overview of the Energy System Model

A. Application example of micrOgridS

The micrOrgridS model was tested in a case study for the Pacific island Lifuka, Tonga, located at latitude = -19.814545° and longitude = -174.35049°. In the case study the model was thoroughly analyzed and compared to results achieved with the software Homer ® Pro 3.11. The project lifetime is estimated to 20 years and the assumed WACC amounts to 0.094. Considering input data used in this case study, most of the values are derived from project specific values of the Outer Island Renewable Energy Project. Hence, load profiles show an overall annual energy demand of 1.35 GWha^{-1}, a peak load of 236 kW and an average load of 154 kW. In Table II the resource data are depicted that is used as an input to the model comparison. Hence, the Clearness Index k, the global horizontal irradiance GHI as well as the ambient temperature T_{amb} and the average wind speed v_{wind} are presented.

TABLE II
WEATHER DATA SET FOR LIFUKA ISLAND [1]

	k	GHI $\frac{kWh}{m^2 day}$	T_{amb} $\frac{°C}{day}$	v_{wind} $\frac{m}{s}$
Jan	0.574	6.69	25.81	6.34
Feb	0.566	6.3	26.4	6.18
Mar	0.559	5.62	26.24	6.14
Apr	0.543	4.65	25.56	7.5
May	0.56	4.04	24.17	7
Jun	0.547	3.58	23.17	6.91
Jul	0.554	3.78	22.27	6.91
Aug	0.557	4.43	21.96	6.95
Sep	0.554	5.23	22.1	6.17
Oct	0.587	6.28	22.59	6.74
Nov	0.583	6.69	23.65	6.75
Dec	0.57	6.7	25.03	7.17

The cost assumptions and installed capacities of the DGs are illustrated in Tab. III. It is shown that three diesel generators are modelled, of which DG1 and DG2 are being considered identical types.

TABLE III
INPUT PARAMETERS: CAPACITY OF DG AND COST OF SYSTEM COMPONENTS

parameter	unit	PV	BSS	DG1=DG2	DG3
installed capacity	kW	free	free	186	320
$CAPEX$	$\frac{USD}{kW}$	2500	300	500[2]	
$O\&M$	$\frac{USD}{kW}$, $\frac{USD}{kWh_{\mathrm{op}}}$	2.5[3]	3.88	0.02[2]	
lifetime	yrs	20	10	20	

Additional input parameters are attributed to the battery, such as the round-trip efficiency of 85 % and a constant C-rate of 0.546 $\frac{1}{h}$. The input parameters were used analogously in both models, micrOgridS and Homer®. Following this, the models were solved according to lowest power generation costs and results are achieved and compared, as illustrated in Table IV. From there, the resulting PV $P_{\mathrm{r,PV}}$ and BSS capacities $P_{\mathrm{r,BSS}}$ as well as levelized cost of electricity $LCOE$, the RE share, the consumed fuel and the excess energy can be obtained. It can be seen that the micrOgridS optimization show lower values for all compared parameters. The highest absolute deviation is found in the BSS size (-392 kW, which equals 46.9 % relative deviation) and excess energy (-20,739 which equals 35.7% relative deviation), respectively. We assumed that one explanation for the lower values can be found in the optimized operational strategy, which is another results of the micrOgridS optimization. This was validated by specifically simulating the optimized capacities of HOMER optimization in the micrOgridS tool which showed better operational performance of the system. The Homer® model applies a per-hour time step decision on the optimal dispatch of power flows. Consequently, the hourly dispatch of power flows and

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[1] These data were obtained from the NASA Langley Research Center Atmospheric Science Data Center Surface meteorological and Solar Energy (SSE) web portal. URL: *https://eosweb.larc.nasa.gov/cgi-bin/sse/sse.cgi?+s01+s04* (Accessed: 05.03.2018)

[2] [13]

[3] 1 % of $CAPEX$ based on [14]

TABLE IV
RESULTS

model	$P_{\mathrm{r,pv}}$ / kW	$P_{\mathrm{r,batt}}$ / kWh	$LCOE$ / USD kWh^{-1}	RE share / %	fuel / l	excess / kWh
micrOgridS	264	338	0.31	33.1	212,419	37,415
Homer®	288	730	0.34	34	266,012	58,154

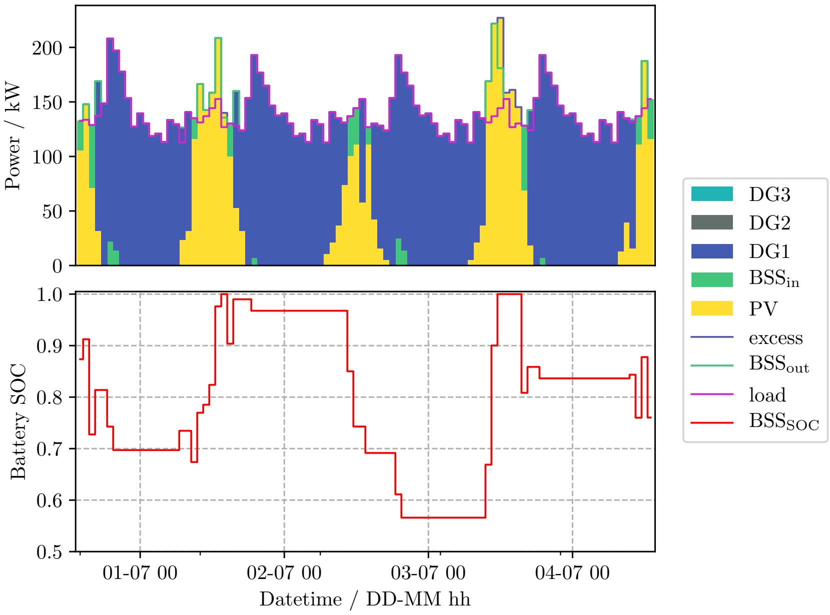

Fig. 3. Hourly dispatch of power flows: micrOgridS simulation for scenario a) (PH=8760)

the BSS State of Charge, that are both calculated with the micrOgridS model are depicted in Fig. 3 for an exemplified sequence of four days from 2017-06-30 until 2017-07-04. It shows an optimized strategy with perfect foresight. In reality it is difficult to achieve these results but it can serve as baseline for optimized operation strategies.

IV. CONCLUSIONS AND FURTHER STEPS

We conclude that with the development of micrOgridS a valid foundation was built for a HMG sizing tool that meets the requirement list. However a few limitations are identified that point out to future development regarding the enhanced applicability of micrOgridS including:

- clear definition of user/developer interfaces e.g. easy-to-use GUI development,
- reduce model complexity in favour of shorter computational time, e.g. investigate in time series aggregation approaches or incorporate rule-based dispatch strategies,
- investigate in more efficient solver strategies, e.g. heuristic algorithms

Additionally, further integration of multiple objective functions and additional components is required as well as the validation of micrOgridS with real operation data is desirable. As micrOgridS is closely tied to a community it is assumed to foster for collaborative development, which could broaden the perspectives on the modelling task, and for continuous maintenance support.

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Drawing on the multiple advantages in terms of collaborative modelling and community based software development, any kind of interest in collaboration in the future development process of micrOgridS is warmly welcomed and intended by the authors. If you are interested in collaboration or if any further information on the topic or data used for this study are required, please contact the authors. The source code of micrOgridS is available on Github: https://github.com/Py-micrOgridS/micrOgridS.git

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