A simulation tool to design PV-diesel-battery systems with different dispatch strategies

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***Abstract* — In far-off regions without a connection to the main grid, primarily diesel generators are used for the power supply. However, hybrid energy systems such as PV-diesel-battery systems have a high potential to reduce CO_2-emissions and fuel costs. As a challenge, on the one hand, smart dispatch strategies are required to compensate the limited part-load capacity of diesel generators and the volatility of PV-generation. On the other hand, generation and storage size have to get optimized to minimize the LCOE (levelized cost of electricity).**

This paper presents a GUI-based extension of a MATLAB Simulink tool to size generation and storage units for selectable dispatch strategies. Realistic outputs are achieved by applying the double diode model for PV plants, the shepherd model for batteries and a genset model to consider additional consumption and emission in volatile operations. As an example, a PV-diesel-battery micro grid of 25 households is simulated. Relevant thresholds for the CO_2-emissions and LCOE are shown.

1 Introduction

Diesel generators are often used for the power supply in remote areas. However, due to far transportation fuel and thus electricity costs are high. Moreover, to resolve the man-made climate change, especially greenhouse gas emissions from combustion engines must be avoided.

Renewable energy sources such as photovoltaic (PV) systems are profitable supplements to the power supply. The operation of such hybrid stand-alone power systems gets more complex, especially if a high penetration of PV is aimed. Therefore, part-load ranges below 50% and sudden load steps on diesel generators can lead to a reduced lifetime or higher emissions [1]. Sudden load steps can be buffered by a battery. However, an increasing number of cycles also reduces battery lifetime. Thus, a dispatch strategy which balances between generator and battery aging can improve the system operation economically and ecologically.

Common hybrid energy simulation software products are TRNSYS [2], INSEL [3], RETScreen [4], HOMER [5], Hybrid2 [6], iHOGA [7]. While [2] and [3] have a focus on technical detailed simulations, a flexible open architecture and dispatch strategies, [4] focuses on feasibility studies and general design. [5] and [6] offer multifunctional tools with dispatch, design and economic functions which are easy to use. Key features of [7] are a sensitivity analysis and optimization by a genetic algorithm.

In previous work an own MATLAB Simulink tool is created to evaluate different dispatch strategies for such hybrid energy systems [8]. The goal is to create a tool similar to [5], but including more realistic behavior models of PV, battery and diesel generators (further also named as gensets).

As a unique feature, this presented tool contains an advanced model of diesel generators which considers additional fuel consumption of sudden part load steps.

Additionally, a MATLAB GUI tool extension is presented which applies the Simulink tool multiple times designing the system by parameter variation. The aim is to manually find the optimal configuration for preferably low levelized costs of electricity (LCOE) and CO_2-emissions.

As an example, the design tool is applied to a PV-diesel-battery system with the load of 25 households (97.84 MWh/a) and an annual global radiation of 1,900 kWh/(m²*a).

2 Hybrid energy tool

The general structure of a hybrid energy system with photovoltaic (PV), genset power generation and a battery storage is shown in Figure 1.

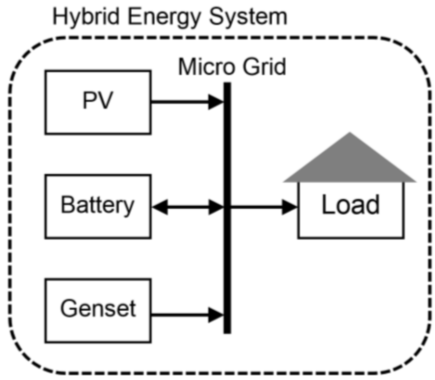

Figure 1: Structure of the hybrid energy system.

2.1 *Models of PV, Battery and Gensets*

The hybrid energy tool HOMER applies a simple model for photovoltaic power generation. The power is calculated with a linear dependency of the global radiation, cell temperature and derating factor [5]. Nevertheless, for a reliable simulation it is desirable to consider the physical behavior, i.e. the I-V-values of solar cells. The double diode model allows to simulate a PV output which is close to real measurements [9].

In this paper such a double diode model combined with a maximum power point (MPP) tracker is applied to simulate the PV output power. For the simulation module specifications such as short-circuit current, open-circuit voltage, I and V at MPP and temperature coefficients are required. However, the default set for these specifications is a proposed type out of an own linked database.

To simulate a realistic battery behavior the Shepherd equation is applied. This equation includes the terminal voltage of the battery and describes battery charging dependent on cell voltage and state of charge (SoC) [10].

Additionally, the Shepherd equation allows to describe battery discharging by means of experimental measured discharge curves and therefore can be applied to multiple battery types.

As a standard, the fuel consumption of a diesel generator is described by the break specific fuel consumption (BSFC) at various generator part loads [11]. However, this fuel consumption curve relates to measurements of static load tests. Additionally, in hybrid energy systems information of dynamic load behavior is important. The applied generator model is based on own field tests with a small genset (5 kVA). Additional fuel consumption was undetectable below load steps which correspond to 50% of the generator rated power. Following linear approach considers additional fuel consumption of generator part load steps higher than 50%:

$$FC_{add} = \left(0.16 \cdot \frac{|\Delta P|}{P_n} - 0.07\right) \cdot FC_{stat} \qquad (1)$$

with FC_{add} = Additional fuel consumption in liters
FC_{stat} = Static fuel consumption in liters
$\frac{|\Delta P|}{P_n}$ = Part load step of the generator

According to (1) the additional fuel consumption at a part load step of 50% is 1%, and at 100% about 9% additional to the static fuel consumption.

2.2 *Dispatch strategy*

The simulation tool contains different dispatch strategies which try to reduce fuel consumption while at the same time reducing harming effects such as low Part-load ranges and dynamics of the diesel generators or battery cycling and depth of discharge (DoD). Thus, they improve both economic and ecological efficiencies. The strategies vary in the priorities whether battery or gensets should age faster and how much energy gets wasted to reduce aging due to volatile operations.

In this paper a strategy is chosen in which the battery take precedence over gensets. However, gensets run only at their minimal loading while supply surpluses are covered by the battery again. Thus, balancing volatility is shared by the gensets (in noncritical part load range) and the battery (in critical part load rage).

The action priorities are shown in Figure 2.

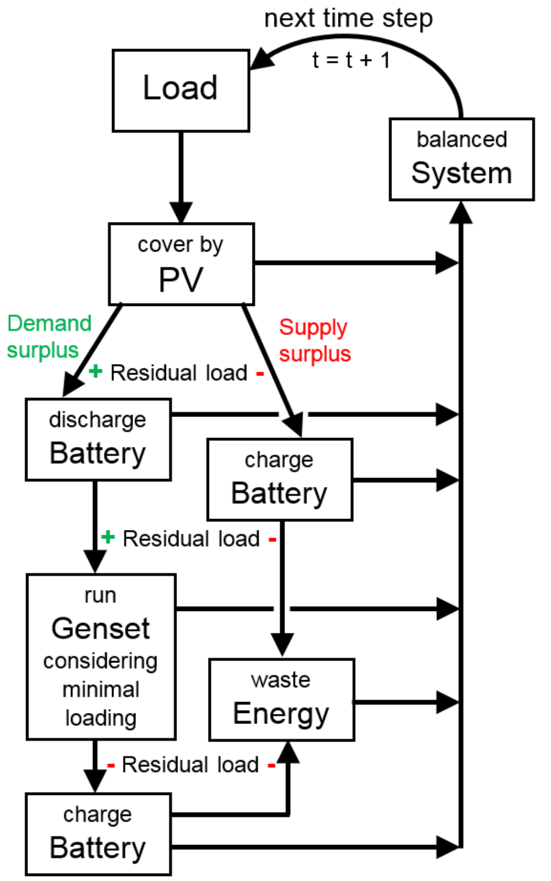

Figure 2: Action priorities of chosen dispatch strategy.

According to Figure 2, in the first priority, the load is covered by the PV system.

In case of a positive residual load (demand surplus) the battery discharges. If there is not enough battery discharge capacity a genset will get started. Considering the minimal load of available gensets, a generator could have to run at a higher load than demanded. In this case, the battery charges, if not fully charged, to balance the supply surplus. The last resort is to waste surplus energy.

In case of a negative residual load after the PV covering the load, the battery charges the supply surplus. If it is already fully charged, again, the surplus energy is wasted. Additionally, all previously running gensets are shut down.

Since the hybrid energy system is successfully balanced, the next time step of the load profile will be calculated.

Since all data of the load profile is processed, a simulation cycle is completed. Final results are time vectors of load, PV, battery, genset and wasted power. Also a time vector of fuel consumption is issued.

2.3 Designing tool

Based on the simulation where above-mentioned models get controlled by a dispatch strategy, a designing tool was created. The GUI-based application allows to vary the battery and PV plant size. The tool executes multiple simulation cycles, gathering the outputs for configurable variations.

As a reference, a cycle with only diesel generation is executed. This enables to evaluate savings which correspond to fuel consumption.

Finally, the LCOE is calculated by means of following simplified equation:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{2}$$

with I_t = Investment expenditures in year t
M_t = Operations and maintenance expenditures in year t
F_t = Fuel expenditures in year t
E_t = Electricity generation in year t
r = Discount rate
n = Life of the system

3 SIMULATION EXAMPLE

Hereafter, an example shall demonstrate the simulation tool to find economic and ecological suitable hybrid energy systems. For this example an annual load profile of 25 households is used. The total electricity consumption is 97.8 MWh/a and corresponds to a 32,867 l/a fuel consumption. The demanded power amounts to a maximum of 49.4 kW and an average of 11.2 kW.

The assumed configuration of four diesel generators is shown in Table 1.

Table 1: Assumed configuration of diesel generators

Genset	Power [kW_{el}]	Investment [$]	min. Load [%]
1	32.1	13,000	50
2	29.2	11,000	30
3	11.9	7,000	30
4	4.6	4,000	30
Total	77.8	35,000	

This diesel-system is designed to be able to cover the load of 45 kW_{el}, with three generators only for the case one generator is out of service.

For the determination of PV power an annual profile of 1,900 kWh/(m^2*a) is applied.

The proposed hybrid energy system costs are shown in Table 2.

Table 2: Costs of proposed hybrid energy system

Element	Investment Costs	Maintenance Costs
PV	2,500 $\$/kW_p$	25 $\$/(kW_p \cdot a)$
Battery	760 $\$/kWh$	20 $\$/(kWh \cdot a)$
Gensets	35,000 $	30 $\$/(kW_{el} \cdot a)$

Investment Costs of the PV and battery already includes the balance of system costs (e.g. construction and inverter costs). The proposed battery type is a lead-acid battery with the capacity-power ratio of 2 Wh/W. The maximum DoD is set to 60% and corresponding cycles per lifetime are 1,400.

For the diesel fuel price two scenarios are considered:

- Scenario 1: 0.90 $/l. This level is the world average and corresponds to current fuel prices e.g. in China, Ghana, Cape Verde, Paraguay and New Zealand.
- Scenario 2: 0.50 $/l. This level corresponds to fuel prices e.g. in Lebanon, Myanmar, Kyrgyztan, Bolivia and United Arab Emirates.

All fuel price information are accurate as at August 21, 2017 [12].

In the parameter variation tool 15 PV sizes up to 150 kWp are combined with 10 battery sizes up to 150 kWh.

The results of the LCOE calculation in fuel price scenario 1 is shown in Figure 3.

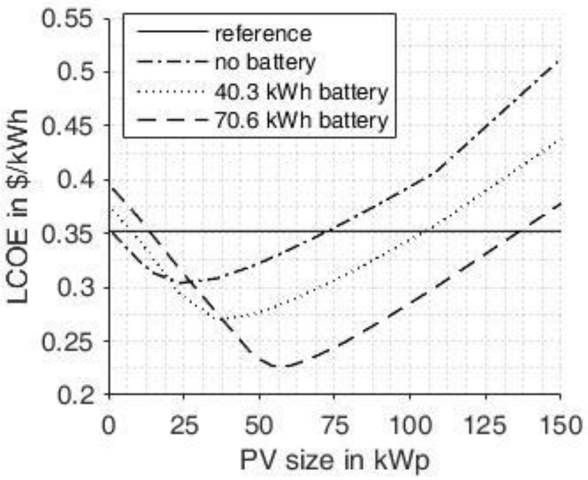

Figure 3: LCOE of PV-battery variations during fuel price scenario of 0.90 $/l.

According to Figure 3, the reference LCOE (0.36 $/kWh) represents the initial supply system of diesel generators only. However, the best LCOE of 0.23 $/kWh is reached by means of a 57 kWp PV plant and a 70.6 kWh lead-acid battery. With PV plants up to 24 kWp a system without battery has the lowest LCOE. With PV plant sizes between 24 and 32 kWp the combination with a 40.3 kWh battery is the most profitable.

The same parameter variation with a LCOE calculation in fuel price scenario 2 is shown in Figure 4.

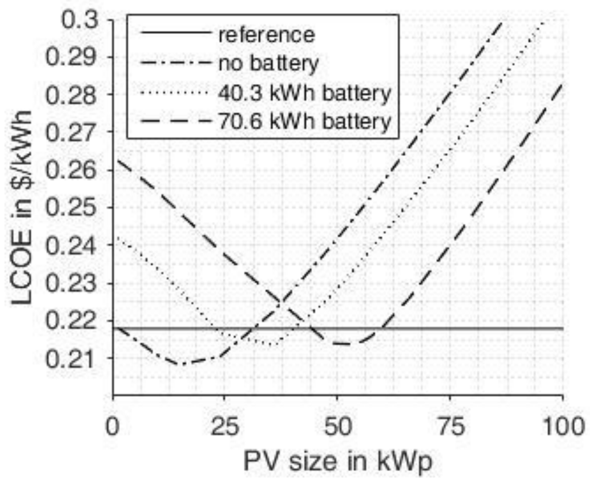

Figure 4: LCOE of PV-battery variations during fuel price scenario of 0.50 $/l.

Due to the low reference LCOE (0.22 $/kWh) in Figure 4 the profit margin with different PV and battery sizes shrinks to 0.01$/kWh. The most profitable system consists of a 16 kWp PV plant without any battery system (0.21 $/kWh). Nevertheless, a 40.3 kWh battery is profitable with a 32 kWp PV plant and a 70.6 kWh battery is profitable with a 57 kWp PV plant (both approx. 0.215$/kWh).

Figure 5 shows the fuel saving potential with different PV and battery sizes.

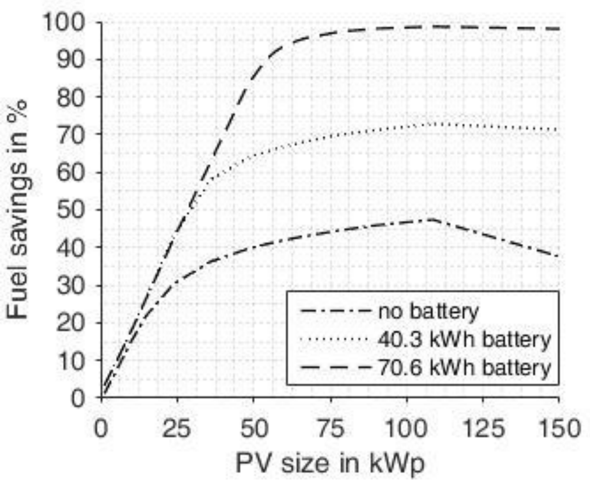

Figure 5: Fuel savings at different PV and battery sizes.

PV-Diesel systems without a battery have a maximum fuel saving potential of 48% (with a 108 kWp PV plant). With PV plants higher than 108 kWp fuel savings decrease again. This is caused by the increasing PV power volatility and thereby more frequent dynamic residual loads for the gensets.

At the given optimum of scenario 1 with a 57 kWp PV plant and a 70.6 kWh battery 94% fuel could be saved. Proposing CO_2 emissions with a factor of 2.63 kg/l at least 81.3 tons of CO_2 emissions could be avoided [8]. In contrast, at the optimum of scenario 2 with a 16 kWp PV plant and no battery the CO_2 emissions achieve only 19.9 tons of CO_2 (23% savings). However, the optimal configuration of scenario 1 is still profitable in in scenario 2. Therefore, fuel savings can be sharply reduced while at the same dispensing only with a little profit.

4 Conclusion and perspective

In this paper, a hybrid energy system simulation tool with the claim of a realistic model simulation is presented. By means of an extension for parameter variations hybrid energy systems can be simulated considering the economic and ecological efficiency.

In a simulation example of a micro grid consisting of 25 households the most profitable and at the same time ecological configuration is a 57 kWp PV plant with a 70.6 kWh lead-acid battery storage.

Further, the tool can be improved by measurements of the dynamic behavior of large-scale diesel generators (>1 MW) to be able to simulate accordingly larger hybrid energy systems. Additionally, a consideration of nitrogen oxide (NO_x) and hydrocarbon emissions (HC) could be interesting to better assess environmental influences.

Further labor will extend the parameter variation by an automatic parameter optimization and will improve the user interface with better links to existing databases.

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References

[1] E. D. Tufte, “Impacts of Low Load Operation of Modern Four-Stroke Diesel Engines in Generator Configuration,” Norwegian University of Science and Technology, 2014.

[2] TRNSYS 17, a TRaNsient System Simulation program, Mathematical References, Vol. 4, November 2009 [Online]. Available: http://web.mit.edu/parmstr/Public/TRNSYS/04-MathematicalReference.pdf

[3] J. Schumacher, INSEL 8 - Integrated Simulation Environment Language, Tutorial, March 2014 [Online]. Available: http://www.insel.eu/fileadmin/insel.eu/diverseDokumente/inselTutorial_en.pdf

[4] RETScreen International, RETScreen Software Online User Manual, Phovoltaic Project Model, 2005 [Online]. Available:

http://publications.gc.ca/collections/collection_2008/nrcan/M39-115-2005E.pdf

[5] HOMER Energy, User Manual, HOMER Pro Version 3.7, August 2016

[6] Hybrid2, The Hybrid System Simulation Model, User Manual, Version 1.0, June 1996 [Online]. Available: https://www.nrel.gov/docs/legosti/old/21272.pdf

[7] R. D. López, iHOGA V2.3 User's manual, April 2017 [Online]. Available:http://personal.unizar.es/rdufo/iHOGA%202.3%20User%20manual-web.pdf

[8] S. Faßbender, C. Brosig, E. Dresch, E. Waffenschmidt, „A tool for the simulation of large PV-diesel-systems with different dispatch strategies," IEEE, 2016 International Energy and Sustainability Conference (IESC), DOI: 10.1109/IESC.2016.7569491

[9] V.J. Chin, Z. Salam, K. Ishaque, "Cell modelling and model parameters estimation techniques for photovoltaic simulator application: A review", Applied Energy, vol. 154, pp. 500-519, September 2015

[10] C. M. Shepherd, Design of Primary and Secondary Cells – Part 2. An Equation Describing Battery Discharge. Journal of Electrochemical Sciety, vol. 112, pp. 657-664, January 1965

[11] ISO 15550:2016, "Internal combustion engines – Determination a method for the measurement of engine power – General requirements," International Organization for Standardization, Geneva, Switzerland, 2nd ed., November 2016

[12] Diesel prices around the world (2017, August 21) [Online]. Available: http://www.globalpetrolprices.com/diesel_prices/

[13] LfU, Treibhausgas-Emissionsfaktoren für Strom- und Wärmeerzeugung in Deutschland, Bayerisches Landesamt für Umwelt, 2016