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Energy storage potential for solar based hybridization of off-grid diesel power plants in Tanzania

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Abstract

In rural areas of Tanzania electricity is mainly produced by diesel plants. To reduce generation costs the introduction of photovoltaic (PV) and battery storage is a viable option. For an implementation strategy, diesel plants are localized with a geospatial analysis and the potential for hybridization with PV and battery systems is investigated by simulating a PV-battery-diesel system. Thereby a maximal potential for 23.6 MWp PV and 56.8 MWh of battery capacity resulting in a cost reduction of 17 ct€/kWh is discovered. Battery costs should be below a threshold of 475 €/kWh to become a significant part of the hybrid system.

Keywords: Diesel power generation; hybrid power system; rural electrification; simulation; geospatial analysis

1. Introduction

Diesel-based mini-grids provide electricity in many rural areas of Tanzania as the national transmission grid only covers small parts of the country [1]. Power generation by diesel generators implies high electricity costs and contributes to local and global environmental pollution by greenhouse gas emissions [2] [3]. Furthermore, the dependency on expensive fossil fuels is a main barrier for a sustainable development of rural areas: High costs lead

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to insufficient energy supply which in turn impedes economic development [4]. As a result the electrification rate of the country is very low with 11 %, falling to below 2 % in rural areas [5].

To reduce the energy poverty the country may exploit its abundant solar resources (Fig. 1). As costs for photovoltaic technologies are decreasing [6], while fossil fuel prices are rising, upgrading diesel-powered off-grid systems with PV modules is already economically viable especially in remote locations. For achieving high shares of solar energy, battery systems are required to store the intermittent solar energy and to assure the reliability of the hybrid system [7]. For an efficient implementation strategy, the localization of diesel power plants and the quantification of the hybridization potential for each site are of utmost importance.

In this work, a methodology is presented for localizing remote diesel mini-grids and acquiring necessary input parameters like energy resource and load data. In a second step the cost-optimized PV-battery-diesel system is simulated. Here, special emphasis will be given to the sensitivity of battery costs on the storage capacity and renewable energy share in the cost-optimized hybrid system.

2. Methodology

For the example of Tanzania this paper describes a GIS-based methodology using ArcGIS 2010[1] to identify off-grid diesel plants [8] and a Matlab[2]-based simulation tool to derive the techno-economic PV and storage potential for hybrid mini-grids. Necessary information required for localizing off-grid diesel power plants in Tanzania such as fuel type, capacity, and position are extracted from a database [9] and visualized in ArcGIS 2010. Additionally, the national electricity transmission grid is included derived from existing geospatial data taken from the African Development Bank [10]. Isolated diesel plants are localized by adding a buffer zone of 25 kilometers around the transmission grid and excluding all plants within this area [11]. The remaining diesel plants outside the buffer zone are identified as isolated off-grid plants (Fig. 2).

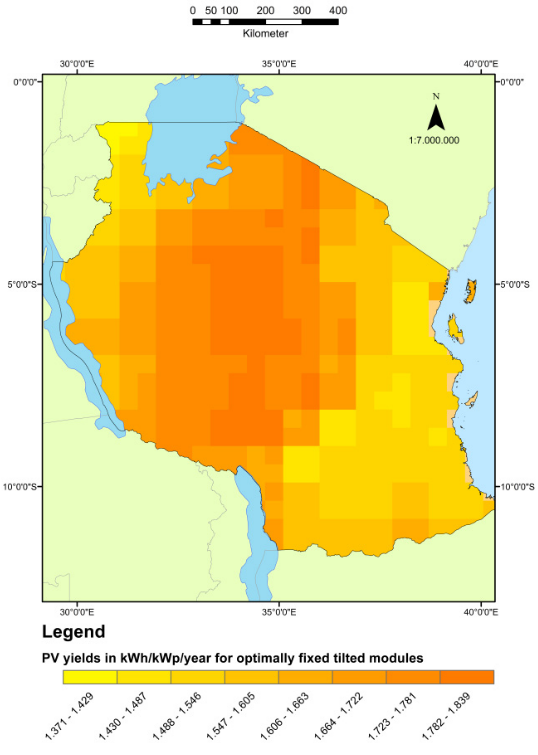

Figure 1: Potential PV yields in kWh/kWp per annum for Tanzania [12]

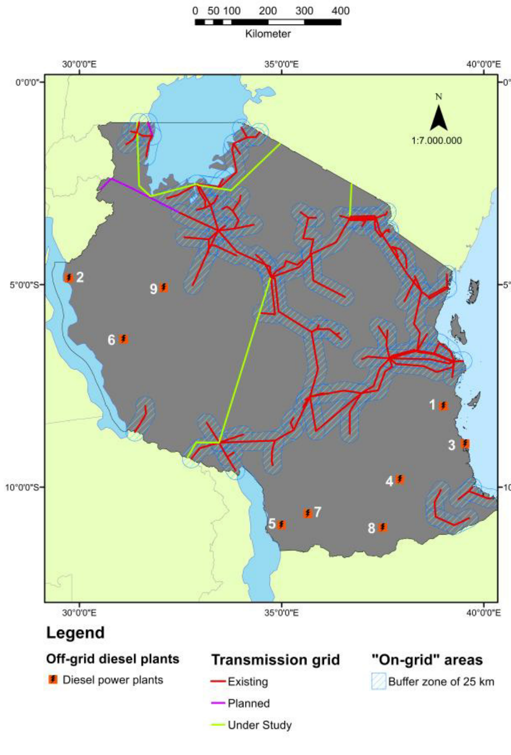

Figure 2: Identified off-grid diesel systems in Tanzania

[1] ESRI ® Arc Map™ 10.0
[2] MATLAB. ® Version R2011b. The MathWorks, Inc.

Further site specific input parameters are derived taking the exact geographic positions of these off-grid plants: This includes the PV yield, diesel price, and energy demand. The potential PV yield is derived from the site specific global horizontal irradiation [12] for optimally fixed tilted mono-crystalline modules [13]. For assessing the local diesel the specific costs required to reach each of the off-grid locations [14] are added to the base diesel price of 1.06 € for 2012 [15]. For estimating the energy demand for each off-grid location a typical load curve is determined [16] and the peak power demand is set to 75 % of the accumulated installed diesel generator capacity.

For the simulation a PV-battery-diesel system is chosen (Fig. 3) Subsequently, the battery cost's influence on the optimized system configuration and the respective levelized cost of electricity (LCOE) [17] of the system are analyzed. Wind resources do not play a role due to the low average wind speed in the given locations with less than 5 m/s [12] corresponding to fewer than 800 full load hours and is therefore not considered for the optimization of the hybrid system. The optimization computes the most cost effective system in terms of LCOE (Eq. 1 & 2) under the precondition of continuous load coverage, based on hourly calculations for one reference year. The results provide the cost-optimized system configurations for a period of 20 years. To analyze the sensitivity of the battery costs on the system configuration and PV share eleven discrete values between 100 and 700 €/kWh (Tab. 1) are chosen to reflect different possible future scenarios for energy storage technologies.

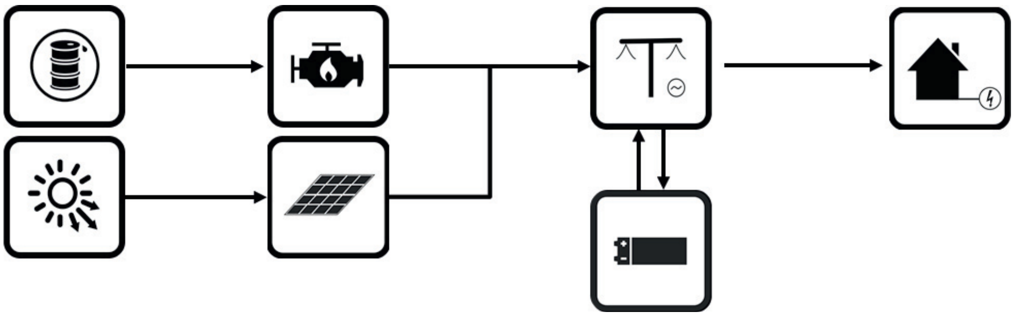

Fig. 3: Design of simulated hybrid mini-grid. (From left to right: Resource data, technical/economic data, load data).

$$LCOE = \frac{Capex * CRF(WACC, N) + Opex + Costs_{fuel} * Fuel}{El_{consumed}} \quad (1)$$

Equation 1: Levelized cost of electricity (LCOE) for power systems. Abbreviations stand for: Capital expenditures (Capex); capital recovery factor (CRF); weighted average cost of capital (WACC); project lifetime (N); operation and maintenance expenditures per year (Opex); cost of diesel per liter ($Costs_{fuel}$); consumed diesel per year (Fuel), consumed electricity per year ($El_{consumed}$)

$$CRF(WACC, N) = \frac{WACC * (1 + WACC)^N}{(1 + WACC)^N - 1} \quad (2)$$

Equation 2: Capital recovery factor (CRF). CRF is set according to weighted average cost of capital (WACC) and project lifetime (N).

The simulation model is fed with the site specific input parameters derived from the previous research step supplemented by the general input parameters given in Table 1. For each location and each energy storage cost step the input parameters are constant. The peak load of the hybrid system is set according to 75% of the respective current diesel power capacity at each location.

With a higher battery capacity the operating time of the diesel generators is decreasing. If no sufficient renewable energy (PV and battery storage) is available to serve the full load the diesel generators cover the remaining load. Operational costs for the diesel power generation are decreasing with higher renewable share and battery capacity as less diesel fuel is consumed. Further beneficial effects of the batteries on the diesel generator exist. With an intelligent operation of the storage system the lifetime of the diesel generator is increased and maintenance costs are reduced. Also unfavorable part-load operation can be avoided, increasing the average conversion efficiency. Both effects were not quantified in this study since diesel generator Capex and maintenance costs were set to zero and can thus not be further reduced by the batteries and the average conversion efficiency was kept constant.

Table 1: Input data for simulation model.

Parameter	Value
Global horizontal irradiation [12]	Range from 1,840 to 2,130 kWh/m²/year
Capital expenditure PV	2,000 €/kWp
Capital expenditure battery	variable (100 – 700 €/kWh)
Capital expenditure diesel generator	0 €/kW
Operational expenditure PV	40 €/kWp/year
Diesel costs	Range from 1.33-1.43 €/l
	(average 2013 - 2033, 2% increase per year)
Diesel generator efficiency	33.3 %
Battery round cycle efficiency	85 %
Battery life time	10 years
Battery C-rate	1:6
Project duration	20 years
WACC	7 %

3. Results

With the geospatial analysis 19 diesel generators are identified in 9 different off-grid locations (Tab. 2) for the mainland of Tanzania. All off-grid locations are situated in the western and southern part of the country (Fig. 2). The majority of the off-grid systems is operated by the state-owned operator TANESCO contrasted by two off-grid locations operated by private cooperatives (locations 5 and 9 in Tab. 2). The installed power capacity of all identified diesel generators adds up to 8.89 MW. Nevertheless, diesel generator imports worth more than 118 million USD from 2008 to 2012 indicate that much more diesel generators are operated privately and bear an even higher potential for hybridization with renewable energies [18].

Table 2: Identified off-grid diesel power plants [9].

Location	Diesel unit	Operator	MW	City	State
1	Ikwiriri IC 1	Tanesco	0.42	Ikwiriri	Pwani
	Ikwiriri IC 2	Tanesco	0.42	Ikwiriri	Pwani
2	Kigoma IC 2	Tanesco	0.50	Kigoma Town	Kigoma
	Kigoma IC 3	Tanesco	0.64	Kigoma Town	Kigoma
	Kigoma IC 4	Tanesco	0.64	Kigoma Town	Kigoma
	Kigoma IC 5	Tanesco	0.64	Kigoma Town	Kigoma
	Kigoma IC 6	Tanesco	0.66	Kigoma Town	Kigoma
3	Kilwa Masoko IC 1	Tanesco	0.35	Kilwa Masoko	Lindi
	Kilwa Masoko IC 2	Tanesco	0.35	Kilwa Masoko	Lindi
4	Liwale IC 3	Tanesco	0.06	Liwale	Lindi

Location	Diesel unit	Operator	MW	City	State
5	Mbinga IC	Mbinga Coop.	0.29	Mbinga	Rubuma
6	Mpanda IC 2	Tanesco	0.50	Mpanda	Rukwa
	Mpanda IC 3	Tanesco	0.66	Mpanda	Rukwa
7	Songea IC 1	Tanesco	0.50	Songea	Ruvuma
	Songea IC 2	Tanesco	0.50	Songea	Ruvuma
	Songea IC 5	Tanesco	0.64	Songea	Ruvuma
	Songea IC 7	Tanesco	0.66	Songea	Ruvuma
8	Tunduru IC 2	Tanesco	0.35	Tunduru	Ruvuma
9	Urambo IC 1A	Urambo Coop.	0.11	Urambo	Tabora
Sum			8.89		

Depending on the battery Capex, the simulation yields a maximum storage potential of up to 56.8 MWh for the off-grid areas (Fig. 4 & Tab. 3). It becomes evident that under the given input parameters a specific threshold within a range of 475 - 500 €/kWh for battery Capex exists that is essential for a significant installation of storage systems (Fig. 4). With battery Capex of above 500 €/kWh storage technologies are not competitive limiting the PV-diesel system to a renewable share of about 40% (Fig. 5). Battery Capex of below 475 €/kWh allow PV-battery-diesel systems with high shares of renewable power.

Table 3: Sensitivity of Battery prices

Battery cost [€/kW]	Battery capacity (summarized) [kWh]	LCOE saving (average) [€ct/kWh]	Installed PV (summarized) [kWp]	PV share (average) [%]
100	56,802	17.0	23,688	0.92
200	53,431	14.8	23,722	0.91
300	51,132	12.7	23,779	0.90
400	49,939	10.7	23,689	0.89
450	46,136	9.8	22,762	0.88
475	36,448	9.3	20,252	0.82
500	23,342	8.9	16,729	0.71
525	12,092	8.7	13,435	0.57
550	4,143	8.6	11,059	0.47
600	181	8.5	9,845	0.38
700	0	8.5	9,786	0.37

Also, this step-wise behavior is reflected by no significant changes in the system configuration below and above the threshold (Fig. 5 & Tab. 3). The LCOE savings compared to the pure diesel system range from 0.08 €/kWh for high battery costs to 0.18 €/kWh for low battery costs. LCOE savings start to increase highly with battery Capex less than 500 €/kWh (Fig. 5). The battery cost threshold is significantly influenced by diesel costs and PV Capex. With increasing diesel fuel costs and decreasing Capex for PV modules the threshold for the installation of cost effective battery systems is shifted beyond 500 €/kWh.

A comparable threshold for the introduction of storage technologies into on-grid systems is quantified with 200 – 350 €/kWh [19]. Both thresholds are comparable if higher fix costs for off-grid systems are incorporated. If current battery Capex of below 300 €/kWh are assumed [20] the simulation reveals that high shares of up to 90% of PV power can be realized in the off-grid systems. The benefits are significant: LCOE reductions of 12 €ct/kWh and the mitigation of harmful CO_2 emissions. Furthermore, it is shown that the identified diesel off-grid locations of Tanzania bear a theoretical market potential for battery storage technology and solar energy with battery capacity of 51.1 MWh and PV capacity of 23.8 MWp.

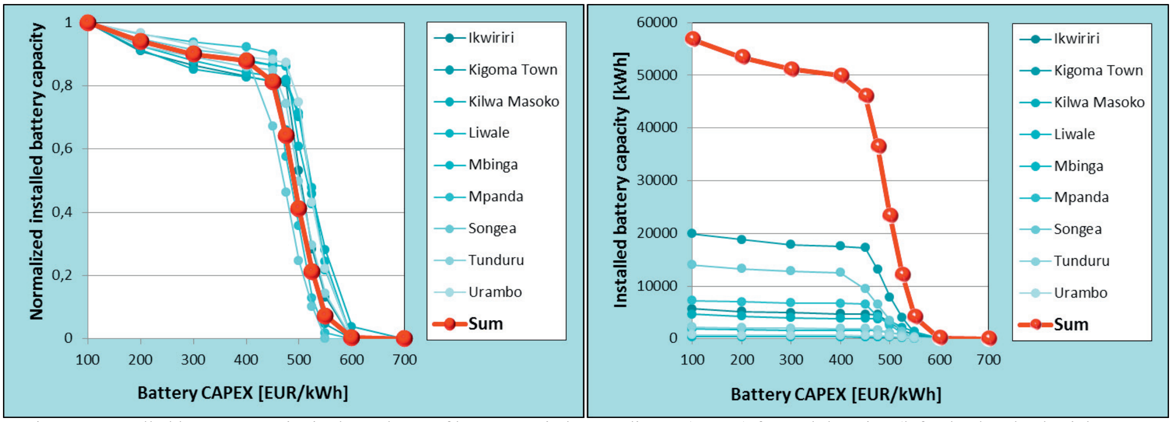

Figure 4: Installed battery capacity in dependence of battery capital expenditures (Capex) for each location (left: absolute kWh; right: normalized to maximal value).

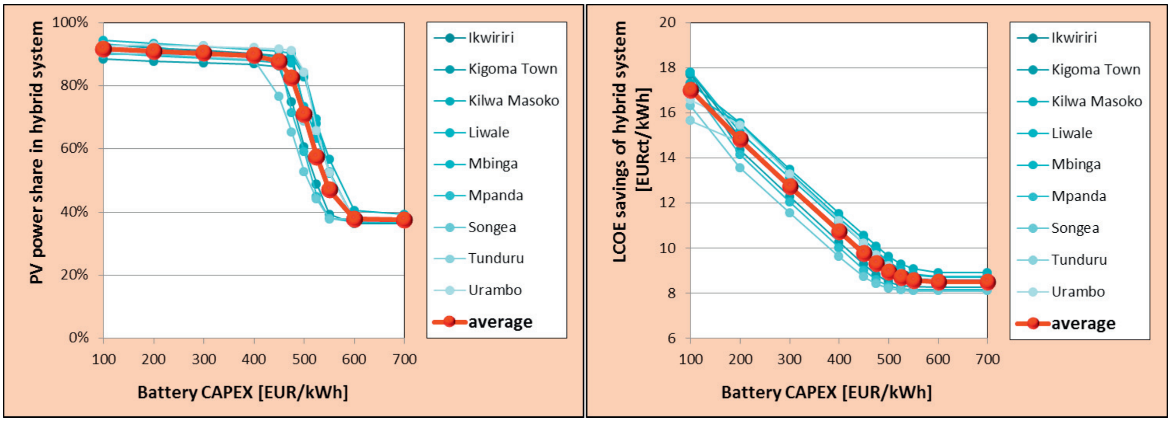

Figure 5: Dependence of battery Capex for each location (left: renewable energy share; right: LCOE savings).

4. Conclusion

Focusing on the effect of battery costs of solar based hybrid systems of off-grid locations in Tanzania several key findings can be derived: Under fixed PV Capex of 2000 €/kW and diesel fuel prices of around 1.4 €/litre the battery costs must be below a threshold of 475 €/kWh to become a significant part of the hybrid system. With increasing diesel prices and decreasing capital investments for PV technologies the battery threshold for cost-efficient PV-battery-diesel system will move towards higher battery costs of above 500 €/kWh. Consequently, the PV share rises due to the increased storage capacity. Furthermore, with reaching a higher share of renewables the study shows that hybridization of diesel-based off-grid systems with PV and storage systems can lead to a significant electricity cost reduction.

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