

Chapter 2

Assessment of Decentralized Hybrid Mini-grids in Sub-Saharan Africa: Market Analysis, Least-Cost Modelling, and Job Creation Analysis



A. Okunlola, O. Evbuomwan, H. Zaheer and J. Winklmaier

Abstract With a growing impetus to meet energy demand through decentralized hybrid mini-grids in rural and semi-urban locations in Sub-Saharan Africa (SSA), the need to accurately assess the market drivers, policy requirements and job creation impacts of this energy system typology within this region cannot be ignored. This work provides a techno-economic impact analysis of decentralized hybrid energy systems in selected locations in SSA. To optimally satisfy an electricity demand time-series for a year and minimize all cost components amortized over a period of 20 years, a least-cost modelling approach and tool is applied. An Employment Factor approach was used to calculate the direct employment impacts across the value chain of different hybrid mini-grid types. Additionally, the Leontief Inverse Input–Output model is used to determine the backward linkage economy-wide-jobs (gross jobs) created. The preliminary results show that the “Solar + Wind + Diesel + Battery” hybrid system (SWDB) has the lowest Levelized Cost of Electricity (LCOE), thus it provides the cheapest means of meeting the electricity demand in the modelled regions. However, the highest locally created direct and net employment impact in the model locations is provided by the “Wind + Battery” (WB) system. Two major sectors, manufacturing and agriculture have the largest number of gross jobs in the local economy for all decentralized hybrid systems analysed. This occurs due to higher linkages between these two sectors and the productive energy use in the area. Conversely, despite higher employment impacts obtained for WB, the cost and duration needed for

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wind resource mapping and assessment serve as a major bottleneck to WB systems market access in the regions. The results of the sensitivity analysis suggest that by de-risking economic factors, such as discount rates, market access for decentralized renewable energy mini-grids can be improved in SSA.

Keywords Decentralized hybrid energy systems • Electricity access
Job creation • Employment impact • Least-cost energy system modelling

2.1 Introduction

It has become acceptable that the motivation for a growth in renewable energy (RE) application globally is not only limited to reasons of energy security or reduction in CO₂ emissions from power generation sources, but also because of the positive employment impacts RE engenders [1]. This in turn supports the point that access to electricity through RE and economic development are strongly interlinked [2]. Countries located in Sub-Saharan Africa (SSA) have huge technologically feasible RE potentials greater than the average energy consumption needs of the sub-continent [3]. Nonetheless, the urban population in multiple countries in SSA remains underserved while many rural areas have little or no access to electricity. Although little literature exists to validate the correlations between electricity and employment generation in Sub-Saharan Africa (SSA), meta-analyses such as Daniel et al. show that investments in renewable-energy-based power generation provides more jobs per installed capacity (Jobs/MW) and per unit of energy generated (Jobs/MWh) over the operational lifetime of the power plant than the fossil-fuel-based power generation [1]. This applies for both centralized and decentralized electricity generation modes. Colombo et al. points out that the deployment of RE systems in decentralized modes of operation have the potential to create a larger amount of jobs per unit energy produced in comparison to conventional centralized methods of production and distribution of RE [4]. To justify that improved energy access enhances job creation, evidence from South Africa by Taryn Dinkelman established that household electrification driven by decentralized energy access increased employment in developing areas, particularly in micro-enterprise development [5].

2.2 Techno-economics and Job Creation

2.2.1 *Techno-economics of Mini-grids in Sub-Saharan Africa*

To assess the techno-economics of individual decentralized technologies, evaluating the technological appropriateness and the associated economic viability of each

technology for a successful application are needed [6]. In their analysis in 2011, Szabó et al. showed the levelized cost of electricity (LCOE) calculated for local mini-grid photovoltaic (PV) systems in Africa ranges from approximately 0.2 to 0.55 \$/kWh [7, 8]. Similarly, Deichmann et al. in 2010 showed that the average LCOE for wind-based mini-grids in Africa ranges between 0.144 and 0.288 \$/kWh [9]. By comparing¹ LCOE results from [8] to [9], wind energy can be considered to be more favourable for mini-grid application in Africa due to its lower LCOE. However, low wind speeds observed across SSA serve as a major limiting factor to its wide application for power generation on the sub-continent [10].

2.2.2 Renewable Energy Employment Effects

The value chain of a RE system consists of economic activities which trigger direct, indirect, and induced employment effects [11]. Direct employment effects refer to un-intermittently created jobs in the value chain such as manufacturing, construction and installation (C&I) as well as operations and maintenance (O&M) jobs. Indirect employment effects accrue from industries which are linked to the renewable energy value-chain. Besides direct and indirect employment effects, there are also induced employment effects which occur as a result of income distribution effects [12]. For analysing the total employment effects of RE systems, the terms gross and net effects are used. Gross employment effects refer to positive job creation in an economy as a result of investment in the RE sector. Net employment effect, on the other hand, shows both the positive job effects (direct, indirect and induced) and negative job effects (job losses in the conventional energy sector). Ürge-Vorsatz et al. points out that in developing regions, such as SSA, the positive employment effects are often sufficient to be analysed because these effects often start at a low level that they almost always lead to positive gains [13].

There are many models and tools used in calculating job creation effects of RE varying on the basis of complexity, data requirements, and computational assumptions. However, two main approaches exist in determining gross employment effects. The approaches are; (1) the employment factor (EF) method, and (2) the gross input-output (IO) approach. EFs indicate the number of jobs generated per unit of installed capacity (MW) or energy produced (MWh) [14], while the gross IO model is applied to assess both the gross and net employment effects of RE systems [12] (Fig. 2.1).

¹The techno-economic comparison does not take into consideration the huge drop in the system cost of solar PV from the years 2010 to 2017 (till date).

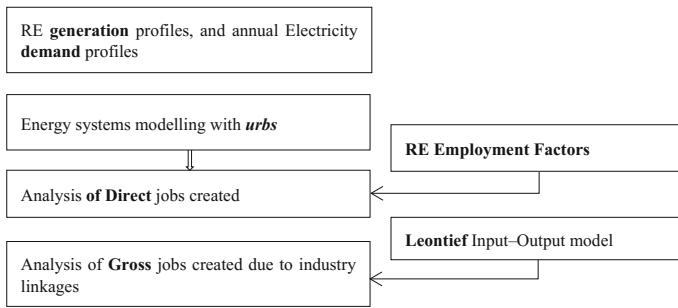


Fig. 2.1 Assessment methodology adopted in the study

2.3 Methodological Approach

In this study, the least cost annual energy supply of a semi-urban location in SSA is computed using urbs, a linear optimization model for distributed energy systems developed at the Institute of Renewable and Sustainable Energy Systems, Technical University Munich, Germany. Details of the urbs model and the optimization logic have been reported in the documentation [15]. The model is used for the techno-economically optimized sizing of ten decentralized hybrid mini-grid scenarios and systems combinations and thus comparing them. Scenarios considered are shown in Table 2.1.

In some scenarios battery storage is added to balance RE supply fluctuations, while the already installed diesel generator served as the conventional backup system. Techno-economic simulation parameters and the energy flow strategy used in the model are adopted from Bertheau et al. [16]. Input technical and economic data for the mini-grid components are provided by ILF BERATENDE INGENIEURE GmbH. An appliance utilization and daily power consumption analysis for 10 energy demand clusters was conducted in the region. The results obtained during this process are used in a Monte-Carlo time-of-use simulation to determine the annual hourly

Table 2.1 Hybrid mini-grid scenarios and configurations used in the analysis

Scenario	Abbreviation
Diesel only	Base
Solar diesel	SD
Solar + diesel + battery	SDB
Solar + wind + diesel	SWD
Solar + wind + diesel + battery	SWDB
Solar + wind + battery	SWB
Solar + battery	SB
Wind + battery	WB
Wind + diesel	WD
Wind + diesel + battery	WDB

electricity demand profile. Annual hourly solar radiation used is derived from NREL and wind speed data are obtained from the Global Wind Atlas [17, 18]. Adiabatic terrain index in Counihan was used to adjust the wind speeds obtained according to the terrain surface roughness of the area [19]. The calculations for adjusted wind speeds of a typical semi-urban terrain type are shown in Mayr [20]. The methodology applied in Bertheau et al. is used to calculate the LCOE for all scenarios at 15% weighted average cost of capital (WACC). The LCOE gives the cost-optimized system configurations for a project period of 20 years. The system sizing results from urbs are used to compute the employment impacts for all scenarios. Replacement and degradation costs are considered to be of negligible effect. Also, system stability simulations are not conducted in this exercise. The direct jobs created are calculated applying the EF methodology in Rutovitz et al. [21]. The country's productivity level obtained from KILM [22] is used to adjust the EF for the region in estimating the direct jobs created locally. The backward-linkage jobs (gross jobs) created in different industries in the region are calculated using the Leontief IO model [23]. The regional IO table required for the IO model is built applying [24–26].

2.4 Results and Discussion

SDB, SDW, SDWB, have the lowest LCOE, thus they provided the cheapest cost required to satisfy the electricity demand in the modelled region (Fig. 2.2). The three scenarios have marginally equal LCOEs because the percentage of energy supply from diesel generators in all three scenarios is approximately 72% (LCOEs are rounded up to 3 decimal places for simplicity; slight LCOE differences are observed beyond this range). The influence of battery storage when a hybrid mini-grid is optimized with a diesel generator is trivial. SB's LCOE is 1.61 \$/kWh cheaper than WB because of solar PV's significantly lower investment cost and

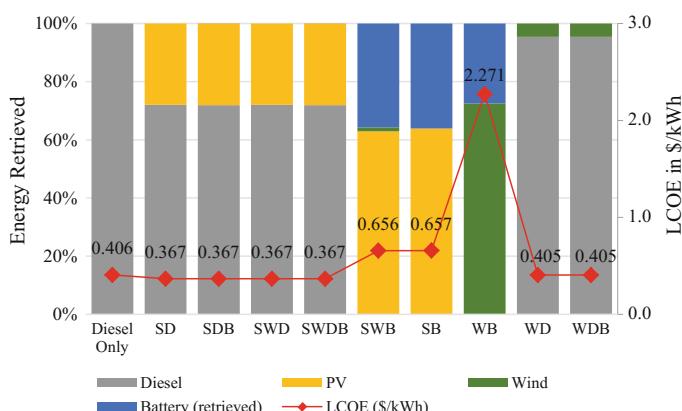


Fig. 2.2 LCOE and energy retrieval by supply source for all scenarios

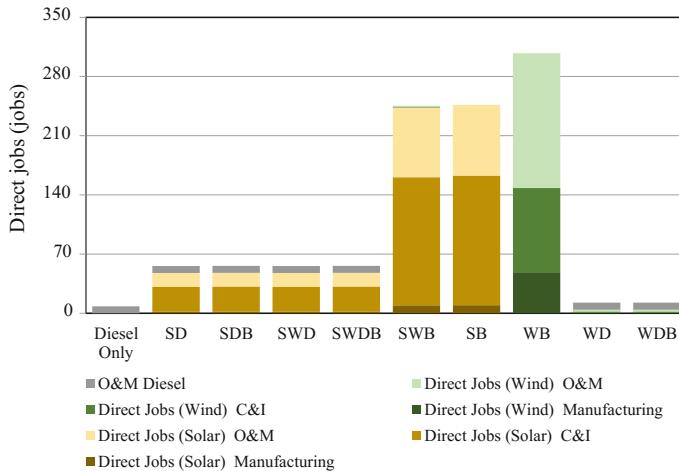


Fig. 2.3 Direct jobs created in Manufacturing, C&I, and O&M for all scenarios

higher on-site capacity factor (CF). WB had the highest LCOE (2.27 \$/kWh), thus, the most expensive mini-grid scenario. The wind turbine has a significantly lower CF than solar due to the poor wind speed (<4 m/s) in the area. This is typical in most locations in SSA [9]. Therefore, scenarios where the hybrid mini-grid has a system configuration of solar with wind, power generation from wind has a near-zero effect on the annual energy supply.

On the other hand, in spite of WB scenario providing the highest LCOE over the lifetime of the project, WB generates peak direct employment (Fig. 2.3) and gross employment effects (Fig. 2.4). This high employment effect is due to a high rated capacity of the installed wind turbine as compared to solar in SB which influences C&I and O&M jobs. This therefore results into huge investment flow from the mini-grid installation into the local economy. The created direct manufacturing jobs are negligible in all ten scenarios because of a low percentage of in-country RE equipment manufacturing. The highest gross employment effects are obtained in the trading, agriculture, and maintenance and repair industries for all mini-grid combinations (Fig. 2.4). These industries create high employment linkage to electricity supply in the local economy as identified from the IO model.

2.5 Sensitivity Analysis

A sensitivity analysis was conducted to investigate the impact of wind turbines optimized for low wind speeds, capital expenditure (CAPEX) reduction, and WACC on the LCOE and direct jobs created in the SWDB mini-grid scenario. The scenario is chosen because of its previous low LCOE result. A new location with an annual demand profile similar to a typical rural area in SSA and also allowing for a

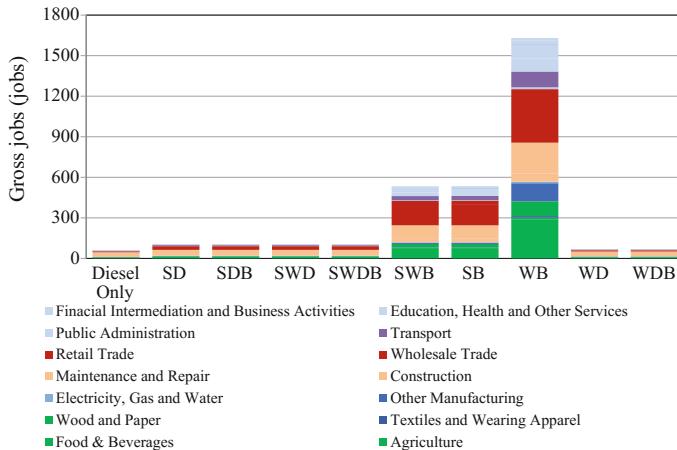


Fig. 2.4 Gross jobs created industries in the local economy for all scenarios

locally manufactured (DIY) low-wind-speed Piggott turbine in [19] to be built is chosen. The results obtained represented in Figs. 2.5 and 2.6 show the effect of WACC changes on LCOE, the corresponding direct job creation, and also the effect of RE CAPEX reduction. Three distinct results are obtained from the sensitivity analysis:

1. Low WACC significantly increases direct jobs and reduces LCOE (Fig. 2.5). This occurs because lower financing cost ensures a reduction in LCOE where an annual levelized capital cost dominates the average annual operating cost, hence increasing the installation of RE technologies in the SWDB mini-grid. The final result is an even higher increase in the number of direct jobs created due to higher investment in RE.
2. At lower WACC, more direct jobs are created for wind turbines optimized for low wind speeds than those created for Solar PV (Fig. 2.5). Optimizing wind turbines for low wind speed increases the CF of the wind turbines in rural areas. Therefore, with low financing costs, more installations of low- wind-speed turbines can be achieved, hence a positive impact of direct local jobs.
3. Solar LCOE is more sensitive to CAPEX reduction, but higher job creation sensitivities can be seen for small-wind turbines as the CAPEX reduces (Fig. 2.6). Solar generates a lower LCOE as compared to DIY wind turbines in rural SSA because it requires lower investment costs as CAPEX reduces. However, from 75 to 90% CAPEX reduction, wind DIY begins to generate more direct jobs than solar, despite having a higher LCOE. This occurs because of lower WACC inducing reduction in investment costs for the DIY turbines coupled with an improved CF of the wind turbines which are optimized to perform better at low wind speeds. This combined effect results in more turbines being installed and thus has a higher positive effect on direct job creation in the value chain.

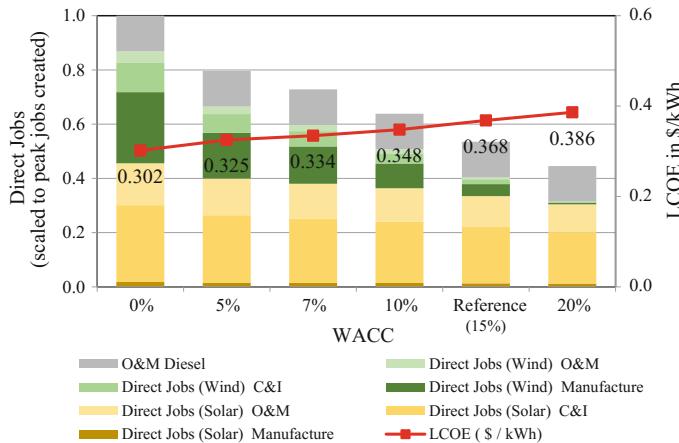


Fig. 2.5 Effect of changes in WACC on direct jobs and LCOE for SWDB

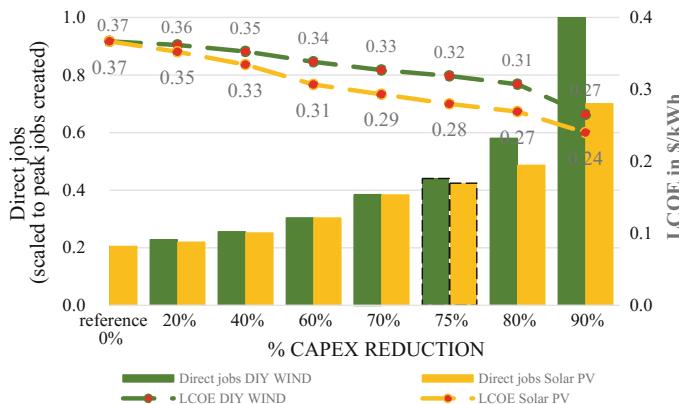


Fig. 2.6 Effect of CAPEX Reduction on LCOE and Direct Job for SWDB

2.6 Conclusions and Recommendations

Results obtained in this study show an optimized configuration for a decentralized hybrid mini-grid in SSA based on the cost of generating electricity and the jobs it creates. Small wind turbines optimized for lower wind speeds are better suited for hybrid combination with solar PV than commercially available wind turbine technologies in locations where annual average wind speeds are below 4 m/s. Notwithstanding the high LCOE of WB mini-grid, the high employment impacts it creates makes it a probable option for rural electricity supply in SSA. Bottlenecks like high cost and duration of site-specific wind resource assessment present a major challenge to the growth of decentralized wind systems in SSA despite the

significant potentials for hybridization. In terms of scalability, the higher modularity of solar PV ensures it remains a major driver of hybrid mini-grids in SSA. By de-risking economic factors such as discount rate, the WACC can be reduced; hence improvement in market access for decentralized RE hybrid mini-grids can be realized in SSA. To achieve desired positive job creation impacts, effective policy measures such as those being developed within the COBENEFITS² project [27] should be considered and applied; these policy measures place specific emphasis on the multiple benefits of increased share of RE in the energy mix [28]. Further studies should focus on developing models to broadly investigate the induced and net employment effects of decentralized renewable energy systems in Africa with respect to the techno-economics, taking into account the distribution costs and system stability requirements.

Annexes

See Fig. 2.7, Tables 2.2, 2.3 and 2.4

Gross IO model principal equations:

$$X = [1 - A]^{-1} * Y \quad (2.1)$$

$$Totaljobs_x = \sum \left(\left[\frac{Wi}{\$output} \right] \left[((1 - A)^{-1}) \right] [Totalcosts_s] \right)_{Ti} \quad (2.2)$$

where:

X = output multiplier matrix;

A = Technical (input) coefficient matrix

$[1 - A]^{-1}$ = Leontief inverse matrix

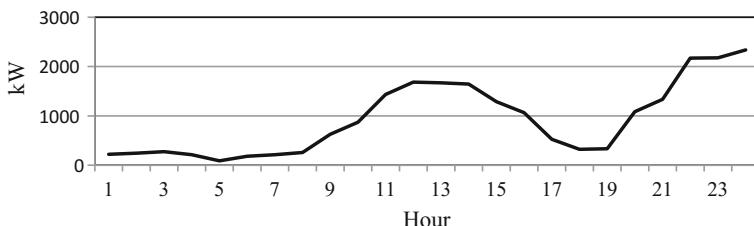


Fig. 2.7 An average hourly energy demand profile for a day obtained from the Monte-Carlo simulation

²The COBENEFITS project at the Institute for Sustainability Studies Potsdam, Germany is part of the International Climate Initiative (IKI) supported by the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB).

Table 2.2 System sizing results

Scenario	Rated power solar PV (kW)	Rated power wind (kW)	Battery (kWh)	LCOE (\$/ kWh)
Base	0	–	–	0.406
SD	2202	–	–	0.367
SDB	2207	–	12	0.367
SWD	2202	–	–	0.367
SWDB	2207	–	12	0.367
SWB	11,241	215	34,351	0.656
SB	11,384	–	34,936	0.657
WB	–	32,550	142,846	2.271
WD	–	452	–	0.405
WDB	–	452	–	0.405

Table 2.3 Employment impact results

Scenario	Direct jobs	Gross jobs		
		Manufacture	C&I	O&M
Base	–	–	–	190
SD	2	30	16	220
SDB	2	30	16	220
SWD	2	30	16	220
SWDB	2	30	16	220
SWB	10	152	84	780
SB	10	153	84	780
WB	49	100	159	1950
WD	1	1	2	200
WDB	1	1	2	200

Table 2.4 Employment factors for the location

Technology	(Jobs/MW)			FUEL (jobs/ GWh)
	Manufacture	C&I	O&M	
PV	8.44	13.46	7.34	0.00
Wind	7.47	3.06	4.90	0.00
Diesel	1.22	2.08	1.96	2.94

Y = Total cost of the minigrid system

$Total costs_s$ = (investment cost + variable costs) in a scenario

T_i = benchmark year. In this case the benchmark year is 2017;

Wi = workers per industry

$Total jobs_x$ = Total gross jobs in a minigrid scenario

See Tables 2.5 and 2.6

Table 2.5 Economic parameters used in the techno-economic analysis

Input parameter	Parameter value
Weighted cost of capital	15%
<i>Diesel generator</i>	
Initial investment cost	240 \$/kW
Fixed cost	\$30 \$/kW/year
Variable cost	0.03 \$/kWh
Fuel cost	\$0.11 \$/kWh
<i>Solar photovoltaic</i>	
Initial investment cost	1600 \$/kW
Fixed cost	2% of Investment/year
Variable cost	0.03 \$/kWh
Economic lifetime	20 years
<i>Wind turbine</i>	
Initial investment cost (commercial)	2000 \$/kW
Initial investment cost (DIY)	3005 \$/kW
Fixed cost	2% of Investment/year
Variable cost (commercial)	0.02 \$/kWh
Variable cost (DIY)	0.05 \$/kWh
Local content requirement (commercial)	30%
Local content requirement (DIY)	90%
Economic lifetime	20 years
<i>Battery storage</i>	
Initial investment cost (power)	500 \$/kW
Initial investment cost (energy)	300 \$/kWh
Fixed cost (power)	2% of Investment cost/year
Fixed cost (energy)	10 \$/kWh/year
Variable cost (power)	0.02 \$/kW
Variable cost (energy)	0.02 \$/kWh
Economic lifetime	10 years

Table 2.6 Technical Parameters the Techno-Economic Analysis

Input parameter	Parameter value
<i>Diesel generator</i>	
Full load efficiency	30%
Minimum load efficiency	25%
Minimum load	25% of rated capacity
<i>Solar PV system</i>	
Module type	Polycrystalline
Module efficiency	16.7%
Rated module power	325 W at Standard test conditions
Solar inverter efficiency	98%
Life span	20 years
<i>Wind turbine</i>	
Wind turbine manufacturer	Bergey
Cut-in speed (commercial)	3 m/s
Rated speed (commercial)	11 m/s
Cut-in speed (DIY)	2 m/s
Rated speed (DIY)	5 m/s
Hub height	50 m
Life span	20 years
Power coefficient (Cp)	0.33 (Commercial) 0.29 (DIY)
<i>Battery storage</i>	
Type	Lithium-ion
Input efficiency	95%
Output efficiency	93%
Initial state of charge (SOC)	50%
Life span	10 years

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