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Economic feasibility of solar PV system for rural electrification in Sub-Sahara Africa

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ABSTRACT

The future of solar photovoltaic (PV) systems as a viable alternative to conventional fossil fuel-based resources seem promising with the rapid decline in the cost over the last decade. Notwithstanding, PV technology is yet to make a meaningful contribution in Sub-Sahara Africa (SSA) where the need for energy is deemed critical. The reason being that the technology is perceived by policymakers in SSA not to be capable of functioning profitably as an independent economic unit that requires project financing. Regrettably, the widely utilized levelized cost of energy (LCOE) in the literature for PV economic assessment only provides a benchmark to assess grid parity. A detailed economic assessment that includes risks and actual capital financing method is urgently needed to encourage potential investors and foster adoption. In this paper, a generalized economic model is developed to assess the cost-benefit of off-grid PV system. The developed method is demonstrated on a case study of rural Gusau, Nigeria. The results show that the feasibility of the proposed system is highly location dependent. Overall, conclusion is drawn that PV technology is eligible for project financing as it can repay its loan within the stipulated time considering the current infrastructure and energy policies in Nigeria.

1. Introduction

Global energy crises continue with the increasing human population. Without additional dedicated energy policies, Kaygusuz [1] mentioned that about 1.2 billion people around the world will not have access to electricity by 2030. The situation is more pronounced in Sub-Sahara Africa (SSA) where the need for energy is so critical i.e. approximately 68% of the 915 million population do not have access to electricity [2]. Moreover, available evidence reveals a wide gap in electricity access between the urban and rural areas in SSA [3,4]. Adequate attention is usually given to the urban areas relative to the rural communities. For this reason, most people living in the rural communities are technologically, socially and economically backward. The electricity access rate of African region is depicted in Table 1 which shows the shortfall of SSA relative to North Africa and other developing countries [3]. Till date, fossil fuel-based resources account for 80% of the global energy supply [5] notwithstanding their environmental impact of global warming, acid rain formation, and ozone depletion. Due to low per capita income, there are speculations that Africa would be more vulnerable to extreme weather conditions associated with the environmental impact of fossil fuels. For emphasis, Wesseh and Lin [6] explained that unlike rich nations, it would be difficult for Africa to import food from abroad, build dams to prevent rising sea water and pay for air conditioning. Moreover, the Africa contribution to the global carbon dioxide emissions are low compared to the other regions. The regional aggregates presented in Table 2 depicts that the carbon dioxide contribution of Africa is less than 4% of the global emissions [7,8]. Conversely, the recent upsurge in the price trend of fossil fuel-based resources is encouraging the consideration and development of renewable energy sector. Sustainable development which can be achieved using renewable energy technologies (RET) have been the main focus of recent policies and development plan of many countries. Most countries now do not only set renewable energy target but also defines the proportion of each RET alternative in the forecasted energy generation mix. In general, the decision on which RET to adopt is not trivial due to trade-offs of economic costs, supplies reliability, environmental concern, and social aspect [9]. The prospect of achieving a sustainable endogenous development via the use of these renewable energy systems was emphasized by Delrio and Burguillo [10]. An endogenous development implies using the available local resources to achieve a localized change which is capable of not only improving the cultural but also spiritual well-being of the community. Moreover, there have been some other studies focusing on various decision frameworks and operational strategies with the aim of minimizing the total energy costs [11–13].

Solar photovoltaic (PV) technology has been accepted as a

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Nomenclature

Symbol

DDD	double declining depreciation
LCOE	levelized cost of energy
NOCT	nominal operating cell temperature
NPV	net present value
O & M	operation and maintenance
PV	photovoltaic
SSA	Sub-Sahara Africa
STC	standard test conditions
TMY	typical meteorological year
TNPV	total net present value
VDD	variable declining depreciation

Parameters

A	area
B	benefit
B_{eff}	battery charging efficiency
B_T	beam radiation on tilted surface
b	risk return rate
C	cost
C_B	battery storage capacity
D_T	diffuse radiation on tilted surface
d_t	demand/load
E	energy
I	solar radiation
f	inflation rate
L	losses
m	lifecycle time of PV system
N_i	number of appliance
n	loan repayment period
P	price
Q	risk degree
R_T	reflected radiation on tilted surface
r	interest rate on loan
T	temperature
t	time
w	power rating of appliance

Greek symbols

β_{ref}	PV array temperature correction factor
β_t	tilted angle
ω	hour angle
θ	angle of incidence
θ_z	zenith angle
$\varnothing$	location latitude angle
η_{inv}	Ac to DC inverter efficiency
η_{PV}	PV array efficiency
η_{ref}	PV reference efficiency
ρ	risk adjusted discount rate
μ	risk free discount rate
γ_s	solar azimuth angle
δ	declination angle

sustainable future alternative to replace fossil fuel among others. For this reason, the PV industry has witnessed tremendous growth over the last decade with 177 GW capacity installed as of 2014, thus, contributing to approximately 1% of global energy supply [14]. Deichmann et al. [15] argued that solar PV would only be economical for rural electrification based on their findings that centralized electrification will continue to be more preferred for the majority of households in Africa when available. Moreover, studies on off-grid PV systems are extensive and can be categorized according to the sizing technique implemented into intuitive [4,16–19], numerical [19–24] and analytical [25–27] following the thorough literature review of Khatib et al. [28]. An in-depth definition of all the sizing technique including their advantages and disadvantages were presented by Khatib et al. [28]. Among the sizing methods described, intuitive and numerical are widely utilized in the literature. For this reason, Kazem et al. [19] compared intuitive and numerical simulation PV system sizing method for remote housing electrification using solar radiation data of Sohar, Oman. They found that intuitive method overestimates the battery

Table 1
Electricity access rates [3].

Region	Population without electricity (millions)	Electrification rate (%)	Urban electrification rate (%)	Rural electrification rate (%)
Sub-Sahara Africa	599	32	55	18
North Africa	1	99	100	99
Africa	600	43	65	28
Developing Countries	1257	77	91	65

Table 2
Regional carbon dioxides emissions, 1990–2025 [7,8].

Region	1990	2002	2010	2015	2020	2025
Mature market economics	10,465	11,877	13,080	13,745	14,392	15,183
North America	5769	6701	7674	8204	8759	9379
Western Europe	3413	3549	3674	3761	3812	3952
Matured Market Asia	1284	1627	1731	1780	1822	1852
Transitional economics	4894	3124	3643	3937	4151	4386
Emerging economics	6101	9408	13,478	15,602	17,480	19,222
Asia	3890	6205	9306	10,863	12,263	13,540
Middle East	845	1361	1761	1975	2163	2352
Africa	655	854	1122	1280	1415	1524
Central and south America	711	988	1289	1280	1639	1806
Total world	21,460	24,209	30,201	33,284	36,023	38,790