Renewable Energy 89 (2016) 475–488

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

A sizing methodology based on Levelized Cost of Supplied and Lost Energy for off-grid rural electrification systems

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ARTICLE INFO

Article history:
Received 3 September 2014
Received in revised form
10 November 2015
Accepted 10 December 2015
Available online xxx

Keywords:
Developing countries
System sizing
Off-grid
Photovoltaic
Simulation
Optimization

ABSTRACT

Off-grid renewable systems can play a pivotal role in the process of rural electrification, thus promoting local development. Moreover, scientific literature is increasingly addressing this issue through the concept of sustainability and appropriate technologies. With regards to this topic, we present a sizing methodology which better relates the results and the sizing process itself to the local context. Specifically, we address the research area of sizing methodologies for off-grid PV systems. Typically, the Loss of Load Probability (LLP) is a key parameter in these methodologies, but is difficult to set as regards the specific context. The proposed methodology employs the concept of Levelized Cost of Supplied and Lost Energy, it is based on the estimate of an economic Value of Lost Load, and eventually, the LLP results to be an output of the process. Therefore, the methodology uses only data characterizing the local situation and results better fit with population conditions. We also propose a simple approach to compute the Value of Lost Load and we apply the methodology for a rural area of Uganda. The results show that the methodology identifies a reliable system which supplies electricity with a fair cost while minimizing the energy bill of the consumers.

1. Rural electrification of developing countries and off-grid systems

Rural areas of developing countries are those which suffer the poorest access to modern energy services. In fact in these contexts, the livelihood of large segments of the population is mainly determined by energy supplied via traditional biomass, kerosene and small batteries [1,2]. Moreover, the electric supply system, when available, is often unreliable (Table 1) and still nowadays it does not reach the majority of the total population. Indeed, electrification rates of rural areas are the lowest (Table 2), thus bringing about an insurmountable barrier to the improvement of households welfare, to the provision of local services, and to the development of productive activities.

When compared with the traditional approach of main-grid extension, stand-alone and micro-grid power systems (i.e. off-grid systems) are often considered the most proper solution – at least as a first step – in the process of rural electrification [3]. Indeed the International Energy Agency estimated that 55% of the additional generation required to achieve the *Energy for All Case* in 2030 is expected to be generated through off-grid solutions which are supposed to be totally employed for rural electrification [4,5]. Off-grid systems are typically based on renewable sources thus reducing dependency on fossil fuels, they are modular and hence can be adapted to different rural energy needs, and they are located near to the consumers thus avoiding transmission and distribution costs [6].

The issue of rural electrification via off-grid systems is often considered in the frame of *sustainable development* and *appropriate technologies*. Indeed, a few examples taken for the broad peer-reviewed literature show that analyses address (i) sustainability assessment as regards energy access in rural areas [9], (ii) new approaches in promoting local development through electricity access [10], (iii) technologies selection according to features of local context and population [11,12], and (iv) multi-objective system sizing which embraces technical, economic and environmental parameters [13,14]. These researches deal with different aspect of rural electrification and renewable technologies while also embracing, distinctly or not, (a) the concept of energy needs and the matching of such needs without compromising the environment, hence considering sustainable development, and (b) the concept of technologies design or selection including specific

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http://dx.doi.org/10.1016/j.renene.2015.12.032
0960-1481/

Nomenclature

Acronyms used in the text

LCC	Life Cycle Cost
LCoE	Levelized Cost of Energy
LCoSLE	Levelized Cost of Supplied and Lost Energy
LHV	low heating value
LL	Loss of Load
LLP	Loss of Load Probability
NOCT	Nominal Operation Cell Temperature
NPC	Net Present Cost
NPC*	new proposed Net Present Cost
PV	photovoltaic
SOC	State of Charge
VOLL	Value of Lost Load

Symbols

$(P/E)_R$	battery power-to-capacity ratio
$C_{B,mobile}$	mobile battery capacity
App Name	name of appliance
B_{size}	battery rated capacity
$c_{recharge\ mobile}$	mobile charge cost
c_{diesel}	diesel cost per liter
CF_i	cycles to failure
$c_{ker\ lamp,h}$	kerosene cost for 1h light

Class Type name of user class

E	electricity supplied to consumers
E_{Bat}	energy flow through the battery
$E_{class,day}$	class daily energy need
E_D	electricity demand
$E_{pc,year}$	per capita yearly energy need
E_{PV}	energy produced by PV
$E_{user,day}$	user daily energy need
G	irradiance
h	reference irradiance
h_{funct}	functioning hours
$h_{light,LL}$	hours of light relating to LL
h_{start}	functioning windows start
h_{stop}	functioning window stop
H_β	solar irradiation on a tilted surface
Inv	investment costs

$Life_{Bat}$ battery life time in year

LT	lifetime
m	number of depth of discharge intervals
N_{App}	number of appliance
N_{US}	number of user within a class
O&M	operation and maintenance costs
P_{App}	appliance power rate
$P_{el,light}$	average power of electric lights
$P_{eq,App}$	equivalent appliance power
PV_{size}	PV power rate
r	discount rate
t	simulation time-step
T	time period
T_{Amb}	ambient temperature
T_{Cell}	PV cell temperature
Tot_W	total functioning windows hours
v	diesel specific volume
$V_{B,mobile}$	mobile battery voltage
$W_{f,n}$	functioning windows
y	year
Z_i	charge/discharge cycle
ΔE	energy balance to the battery
η_{BOS}	balance of system efficiency
η_{CH}	battery charge efficiency
η_{DISCH}	battery discharge efficiency
η_{gen}	diesel generator efficiency
η_{Inv}	inverter efficiency
ρ_T	temperature coefficient

Table 1
Electric outages and duration in developing world macro-regions.

	Number of outages (days per month)	Duration of the outages (hours)
Sub-Saharan Africa	8.0	5.0
Middle East & Northern Africa	25.8	12.4
East Asia & Pacific	3.3	2.0
Latin America	2.5	1.3
South Asia	18.0	1.3
World	5.3	2.7

Source [7].

conditions of the targeted areas (people's needs, and social, cultural aspects), hence considering the concept of appropriate technologies [15].

Coping with these concepts, a sizing methodology for off-grid systems which better relates the results as well as the sizing process itself to the specific features of the local context is suggested in this paper. Specifically, we address the area of interest of sizing methodologies for off-grid PV systems. The proposed methodology employs the concept of Levelized Cost of Supplied and Lost Energy (LCoSLE), it does not require the Loss of Load Probability (LLP) as input datum, and it is based on the estimate of the economic Value of Lost Load (VOLL) for the targeted context. The methodology uses as input only data that characterize and come from the local situation, and hence, in our opinion, it is more appropriate in designing energy systems for rural electrification.

The paper is structured as follows: in Section 2 we briefly review the methodologies for off-grid PV system sizing and we highlight the limitations as regards the application in rural areas of developing countries, in Section 3 we present the new methodology while in Section 4 we propose a procedure to define the VOLL for a rural context. Finally, we explain the overall structure of the novel sizing methodology (Section 5) and we apply it to a case study for a PV micro-grid in a rural area of Uganda (Section 6). The physical model of the micro-grid as well as the numerical technique employed to optimize the system size are quite similar to others available in the literature and we briefly describe them in Appendix A. All numerical examples as well as graphs that we show in the paper refer to the mentioned physical model, the numerical technique and to the Ugandan case. Finally in Appendix B a detail of the figures adopted for the study is reported.

2. Sizing techniques for off-grid PV systems

In the context of renewable technologies, off-grid PV systems are those which probably will contribute the most to rural