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Techno-economic assessment of an off-grid PV system for developing regions to provide electricity for basic domestic needs: A 2020–2040 scenario

Ghassan Zubi *, Rodolfo Dufo-López [a], Guzay Pasaoglu [b], Nicolás Pardo [c]

[a] Electrical Engineering Department, University of Zaragoza, Calle Maria de Luna 3, 50018 Zaragoza, Spain
[b] Istanbul Technical University, Istanbul, Turkey
[c] Austrian Institute of Technology, Vienna, Austria

HIGHLIGHTS

- Off-grid PV has a huge potential to provide effective solutions for energy poverty.
- Its implementation barrier is economic, but paths to effectively tackle this exist.
- The implementation barriers will be reduced by a favourable technological evolution.
- Cost reductions to the level of grid-connected power will be eventually achieved.

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ABSTRACT

While in the developed countries electrification is paving the way for progress and prosperity, nowadays electricity is still not accessible for about 18% of the world's population. Lack of power grids is the main reason that prevents millions in remote areas in developing countries from using electricity for the daily basic needs. PV systems provide an effective solution for these regions, but affordability remains an issue. This barrier can be widely overcome on the short term by limiting PV power supply to very high added value applications and by properly exploiting innovations, especially in energy efficiency and cost reductions. Additional to that, the long-term perspectives of off-grid PV are very favourable based on its ongoing technological improvements and cost reductions. This paper studies four off-grid PV cases of which each could cover a combination of basic energy needs regarding light, cooking, food conservation and electronic appliances. Case I considers a system that supplies power for LED lamps and electronic devices. Accordingly, Case II adds a fridge and Case III an electric rice cooker to Case I, while Case IV adds both. The paper elaborates on available technologies and future developments regarding all components in order to assess the long term evolution and potential of these applications, most specifically how their affordability would evolve over time. The modelling and optimization of the four cases are performed using the software iHOGA, which is an efficient tool to provide the lowest cost solution for off-grid PV systems. The use of iHOGA for the four cases and the installation years 2020, 2030 and 2040, taking thereby into account different developing regions, provide an evolutionary techno-economic assessment of these applications and a clear picture about the developments to be expected from off-grid PV in general.

1. Introduction

Close to 1.3 billion people around the world do not have access to electricity, most of them living in rural areas in South Asia, Southeast Asia, and Sub-Saharan Africa. No access to electricity implies exhausting work for covering basic needs and hampers economic and social development.

Abbreviations: AC, Alternating Current; AGM, Absorbed Glass Mat; CdTe, Cadmium-Telluride; CIGS, Copper Indium Gallium Selenide; C-Si, Crystalline Silicon; DC, Direct Current; DoD, Depth of Discharge; GHG, Green House Gas; HDI, Human Development Index; iHOGA, improved Hybrid Optimization by Genetic Algorithms; LCoE, levelized cost of electricity; LED, light emitting diodes; Li-ion, Lithium-ion; MPPT, Maximum Power Point Tracking; NPC, Net Present Cost; O&M, Operation and Maintenance; RoHS, Restriction of Hazardous Substances; VAT, Value Added Tax; VRLA, Valve Regulated Lead Acid.

* Corresponding author.
E-mail address: ghassanzubi@gmail.com (G. Zubi).

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A concern on the global level is to boost the growth of the Human Development Index (HDI) of developing countries [1–3]. The HDI is a country development indicator that takes into account health (life expectancy), education (years of schooling) and standards of living (per capita gross income). Access to electricity can improve all these factors and with that boost the HDI significantly. Availability of electricity opens new business opportunities, while reducing the work in many domestic tasks, leaving time to more profitable labour activities. This is especially important in regions where people rely on biomass for cooking and spend many hours daily collecting it. Life expectancy can be increased significantly by the availability of sufficient potable water, which can be produced easily if electricity is available onsite. LED lamps can substitute combustion based lighting and with that avoid the health damage associated with indoor fire [4]. Also education can profit much from the availability of electricity as children can have access to computers and can study after sunset.

This urgent need for global access to electricity should bring a transformation which gives priority to sustainable growth and minimal environmental impact; among others the reliance on low-carbon energy technologies is vital. This matches with regional and global sustainability efforts [5–16]. PV is especially an interesting option here as most of the global population that don't have access to electricity live in regions with high solar radiation. Table 1 lists the world countries where most people without access to electricity live. As to be expected, the HDI in these countries is medium to low. The table provides also rough details on the solar conditions of the most affected countries, showing that these are very favourable sites for PV applications.

Dealing with developing regions implies that severe economic restrains are in place, while energy supply costs in terms of €/kWh are often higher than in developed regions. Affordability remains an implementation barrier for off-grid PV in developing regions. Nevertheless, affordability could be widely improved by focusing on basic needs and exploiting the potentials of energy efficiency. This approach is followed in this paper. The focus thereby is on basic domestic needs, most specifically lighting, cooking, food conservation and recharge of portable electronic devices (mobile phone and similar). The appliances used to satisfy these basic needs imply a wide range of technologies. For an off-grid PV system for developing regions it's highly relevant to rely on the most energy efficient technologies, for instance LED lamps instead of other lighting technologies (incandescent, halogen and fluorescent). This approach allows to achieve applications with highest added value and lowest energy demand, which translates into improved affordability. Furthermore, as off-grid PV has an ever growing competitivity, based on ongoing technological improvements and cost reductions, it is highly important to assess the long-term tendency of this aspect for the purpose of understanding the real potential behind it.

There is a big number of scientific publications on stand-alone PV systems, both pure solar and hybrid systems in combination with other renewables [18–26]. These focus on the application, simulation, engineering, monitoring and performance of PV systems in different countries and locations. For instance, Ma et al. provide a detailed assessment and performance analysis of a monitored off-grid PV system in Hong Kong, elaborating thereby on all relevant system operating data for an entire year such as the power flow between the generator, the battery and the consumer and the state of charge of the battery. On the other hand, this paper highlights the solutions to reduce the affordability barrier for off-grid PV systems for domestic users in developing regions and captures the evolutionary techno-economic aspects of these solutions on the short and long term and with that their exploitable potential in the energy poverty affected areas. This provides also a clear picture about the developments to be expected from off-grid PV in general.

2. Method

The purpose of this paper was to define off-grid PV solutions for developing regions and provide a clear understanding of their evolutionary techno-economic aspects. The focus is on single family installations. As reference coordinates locations in India, Pakistan, Bangladesh and Indonesia are used. This is based on the fact that there is high implementation need in these countries (see Table 1). Taking into account the reference years 2020, 2030 and 2040, provides the evolutionary techno-economic assessment of these solutions and a clear picture about the developments to be expected from off-grid PV in general. While this paper tackles extensively the cost reduction path and with that the affordability barrier of the emphasized solutions, it's not within the scope of this paper to tackle other implementation barriers, such as the availability of capital and policy requirements. This would be the topic of future publications by the authors. The following method is followed to achieve the mentioned objectives:

1. Define the basic domestic energy needs in developing regions and build based on these case studies.

Table 1
Global situation on access to electricity [3,12,17].

	Population (million)	No access to electricity (%)	No access to electricity (million)	HDI[a] 2014 (global rank)	Solar irradiation (kWh/m^{2}y)
World	7240	17.8	1285	0.702	–
India	1270	24	305	0.586 (135)	1600–1900
Bangladesh	158	39.2	62	0.558 (142)	1600–1700
Indonesia	255	23.5	60	0.684 (108)	1700–1900
Pakistan	190	29.5	56	0.537 (146)	1800–2000
Burma	51	70.6	36	0.524 (150)	1500–1800
Rest Asia	–	–	102	–	–
Nigeria	184	50.5	93	0.504 (152)	1900–2000
Ethiopia	90	44.4	70	0.435 (173)	2000–2300
DR Congo	71	84.5	60	0.338 (186)	1800–2200
Tanzania	47	76.6	36	0.488 (159)	1700–2400
Kenya	47	74.5	35	0.535 (147)	1700–2400
Rest Subsaharan Africa			328		
Rest World			43		

[a] HDI index rough classification: Low (<0.55), medium (0.55–0.7), high (0.7–0.8) and very high (>0.8).