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A review of the potential benefits and risks of photovoltaic hybrid mini-grid systems

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ABSTRACT

Photovoltaic hybrid mini-grid systems (PVHMS) are expected to play a major role in facilitating rural electrification in the developing world, however these systems still face significant barriers to adoption. The technology occupies a middle ground of electrification options – between traditional network extension and individual home systems, possessing elements of each yet also their own distinctive characteristics. Given this, and their relatively limited application to date, such systems are the focus of a growing body of literature. This work has highlighted a range of potential benefits and risks associated with the technology. However, there still hasn't been a comprehensive review of these documented benefits and risks; an understanding of which is crucial for informed project investment and implementation decision making. This paper presents a preliminary review of the existing literature to identify claimed and demonstrated benefits and risks. The most commonly identified benefits are those that are easy to measure: reduced cost and provision of improved electrical services. Other benefits such as the social or environmental benefits are less commonly demonstrated, but are frequently claimed. The major risks identified included incorrect system sizing due to load uncertainty, challenges related to community integration, equipment compatibility issues, inappropriate business models and risks associated with geographical isolation. For all of these types of risks, associated mitigation strategies were also identified in the literature. Further research including industry surveys and additional case studies will be required to validate what has been observed in the literature to date, and identify progress as the technology matures, costs fall and stakeholders learn from these previous experiences.

1. Introduction

The potential impact of mini-grids on the provision of rural electrification has been likened to the revolutionary impact of wireless and mobile technology on telecommunications services in developing countries [1]. Large networks of 'land-line' poles and wires used to connect centralised telecommunications service providers to their customers begin to look redundant as more nimble cellular networks overcome geographical challenges quickly and at low cost, in order to meet demand where and when it is needed.

Considerable progress has been made in recent decades to extend the main grids within developing countries to reach more of the rural population. However, the number of people without access to modern energy services is still estimated to be around 1.4 billion [2]. Those that remain unconnected are increasingly in locations that are very difficult or expensive to serve through extension of the existing grid.

Distributed approaches to electricity service provision, including mini-grids and stand-alone systems, just like wireless communications, provide opportunities for new technology and new markets [3]. For remote rural communities, this could mean electricity access where it would otherwise be economically or technically unfeasible, or have taken decades to achieve [4]. If rural electrification programs can be designed and implemented effectively, additional benefits for communities could include a more reliable grid connection, a lower cost service – driven by demand, rather than supply, with potential added benefits of local economic development, jobs and training [5,6]. Mini-grids could play an important role for energy provision in communities that are too remote to be connected to the main grid, but whose energy service needs are beyond the capabilities of individual solar home systems, and where there is an opportunity to aggregate resources – equipment and financial – across multiple energy users.

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It appears that mini-grids have not yet reached their rural electrification potential. While Solar Home Systems (SHS) have now achieved major and growing deployment [7] mini-grid technology has struggled to scale up and to fulfil its potential; estimated by the IEA to be over 40% of new electricity generation required to provide universal access to modern energy services between 2010 and 2030 globally [2]. A number of substantial barriers to up scaling have been identified in the literature [8,9]. Autonomous mini-grids commonly rely on diesel fuel supply. The high price of diesel fuel, which is volatile and trending up [10]; and the associated transportation logistics which substantially increase its cost in remote locations are a substantial burden for utilities and consumers, as well as those governments that subsidise diesel in many countries. Fuel costs and the operational characteristics of diesel systems also mean that they are often run for only a certain number of hours a day, meaning significant periods of time without electricity. SHS provide an alternative that avoids exposure to diesel fuel prices, as well as network investment, but are only able to supply a limited amount of electricity. Mini-grids capable of delivering more electricity and serving larger loads have been developed based purely on Renewable Energy Systems (RES), the least cost generation technologies being wind or Photovoltaics (PV). However, these intermittent generation sources require storage (usually lead-acid batteries) and associated power electronics which often involves high capital costs (CAPEX), and ongoing operational costs and challenges (OPEX) as these batteries require careful maintenance and periodic replacement during the life of the system.

There exists something of a middle path – a mini-grid with generation provided by RES combined with conventional diesel systems (referred to as a hybrid mini-grid) has widely been identified as a method to reduce fuel consumption, and achieve load and generator scale and diversity while avoiding the high costs and inconvenience of large battery storage [11–14]. PV is lower cost and more appropriate than wind in most remote mini-grid applications, as wind turbines become less cost effective as they become smaller, and the wind resource is spatially more variable and more difficult to estimate than the solar resource.

Of recent note, major decreases in the price of PV modules over the past five years have resulted in PV's levelised cost of generation falling below that of diesel generated electricity for many mini-grid applications [11]. Indeed, PVHMS are now frequently found to be the least cost option to meet rural electrification needs [12]. There are a wide variety of PV hybrid mini-grid systems (PVHMS[1]) system configurations and PV penetration levels that fall within this category [15,16]. Werner and Breyer [17] have completed a comprehensive review of the configurations of installed systems as documented in the literature.

This investigation therefore focuses on PVHMS and, in particular, the question why are we have not seen wider deployment of these mini-grids to date? The focus of our analysis is on the interplay of benefits and risks associated with the deployment of such systems. In particular, work to date has not systematically considered all of the potential benefits and accompanying risks associated with PVHMS.

This paper aims to address this existing gap in the literature and compile a qualitative review of known risks and benefits in utilising PVHMS as a first step to better understanding the risk/benefit profile of PV hybrid mini-grids. It begins by discussing the importance of considering ownership, risks and benefits in Renewable Energy projects in developing countries. In Section 3, a literature review of PVHMS is used to categorise benefits and risks previously described, and quantify how often they have been identified in the literature to date, and the weight of this identification e.g. has a risk been demonstrated or simply claimed. Finally, the results of the review and potential for further work are discussed.

[1] Sometimes referred to in the literature as MSG (abbreviated from Multi-user Solar Grids or Mini-grids with Solar Generation).

2. Defining ownership, benefits and risks

The identification and assessment of benefits and risks is vital in any decision making. Benefits and risks accrue to different parties involved in a decision and are therefore seen differently depending on the role and responsibilities of the party considering them. For example in the case of rural electrification, while system designers might focus on technical aspects, potential financiers might see economic or political benefits and risks. For the purpose of this investigation, benefits and risks are primarily assessed from the perspective of the *owners* of the systems, as this will give us the most comprehensive viewpoint.

For the purpose of this paper, the owner will be defined as the entity that initiates the project and finances its delivery (or in many PVHMS applications, facilitates finance through donated funds). Other interpretations of ownership include those responsible for operation and maintenance of the system, which is not appropriate for the case of PVHMS, since this role is often contracted out to third parties [12]; or commonly, the entity that receives benefits from the project [refs to show it is common]. The latter is also often not the case for PVHMS, for example, a government funded utility may own a system but operate it at a break even cost (or perhaps make a loss), and the beneficiaries are instead the end-users.

Owners of PVHMS can be private or public organisations, seeking access to new markets, or charged with providing reliable electricity service in rural communities. They may receive support from international funders towards rural energy provision, and may rely on separate project developers or NGOs for implementation. A major success factor for all projects is possessing clarity on ownership and the accompanying responsibilities of each stakeholders throughout the life of the project (as highlighted in Ref. [18] for case of SHS). Depending on the goals and contractual responsibilities of the owner, benefits and risks may accrue to a range of different stakeholders. The most important stakeholders should, of course, be the communities that these systems are intended to serve. Good alignment of incentives, or costs/benefits and risks seen by decision makers and communities is likely to lead to the best outcomes.

For the purposes of this paper, benefits are defined as an advantage gained through the choice of PVHMS relative to other technical options. Risks are considered in the project sense, i.e. uncertainty, or the risk of an unforeseen event or activity that could impact the project's progress or outcomes in a positive or negative way. The risks and benefits must be considered together, since if the benefits increase then this will inevitably increase the risk appetite of the decision maker.

In the case of renewable energy technology, the lack of understanding and misrepresentation of perceived risks and benefits has been identified as a barrier for adoption [19,20]. From a project financing perspective, renewable energy projects require a greater upfront capital expenditure than fossil fuel based projects and therefore harbour greater risk.[2] PVHMS have different investment

[2] Consider a hypothetical rural electrification project with two possible solutions – a diesel generator or PV – both provided by debt financing. In the years before payback the cost of debt financing for renewables may be equivalent to the fossil fuel cost. However, if the project was to fail early (for instance a technical reason), then the PV would face a much heavier risk consequence as it would still need to pay back the large CAPEX borrowed, while for a fossil fuel system the fuel cost would disappear along with the service provision.

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