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.

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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.

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.

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 [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

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

projects require a greater upfront capital expenditure than fossil fuel based projects and therefore harbour greater risk[2]. PVHMS have different investment characteristics with the PV driving higher up-front deployment costs, whilst lowering ongoing project costs, largely diesel fuel. PVHMS are also viewed to carry more risks due to technological complexity and limited experience with the technology compared with conventional diesel only systems [21]. Furthermore applications of the technology in remote communities in developing countries, carry additional technical, institutional and economic challenges.

The majority of the existing literature on PVHMS focuses on the benefits of the technology and/or an analysis of barriers, but the benefits and risks accruing to different stakeholders have not been considered in aggregate in the literature. In addition, as we will see in this review, many of the risks and benefits identified in the literature are context specific or are simply claimed rather than demonstrated.

In order for PVHMS to reach their market potential at the scale required to achieve the goal of modern energy access for all, investment conditions that are attractive to the private sector and financiers will almost certainly be required. This will likely require the support of government and international development funding decision makers. One necessary step in achieving the required level of confidence in the technology is identifying and understanding the benefits and risks. The remainder of this paper reviews the documented risks and benefits from the literature, and where the literature suggests risk mitigations, these are also noted.

3. Methodology

A literature review was based on selected papers from academic databases, online reports, conference proceedings from the largest industry conference focusing on PVHMS - the European Conference on PV Hybrids and Mini-grids[3], and the International Energy Agency (IEA) Photovoltaic Power Systems (PVPS) Task 11 on PV-Hybrid Systems within Mini-grids.

It was observed that work on PVHMS can be loosely categorised into three groups:

- Technical Simulations (e.g. control systems, alternative storage)
- Project Simulations (e.g. economic modelling, PV penetration)
- Operational Experience (e.g. case studies, lessons learnt)

This review focused on Project Simulation and Operational Experience papers as these were deemed to be most relevant to project implementation and system ownership, whereas technical simulations are often focused on testing specific, often pre-market technologies or novel operating strategies.

Papers were reviewed with an eye to identify benefits and risks. A clear distinction was made between those papers that simply mentioned a particular benefits/risks to those that demonstrated or recorded experiences of a benefit/risk. Demonstrated examples from the literature are of particular interest given that many general discussions of benefits or risks attributed to the technology do not provide much guidance on the extent of these benefits or risks, and how they might be addressed.

Risks (Table 1) and benefits (Table 2) have been grouped into types, with a summary of what has been written about each in the literature. In Table 2 accompanying mitigations have also been included.

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[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.

[3] The 3 most recent conferences were included – 2008, 2010 and 2012

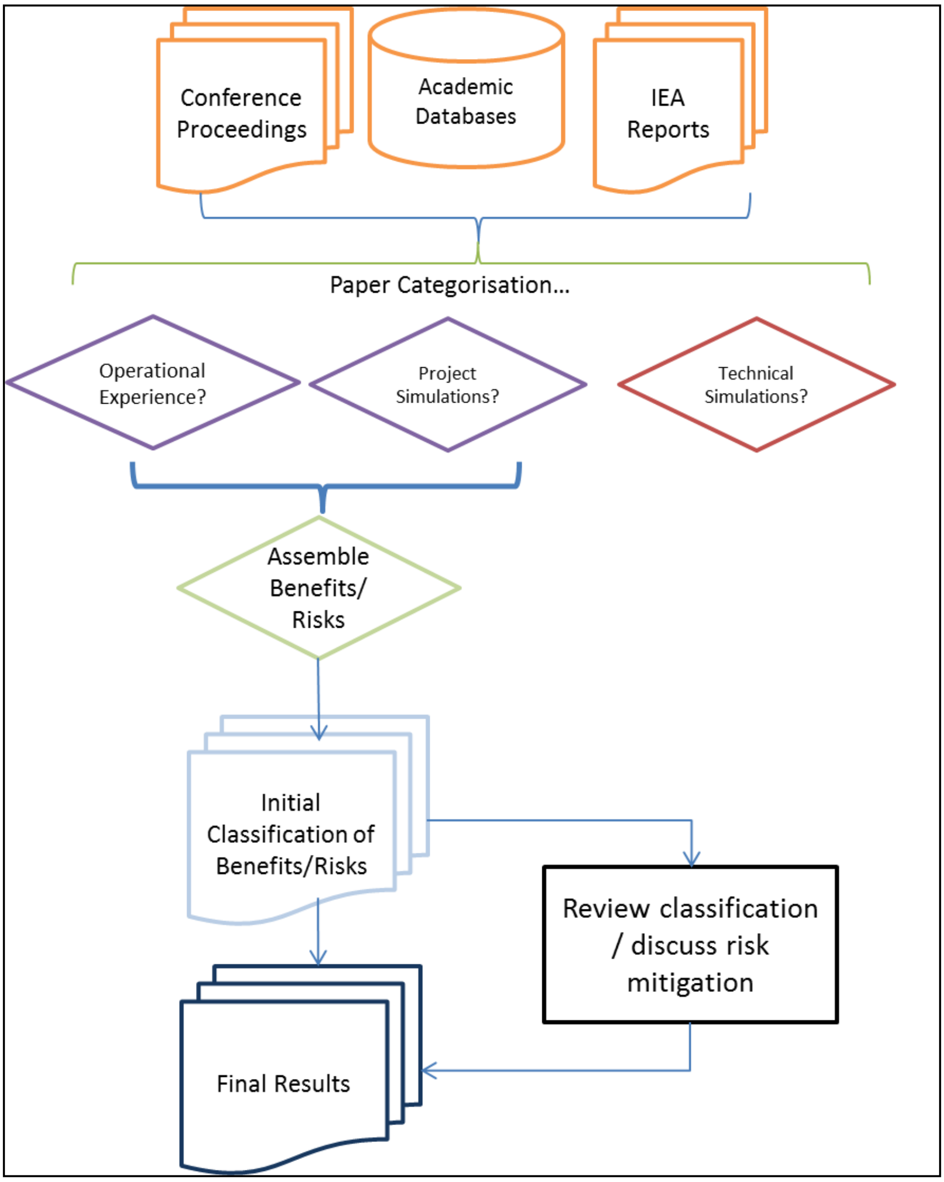

Figure 1 Visualisation of Review Method: Papers first categorised into groups then reviewed to compile benefits/risks

4. Results

Table 1 Benefits

Benefit Category	Benefits	Description	Demonstrated by	Referred to in
Technical/ Operational	**Improved Electrical Services**	PVHMS can offer improved electrical services to the customer compared to traditional single-source systems. Hybrid systems have at least partial redundancy, while the PV Battery combination provides the opportunity to supply a low load overnight, which is typically unserved by strictly diesel systems due to inefficiency at low load. Improved electrical services also achieved via the fast rollout of services to un-electrified areas (such as that witnessed in China: 300,000 people in 20 months [22]), improving reliability of existing but unreliable grids (such as demonstrated in Lebanon [23]), provision of additional power over that available from individual systems (see Moix [24]), or to areas where fuel is not available (as in Amazonas [25]).	[22]–[27]	[12], [14], [28]–[35]
	Reduced Fuel Dependence	With the increased penetration of Renewable Energy diesel fuel consumption is offset, and the diesel generator may not need to be run at low loads (which lowers efficiency). The inclusion of Renewable Energy generators therefore reduce operating costs but also reduce reliance on an often uncertain supply chain, and volatile commodity prices, and can therefore benefit service reliability as well as reduce price risk (see [36] for simulation results based on South Africa).	[29], [36]–[38]	[12], [34], [39]–[42]
	Reduced Maintenance costs	As above, the reduced need for the diesel generator will mean the run hours of the generator will accrue at a lower rate. Also, by not being required to service low loads the generator lifetime (run hours to failure) would increase.		[30], [40]
Financial	**Improved LCOE for Operators**	The levelised cost of electricity for mini-grids is often lower than that of grid extension, and can be optimised by a combination of PV / Diesel / Batteries. Furthermore compared to SHS the cost of BOS/storage can be reduced, since it is shared amongst users, while the benefits of load diversity can reduce system capacity requirements. Compared to strictly diesel systems, maintenance costs are also said to be reduced because the diesel engine is running less and running at low load may be avoided [34], [37].	[14], [31], [35], [36], [38]	[12], [34], [37]
	Increased Willingness to Pay	Due to an improvement to electrical services (e.g. less blackouts) customers may have demonstrated greater satisfaction with energy services and have been found to be more willing to pay for the service [23]. In one case willingness to pay had been problematic in prior technologies, but the switch to PVHMS had drastically improved revenue collection, mainly due to it an inbuilt prepayment system. [42]	[42]	[23], [43]
Social	**Opportunity for Rural Enterprise**	A shortcoming of SHS technology is the inability to service larger loads, including those required for many types of income generating activities. PVHMS offer significantly greater power and reliability to serve these loads. It has also been observed that some implementation models for operating PVHMSs can economically benefit the community directly through creation of jobs or entrepreneurial opportunities [33].	[33]	[9], [12], [39]
	Strengthening community	Access to electricity contributes to a whole raft of social benefits, such as improved healthcare, communication and standard of living. For a quick overview, interviews of end users from PV Hybrid systems in the Amazon [25] detail specific community benefits. Also attributed to hybrid mini-grids is the potential for improvements to community cohesion to arise as noted in Palestine [39] and Vanuatu [44], and this would be relative to individual solar home systems or private gen-sets.	[25], [26]	[31], [33], [34], [39], [44]
	Local Capacity Building	Where capacity development is incorporated, PVHMS implementation can contribute to increases in local skills and build new community institutions (village training empowerment is discussed in Laos [33]). Models of community ownership have also been developed whereby the end users are also the owners and operators of the system, this ensures incentives are aligned [12].	[12], [33]	[45]
Environmental	**Environmental Protection**	By reducing combustion of diesel, PV and PV/Hybrid systems reduce greenhouse gas emissions and improve local air and noise pollution. Gül showed air pollutants to be significantly lower than equivalent diesel and biogas alternatives yet, obviously, higher than purely PV [28]).	[28], [36]	[32], [39], [46]

Table 2 Risks

Risk Category	Risks	Description	Demonstrated by	Referred to in	Mitigation and Citation
Technical	**Load Uncertainty**	As with all decentralised electricity supply solutions, poor estimation of load size, growth and schedule creates risk. Lack of knowledge about load conditions can result in oversized systems (increased investment & running cost, lower efficiency (as high as 20% losses [45]) or undersized system (unreliable supply) [47]. Accommodating loads that inevitably change over time is an additional challenge (see instance where load doubled over ten years [48])	[42], [45], [48]–[50]	[9], [12], [14], [21], [22], [26], [43], [47], [50]–[54]	• Use of design tools to estimate load (such as [47]) • Modular designs • Where possible design with future expansion in mind (business case described in [52]) • Prepayment schemes such as the 'Daily Energy Allowance" can control growth [51] and for limited communal systems, load control is recommended [22] • Energy efficiency measures [42]
	Power Quality Risk	Particularly relevant to retrofits on existing systems, the integration of PV and batteries may be disruptive to grid stability if components are not compatible and an effective control system is not deployed. This risk is dependent on the PV peak penetration level, as very low peak penetration levels <50% PV contribution can be treated as a negative load and no additional control requirements are required [16]. With higher penetration, a more complex control strategy is required. This was a focus of subtask 20, IEA PVPS Taskforce 11 [55].	[16], [55]	[14], [28], [56]–[60]	• Appropriate control strategy (IEA PVPS Task 11 Subtask 20 [55]) • Appropriate design simulation prior to implementation [56], a variety of tools are available [61],[62] • Distributed generation in mini-grid shown to be less variable than centralised source [58]
	Equipment failure	Premature failure of hardware would in many cases cause interruption of service, but could also potentially result in damage to the entire system. See early inverter failures ([16],[63]); data logger failures (see [50]) or PV encapsulation failure [63]. While many components are covered by warranty or guarantee, enforcing these is challenging for poor isolated communities in areas where markets do not operate effectively and distributors are not well established [14]	[16] [50] [63]	[14], [64], [65]	• Equipment should meet minimum quality standards, [66] and be appropriate for the environmental conditions [64] • Operators should exercise appropriate routine maintenance [26]
	Hardware compatibility issues	Incompatibility of system components creating problems at commissioning phase (see PV-Diesel compatibility problems [42]). Some components use a proprietary protocol, leading to incompatibility.	[42],	[13], [67].	• Turn-key solutions with a single provider simpler as multiple suppliers need site specific adaptation [42] • Use an open based protocol [67]
	Limitations for Continual Supply/Storage	Batteries are expensive, have limited life spans and usually the vulnerable component to misuse [21]. Furthermore ageing of batteries has an enormous influence on energy balance and supply, and this reduced capacity may have a kick on effect to operating strategies of the generators [40]. Recorded end user experiences in China showed that people were generally dissatisfied with the unpredictable supply [22]	[26]	[14], [21], [40]	• Manage user expectations • Appropriate product selection (see [14] for considerations • Spare parts, planning/budgeting for replacement [9]
Organisational	**Inadequate business models**	Effective business models are required to increase deployment, and may need to be adjusted in order to scale up. One such example was prepayment systems disrupting business revenue streams in South Africa [30]		[1], [9], [11], [12], [21], [30], [31], [45], [53]	• Information sharing about pilot projects will assist in the development of adequate business models [9] • Organisations require government support for capacity building, and access to finance.
	Geographical Isolation	Due to the long distances, transportation challenges and lack of skilled personnel, system installation and repair in remote locations often proves technically challenging, time consuming and costly (demonstrated well in rural Malaysia [68]). Furthermore the availability and supply of spare parts can have presents an ongoing challenge for operators. C	[41], [68]	[21], [25], [53], [69], [64]	• Local capability building for routine maintenance[25] • Routine maintenance built into the initial design model. • Locally available spare parts

	Supply and installation issues	Problems relating to incorrect installation and operation of hardware have been noted, including non-optimal panel tilt and incorrect part supply [70]. Often in remote areas, the local ability to deal with serious technical issues is a problem [12].		[12], [14], [53], [70]	- Ensuring installers and operators are properly trained [66] - Incorporate capacity development in the project scope
Social	**Community/Social Integration**	Likened to a village water supply, mini-grid implementation requires careful planning and cooperation. Over-consumption from one of the users can cause a global black out in the village [40]. Examples of theft of power ([71], [53]) and users connecting loads well beyond their allotted quota to the detriment of the community [22] have been documented.	[22], [40], [71],	[12], [14], [30], [51], [53].	- Community engagement from the outset and follow up [25], [44], avoid a top-down development approach [53] - Respect local organisational structures [12] - Manage user expectations/follow up [53] - Enforce load control measures - Tariff system to prevent overconsumption [40]
Sustainability	**Diesel cost and supply**	Even with reduced diesel requirements, the risk of price impacts and supply failures are significant. While renewable energy prices, particularly PV, have fallen diesel prices have risen and are volatile.	[12]	[21], [43], [46] [72]	- Maximise other sources of generation[12] - Develop time of use tariffs to discourage consumption when diesel would be required.
	Future Connectivity	Mini-grids have traditionally been viewed as an interim solution, however the ideal scenario is that they become interconnected/ or connect with the main grid if it becomes available. It is important the systems are designed with this in mind, or the risk is the system will become obsolete.		[14], [9], [11], [30]	- Design mini-grids to the same standard as the central network,[30]
	Stakeholder Management	Multiple parties may be involved in designing, operating and maintaining the systems or it may even be the case that separate parties are responsible for different elements of the systems (e.g. privately owned PV, utility owned grid/diesel). There is therefore the risk that incentives will not align between parties which may lead to negative outcomes.	[43]	[12], [14], [53]	- Parties need to be aware of their obligations, and maintain a collaborative approach if issues arise [53]. - Standardised and fair Power Purchasing Agreements (PPAs) which protect every actor equally [12]
Financial	**Appropriate Pricing and payments**	Rural customers are usually poor, typically requiring subsidies to access energy. It can be challenging to set a price that is both sufficiently high to give the investor a return and low enough to make it affordable to the consumer [73]	[73]	[12], [30], [43], [53]	- Time of use tariff structure and pricing structure is a proposed but un-demonstrated solution [73] - PPAs should be flexible and revisable when it comes to tariff
Safety	**Safety of Operators/ End Users**	Mini-grids operate on AC and much higher voltages relative to solar home systems, so risks of harm to operators and users is increased [30]. The dangers of AC electricity may not be known to new users, and extensive wiring throughout communities may present dangers not well understood [53].		[12], [30], [53]	- Design and install to international standards - Provide appropriate training to operators and users

5. Discussion of Results

The most commonly cited benefits of PVMHS in the literature are improved electricity service and lower operating costs. The first usually stems from the capabilities of PVHMS to serve larger loads relative to individual PV systems, and their ability to provide a more reliable supply in the challenging context of rural electrification. This benefit is also common to other technology choices (e.g. purely diesel mini-grids), but technology decisions must consider the net benefits and risks. It is now well demonstrated that significant cost reductions can be realised through the use of PVHMS, if the solar resource is good and the penetration level is appropriate to the load.

It has been observed that other benefits such as capacity building, willingness to pay and other social benefits, are less often identified in the published literature. This is likely because they are harder to demonstrate and measure, and also dependent on the specific details of implementation under the PVHMS program. In general there was little quantification of benefits reported – a clear area for future work.

Commonly identified risks in the literature include load uncertainty, lack of effective business models and power quality issues. The first two have been most frequently identified throughout literature, and have persisted over time, from 2001 [21] to 2013 [8]), so appear to be critical barriers to increased implementation of PV Hybrid Minigrid Systems. Other commonly identified risks include geographical isolation and inadequate community and social integration. It has been noted that inadequate organisational structures for system operation, maintenance and fee collection are common barriers to long term sustainability [13] [53]. Where risks have been identified in the literature, mitigation options have been commonly suggested, as summarised in Table 2. Whether or not these are transferrable between contexts is a question for further research.

It should be noted that much of the literature, in particular conference proceedings, which are heavily cited in this review, have been contributed by industry participants developing these systems, which tends to advocate for the technology. Independent and systematic analysis would therefore be of great value.

Further work is required to better understand how benefits and risks accrue to different stakeholders, and how the implementation of PVHMS projects and programs can be designed in order to maximise benefits, reduce risks, and align the interests of communities with decision makers. An assessment of the way that the risk/benefit profile of PVHMS has evolved over time could also help to predict how it might do so in the future. In order to further this research, the authors propose to track risks and benefits throughout a project’s implementation and subsequent lifetime, via examination of specific case studies and consultation with stakeholders involved at the project level.

6. Conclusion

Photovoltaic hybrid mini-grid systems are expected by many to have a significant role to play in providing rural electrification, but there are significant barriers to their adoption. While the technology is the focus of a growing body of literature, there has been no comprehensive review of the documented benefits and risks, crucial for project implementation and investment decision making. This paper has provided a preliminary review based on existing literature. The most commonly identified benefits are those that are easy to measure: cost reduction and provision of improved electrical services. Other benefits such as the social or environmental benefits are less commonly demonstrated, but mentioned frequently. 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 mitigations were also identified in the literature, but risks and appropriate mitigation are often context specific. Further research has been proposed to validate what has been observed in the literature with the views of industry and case studies.

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