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Review Article

Humanitarian Engineering for Renewable Energy and Flood Early Warning in Remote Communities: A Scoping Review of Enabling Factors and Sustainability

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ABSTRACT

Small communities in remote, riparian sites often have limited resources, and experience energy insufficiencies and poor disaster resilience to intensifying weather hazards such as rainstorms and floods. Humanitarian engineering interventions for off-grid renewable energy generation and flood response at the local level have the potential to support community hazard management and socio-economic development. This scoping review examines communities in low and lower middle-income countries, and their use of renewable energy and flood warning systems. Its primary focus is vulnerable communities and how they can achieve hazard protection as part of sustainable development initiatives. The findings highlight that it is important to consider institutional, environmental, social/ethical, economic and technical indicators in developing a comprehensive understanding of the success or failure of a given system. The study concludes that an integrated renewable energy and flood warning system may provide an optimal, community-managed approach to address priority needs.

KEYWORDS

Hydropower, Solar energy, Appropriate technology, Developing countries, Hybrid system.

INTRODUCTION

Localised renewable energy is an affordable, clean alternative to fossil fuels that is gaining popularity for use in remote 'off-grid' communities [1-4], particularly in low and lower-middle income countries [5], where reducing costs make it more feasible [4, 6, 7]. To support such communities and their ecosystems, national and international organizations often provide development assistance programs alongside specific forms of humanitarian intervention. Key goals of these programs, respectively, include enhancing community capabilities regarding energy sufficiency [8-10] and disaster risk reduction at the local level [11-13].

Access to resources and knowledge on how to establish, operate, repair and maintain local infrastructure and services increases community self-sufficiency. Frequently however, this is not the case for the remote, riparian communities in low and lower middle-income countries. Assistance provided to these communities is often temporary, or promised longer-term solutions fail over time as they cannot support (or be supported by) end-users in a realistic and sustainable manner. Such communities are often small, agriculture-based monoeconomies with low incomes, power insufficiencies, and increased exposure to extreme weather events due, in part, to limited response capability and technological support [14-16]. In this study, communities with such characteristics are described as vulnerable or remote. Its focus is on their current use of support technologies and potential future development of such assets.

The United Nations 2030 Agenda for Sustainable Development [8] highlights the importance of Sustainable Development Goal 7: Affordable and Clean Energy as essential for socio-economic development and self-sufficiency, as well as for the success of other Goals [17]. Off-grid renewable energy systems (OGRES), such as small-scale hydropower generators and solar panels, offer a range of potential benefits to vulnerable communities, including enhanced disaster response capability when generated power can support flood early-warning systems (EWS) [18]. According to the Sendai Framework for Disaster Risk Reduction, community resilience against natural hazards is an essential element of sustainable development [11]. Successfully combining OGRES and EWS would provide a comprehensive humanitarian engineering solution that accords with the principles of both of these international frameworks [19].

In this study, humanitarian engineering is defined as the technology-focused applications that can support the basic needs (e.g. energy generation, shelter, water sanitation) of an affected population, including preparation for, and response to hazard events [20-22]. Such applications can be either temporary or permanent [23]. Humanitarian engineering is often conceived by aid practitioners and field engineers as providing innovation and 'elegant solutions' to more than one issue simultaneously (e.g. a micro-hydropower system for irrigation may also power public lights and a school facility) [24, 25]. While humanitarian engineering has the potential to provide such multi-faceted solutions in vulnerable communities, a key requirement is that such solutions are sustainable over time and within community resources, especially after the professionals leave or external funding discontinues.

To evaluate sustainability, it is essential to determine the appropriateness of a proposed technology to the community (perceived value and sustained use) and its environmental context (i.e. low and/or positive impact). So-called 'appropriate technology' frameworks consider local characteristics and allow slow adaptations while end-user communities reach and maintain sustainable forms of development [26-29]. Assessments of technology appropriateness for local-level renewable energy systems typically examine technical, economic and social indicators that would support effective use in a specific community [30], [31]. Bauer and Brown [32] developed the 'Appropriate Technology Assessment Tool' which uses 47 indicators to determine technology appropriateness. The tool has a strong evidence base, with its indicators derived from a meta-analysis of 53 articles, books and conference proceedings in appropriate technology. In addition to appropriateness, Ilskog [33] has argued for additional analysis of the sustainability of community-level technology developments across two categories: environmental and institutional. Her proposed method assesses these across 39 indicators, with these articulating closely with the United Nations Millennium Development Goals, and the United Nations Sustainable Development Goals. Importantly, this assessment framework has also demonstrated specific utility in sustainability evaluations of energy-related projects [34]. The frameworks of Bauer and Brown [32] and Ilskog [33] provide comprehensive coverage of the appropriateness and sustainability of community developments which have a technology focus, and both will be used in the evaluation of case studies identified in this review.

This scoping review investigates the uses of OGRES and flood EWS in vulnerable communities, including specific indicators of strengthened or undermined end-user confidence in these systems or their sustainability. While individual case studies have detailed the successes and failures of OGRES or EWS in remote communities, a comparative analysis of these systems following the four-stage framework of Arksey and O'Malley [35] has not previously been conducted. Such an analysis can inform researchers, government authorities, development, and humanitarian agencies, as well as communities themselves, as to the viability and cost-benefit of such systems in these contexts. These data will also inform a wider study at Western Sydney University in Australia which is examining whether community-level renewable energy sources can reliably power flood EWS as a hybrid system. To the authors' knowledge, there has been no such study of combined systems for sustainable development and flood resilience at the local level. While some researchers have examined solar energy use in EWS [36-38], there are no published data regarding other OGRES (i.e. hydropower) powering localised EWS for community response. While the primary focus of this review is the community use and effectiveness of OGRES and EWS as individual 'sub' systems, a secondary focus will be the implications of these findings and potential applications for a future hybrid system. Community-focused features that enhance acceptability and sustainability of the sub-systems among different populations facing similar threats will likely be integral to hybrid systems [39].

METHOD

This article presents a scoping review analysis that follows the four-stage framework of Arksey and O'Malley [35]: (i) identification of research questions, (ii) identification of relevant studies, (iii) selection of studies, and (iv) collation and report of findings. This method has been used by many scholars, and has been adopted for use in a wide range of disciplines [40]; for example water, sanitation and hygiene (WASH) [41], aging studies [42, 43], education [44], and occupational safety [45].

Research questions

The aim of this scoping review is to collect research findings (success cases, lessons and failure factors) related to community-based renewables and flood EWS installed in low and lower middle-income countries. The review was guided by the following questions:

1. What are the elements of successful OGRES and EWS within vulnerable communities experiencing energy insufficiency and/or flood risk?
2. What factors contribute to (or enable/disenable) the successful establishment and ongoing maintenance of such systems in low and lower middle-income countries in order to achieve sustainable development?
3. What features should a hybrid system have in order to be sustainable longer-term?

Search strategy

A range of terms are used in the literature to describe the focus areas highlighted in this article. For example, "renewable energy" is sometimes used interchangeably with terms like "green energy", "clean energy" or "sustainable energy". We conducted our search based on the most commonly used version of these terms. The following string was used for the identification of relevant studies: ("success" OR "lesson" OR "failure") AND ("renewable energy" OR "flood early warning" OR "technology acceptance" OR "technology transfer") AND ("developing countr*" OR "low income countr*")

Identification of studies

ScienceDirect was selected as the primary source for research articles in multi-disciplinary themes (e.g. engineering, energy, environmental, social and sustainability) fields. Google Scholar was also used to broadly search for relative scholarly literature. In addition, the following key academic journals were selected for this search due to their high relevance in their fields:

- Energy for Sustainable Development;
- Engineering Failure Analysis;
- Environmental Science & Policy;
- Journal of Cleaner Production;
- Journal of Rural Studies;
- International Journal of Disaster Risk Reduction;
- Procedia Engineering;
- Progress in Disaster Science;
- Renewable Energy;
- Renewable and Sustainable Energy Reviews.

Lastly, the authors examined so-called 'grey literature', which is understood as literature produced and/or delivered by international and multinational organizations and agencies that are not primarily focus on 'traditional'/academic publishing. The following bodies were searched:

- International Centre for Integrated Mountain Development;
- International Renewable Energy Agency;
- United Nations Framework Convention on Climate Change;
- United Nations University Institute of Environment and Human Security.

Inclusion criteria

Review articles, research articles, case reports and product reviews available in English were included; all other types of publications and languages were excluded. As interest in renewable energy and early warning technologies dates roughly from the beginning the selected period was from January 2000 to December 2020. This is a period that has witnessed a plethora of innovations and optimizations. Furthermore, the Sendai Framework for Disaster Risk Reduction, and the 2030 Agenda for Sustainable Development were also initiated during this period, guiding responses for disaster resilience, environmental protection, humanitarian aid and sustainable development.

Selection of studies

A total of 2,449 studies were identified from ScienceDirect and Google Scholar, with the period of examination lasting up until December 31st, 2020. After journal searching, 325 studies were retrieved. Firstly, titles and abstracts were screened which resulted in 42 studies. Full-text screening of the included studies resulted in nine studies. After bibliographical searching, one study [14] was additionally included. Two other studies [46, 47] were added due their high relevance to the topic and response to research questions; these were found by using the string keywords in the Google search engine. The 'grey literature' search resulted in six reports, while full-text screening led to the inclusion of only two reports. The full-text analysis thus resulted in 14 studies for final inclusion. The entire process is visually explained in **Figure 1** and a summary of the studies is provided in **Table A1** in Appendix.

Data analysis

The selected-for-inclusion studies were coded following the 6-step process as detailed by Braun and Clarke (2006) [48]. This process includes: (i) data familiarization by reading and re-reading the studies, (ii) initial codes generation; (iii) codes grouping into relevant themes; (iv) review themes to develop a 'thematic map', (v) themes definition and naming, and (vi) themes narration.

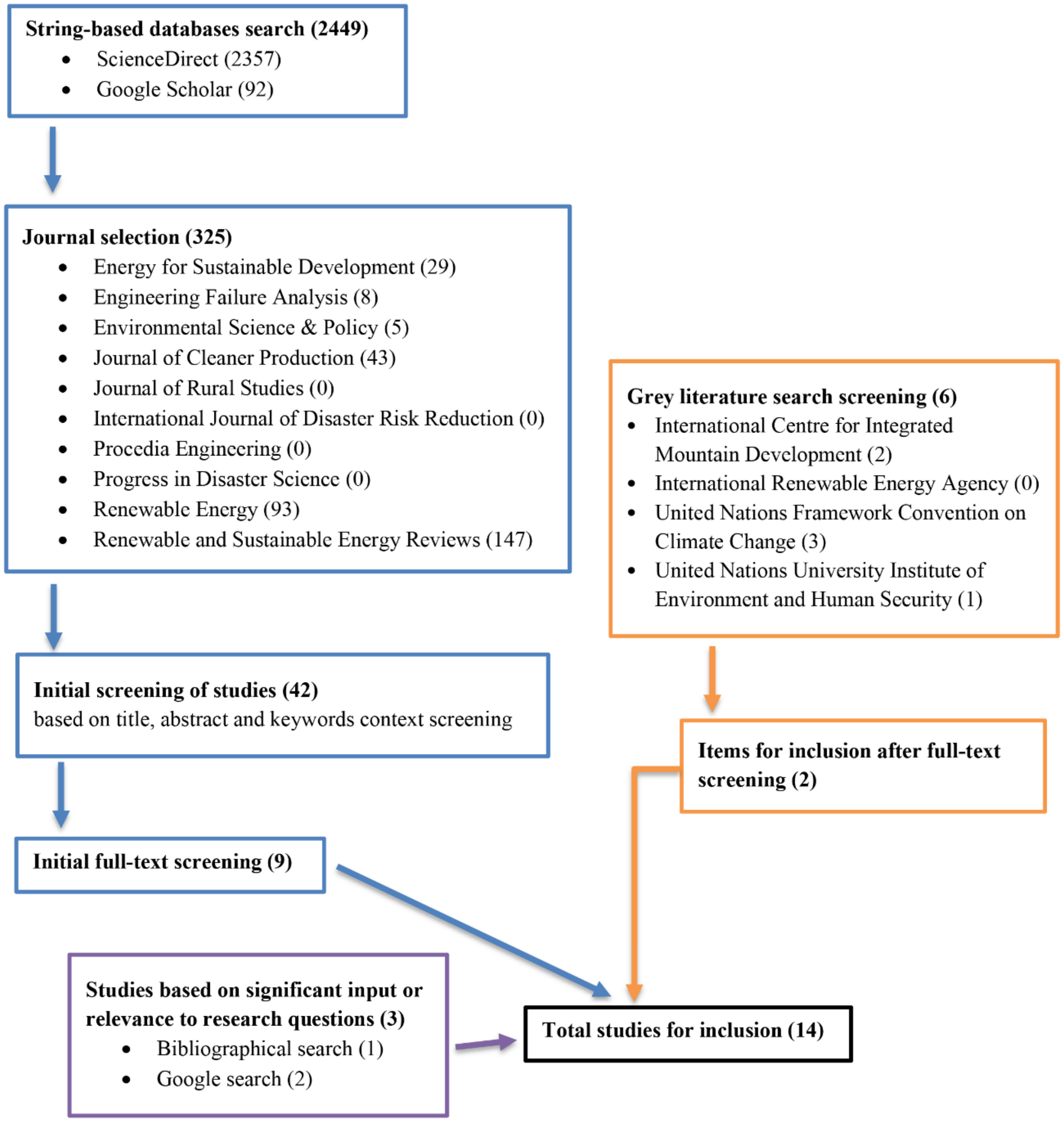

Figure 1. Study selection flow chart

RESULTS

The scoping review led to three major findings:

- Despite the differences in socio-cultural, economic and environmental conditions, many communities have similar needs and lack similar capabilities;
- Many cases shared either the same or similar system failure/success indicators;
- Long-term community engagement and equitable socio-economic benefits delivery were crucial in the success of both systems, while lack of support, technical know-how, funding and system service were major indicators for failure.

Three primary themes were distilled from the findings:

i. Recognition of diversities and similarities in vulnerable communities;
ii. Appropriate technology and sustainability mapping:
iii Enablers for success and failure factors.

Recognition of diversities and similarities in vulnerable communities

The review summarised OGRES case studies (hydro, solar, and wind-power, and mixed projects) from Bolivia, Philippines, Nepal, Rwanda, Ethiopia, Gabon, Ghana, Kenya, Malawi, Mozambique, Nigeria, Tanzania, Cameroon, Central African Republic, Chad, Republic of Congo, Afghanistan, and Papua New Guinea. The EWS case studies (flood or multi-hazard) were located in Kenya, Sri Lanka, Egypt, Mali, Afghanistan, India, Nepal, and Pakistan. The findings indicate that most cases for renewables were located in the African region, while for flood EWS they were located in both African and Asian regions. Another observation from the data in **Table A1** is that some of the OGRES and flood EWS cases were located in the same country (e.g. Kenya, Nepal). This shows that some regions in these countries are in need of both energy and flood resilience aid.

Besides the similarities in the lack of sufficient energy and flood resilience infrastructure, communities demonstrated differences to each other due to their differing needs, capabilities and socio-cultural makeups. For instance, communities in Bolivia used electricity for powering refrigerators, while communities in the Philippines did not. The OGRES in Bolivia and the Philippines increased income and created more jobs but not in Afghanistan. In Mali, neighboured communities and different groups were in conflict with each other due to water scarcity, however, in Hindu Kush Himalaya, communities worked well together to face floods.

Appropriate technology and sustainability mapping

The complimentary assessment frameworks **[32, 33]** described in Introduction are suitable to combined use to support a comprehensive review of the identified studies. **Table A2** in Appendix summarises the findings and classifies the cases based on information of failure or success outcomes. The following session further details the results of **Table A2**.

Enablers for success and failure factors

Table A2 presents important information for the technology appropriateness of both OGRES and EWS installations. Importantly, it frames enablers for successful approaches and problem solving, as well as conditions that lead to failure.

Regarding the institutional indicators, community engagement was perhaps the most important enabler for technology appropriateness as it was highlighted in many OGRES and EWS cases. Ownership and management, as well as autonomy were also important, especially when local stakeholders were involved in system development. None of the reviewed OGRES and EWS were reported to have caused any significant impacts to local ecosystems. Conversely, some OGRES were found to have supported 'damaged' ecosystems (e.g. reduced use of firewood). Both types of systems were most successful when adjusted to local environmental conditions (e.g. could operate/multi-function in high and low water levels). In social/ethical matters, post-installation improvements in daily activities, health conditions (e.g. reduced use of kerosene) and services, education, socializing and entertainment were crucial enablers for the success and acceptability of both system types. In the economic realm, the generation of income, creation of new jobs and low installation and maintenance costs were major success indicators. With respect to technical matters, and for both systems types, adaptability, simplicity, effectiveness, multi-purposing capacity, and materials availability were good enablers. Notably, one EWS presented hybrid characteristics (self-powered by solar panels).

In terms of failure factors in institutional matters, issues occurred when the legislation and regulations were not appropriate to such systems development. The lack of support of all kinds was also a significant disenabling factor. With respect to the environment, the systems could not operate well when they were not designed for local site conditions, while for social and ethical issues, the lack of benefits or inequitable delivering, fear of identity loss and conflicts, theft and jealously were serious failure factors. Knowledge, training and ease of use were also important criteria for the success or failure of a system. In terms of economics, the most important factor was the high cost of the systems. Furthermore, marketing strategies in local populations also contributed to the acceptance of or apathy toward systems. Lastly, in technical matters, most failures occurred when the system was not appropriately constructed, vulnerable to extreme weather conditions, energy inefficient, poorly maintained, broken, and complex. These issues were primarily the outcomes of a lack of funding, knowledge and skills and overall support.

DISCUSSION

The findings from this scoping review can help improve humanitarian engineering interventions regarding the appropriateness of OGRES and EWS in remote communities, with the outcome data examining both failure and success factors.

As noted above, OGRES were largely situated in African regions where instability in electrical power provision is common. Africa has the physical characteristics required to develop a range of renewable energy applications and increase energy supply [49-52]. For example, the Sub-Saharan region is one of the least developed regions globally with major electrification problems, so there is great potential for OGRES [16], [53-60]. The local atmospheric and hydrogeomorphological conditions permit both hydro and solar-power installations. However, countries in the Sub-Saharan region often lack resources, infrastructure, political will and funding to establish such systems on a sustainable basis [50, 54], [61-68]. **Figure 2** presents the Population without Access to Electricity 2019 Map*, developed by the International Energy Agency – IEA [69]. The map focuses on countries in the ‘Global South’.

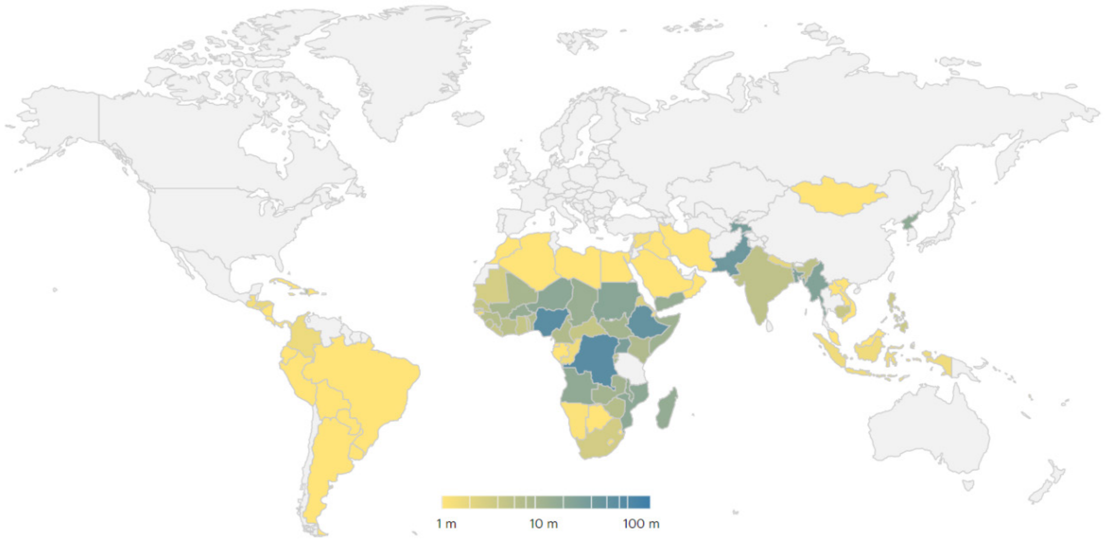

Figure 2. Population without Access to Electricity 2019 Map

Figure 2 illustrates the serious energy insufficiency of Sub-Saharan Africa. It also shows that regions in Asia (primarily Southeast Asia and Hindu Kush Himalayan) and Latin America are also in need of OGRES as their power capacity is not sufficient. Our review findings articulate with this data.

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* This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Besides the Sub-Saharan region, the conditions for renewable installations in the other regions are also encouraging. For instance, the hydrogeomorphology of the Hindu Kush Himalayan is appropriate for installing small scale hydropower systems [70-72] - it is riparian and mountainous. Nepal, a country in that region, has high hydropower potential with proven economic feasibility [73-78]. Its annual average water run-off is 225 billion m^3 from more than 6,000 rivers and other stream flows [79]. Therefore, local communities can greatly benefit from localised hydropower compared to other energy sources, such as portable diesel generators and solar energy.

The findings for EWS indicated that African, as well as Asian countries were in need of flood warnings. Both the Sub-Saharan [80-82] and Hindu Kush Himalayan [83-88] regions have experienced increasing vulnerability to the impacts of climate change, particularly floods, due to increased temperatures [89, 90]. **Figure 3** presents the Overall Water Risk Map, developed by the World Resource Institute's Aqueduct tool [91]. It presents evidence that Africa, Southeast Asia, Hindu Kush Himalayan and Latin America are at great risk of water-based disasters.

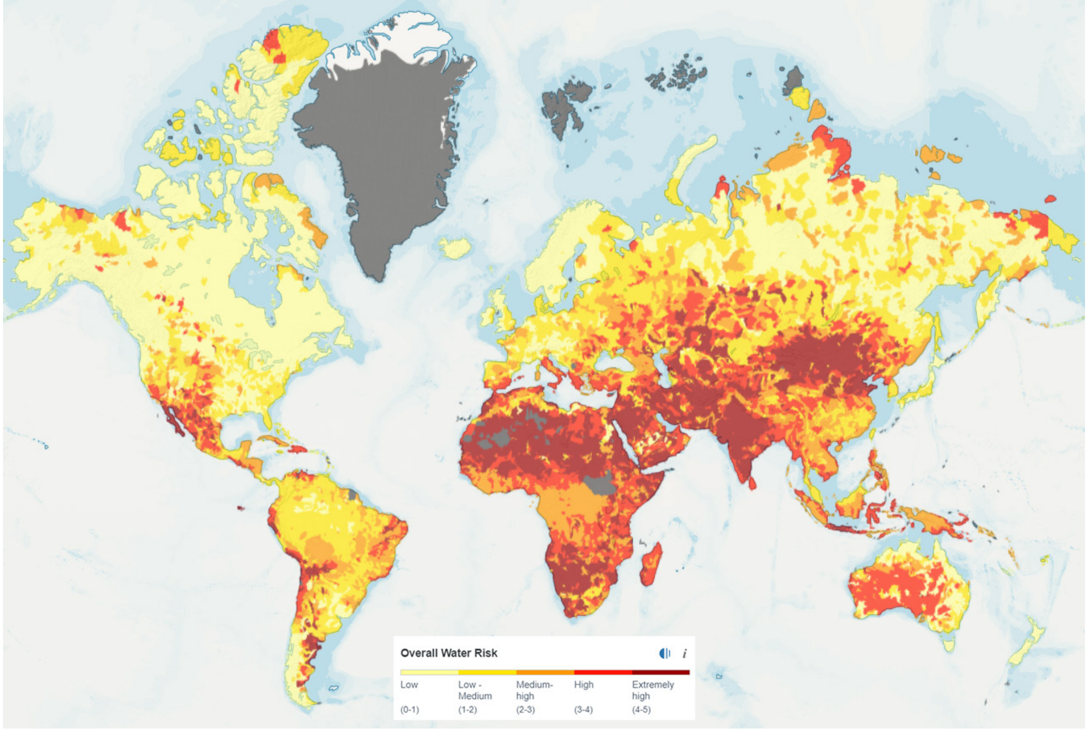

Figure 3. Overall Water Risk Map

However, it should be noted that besides the identified similarities above, differences between communities were obvious and this should be highlighted. Differences in populations exist not only between different countries and regions, but also within the same communities. Therefore, any systems developed for remote communities cannot be considered as a "one size fits all" solution - it must be co-developed with community stakeholders based on their knowledge of local conditions, values and needs, and the available/needed resources to sustain these solutions over time [92, 93].

In addition, the review identified common factors that undermined or strengthened systems' workability and longer-term use by applying the combined appropriate technology and systems evaluation tool. The findings stress the importance of collaboration between end-user communities and professionals, including key interest groups. Equity in resources and benefits, consideration of traditional or local knowledge in the processes, and community-centred management clearly contribute to increase efficiency in similar interventions [93]. A key finding with both EWS and OGRES was that community end-user groups were often minimally involved with system development, deployment and maintenance. This reflected a lack of community-focused development by implementing groups, yet it also shows community perceptions of the insufficient gain derived from them. Further, there is a clear lack of community stewardship over such systems, a critical asset in these contexts if the systems are to be maintained and scaled up over time.

The scoping review highlighted those indicators related to the complexity of the systems and unfamiliarity of end-users in proper installation, repair and maintenance. Automatic, low-tech and user-friendly localised solutions (e.g. portable, plastic, colour warning rain gauges) that correspond to the limited capabilities and resources of vulnerable communities could strengthen the success of future systems. Site-conditional indicators causing dysfunctionality in the system were also identified. As the impacts of climate change can be intense, the development of such units should endure products of extreme weather events (e.g. logs and floating debris). Climate change is contributing to more unstable weather patterns, resulting in more frequent and extreme weather events [94]. This leads to a twofold issue; it is imperative to build stronger systems in order to survive such disasters, but they must also be effective in terms of their maintenance and operations in order to overcome prolonged dry/wet periods so that they can re-focus a community's attention when flood risk returns.

Finally, one flood EWS that was self-powered by mini solar panels was detected in the review [95]. While there was no information about how other EWS were powered, this case study can be considered as a 'proof of concept' hybrid system, where renewable energy is used to power the EWS alone (i.e. system-level power). Solar energy was one of the most common type of OGRES in the reviewed case studies (along with hydropower). Collectively, this evidence suggests that that a 'scaled-up' hybrid system is feasible and could be developed, for example, a set of panels that support 'everyday' energy needs could also power local EWS (for flood and other hazard types).

A potential hybrid system for renewable energy generation and flood-warning detection at the local level could have multiple benefits for vulnerable communities and their ecosystems. It could generate free, clean continuous electricity securing energy availability to local end-users. It could also detect water level changes and inform nearby communities of potential flood development, increasing awareness and response levels. However, the data gathered regarding its constituent systems indicate that a hybrid system would need to address key issues to support successful and sustainable use in these contexts, including:

- The selection of appropriate OGRES type and parts. This should be decided based on local atmospheric and hydrogeomorphological conditions. For instance, solar panels for covering both EWS and community energy needs in mountainous areas, such as the Hindu Kush Himalayan region, may not be an appropriate solution. A key issue is the availability of solar energy equipment in the local area. In the case of malfunction (e.g. a broken solar panel), end-users may not be able to find replacement parts in the local markets or conduct repairs on their own, undermining the long-term feasibility of these systems. In this scenario, small scale hydropower generators may be the optimal solution for remote, riparian communities.
- The selection of appropriate EWS-part type: Due to the differences in response levels between communities, the flood warnings should consist of localised sirens and outdoor lights so as to serve more populations with limited capabilities. These warning devices are widely available, energy-efficient, and easy to repair or replace. Colour code variations (e.g. traffic light colour gauges, emergency lighting or different siren tones depending on flood development stages) could prepare local communities more effectively in case of scheduled or immediate evacuation.

Potential solutions to these issues could be extrapolated from the reviewed data and inform the design and development of this system so as to meet its dual aims: supporting socio-economic development and increasing flood/hazard response capabilities. Drawing on these findings, a hybrid system should combine community-level flood risk education with training planning (e.g.

evacuation drills). This would increase the response efficiency, particularly in remote communities. Based on local environmental conditions (e.g. water flow) the system should be able to generate minimum energy amounts to cover basic energy needs under both normal and extreme conditions. Excess energy could be stored in batteries for later use or delivered to other community needs.

Even when systems are seen by remote communities as providing community benefits, local participation often remains minimal. One solution to this could be a more direct and substantial involvement of communities at the planning and development stages. For example, aid organizations or civil protection authorities could work with local populations to prioritise needs, both power use and hazard management. This was the case with local communities in Nepal [14, 95]. As the system may not be able to satisfy every energy need, consultation about equitable use or common purpose may support harmonious and sustainable maintenance of the system. For example, the system could power a local classroom or public lights. Under normal conditions such lights could provide safety during the night, or increased working or study hours. This could increase income, and consequently community interest and maintenance of the system. During floods, the lights could act as emergency lights (e.g. powering an evacuation route and community hall/shelter). These developed capabilities could be used to increase disaster risk awareness and improve response (e.g. evacuation drills). This may be of particular benefit to the community's planning for, and developing the capabilities of, vulnerable groups such as the elderly and people with mobility issues.

The co-design of such systems between professional and community stakeholders could increase community interest in the longer term. Professional stakeholders should provide information on technical aspects of the system, while community engagement should emphasise traditional know-how, and address potential concerns about changes for the community, and enhance familiarization with the system's functions. In such instances, a system is less likely to be 'foreign' and different community groups are more likely to collaborate to support proper operation. This approach would minimise failures. In order to increase end-users' involvement in pre and post-installation phases, the system could be made of readily available materials (e.g. recycled components or parts that are available in most countries and online) and/or be designed using do-it-yourself (DIY), and easy-to-deploy-and-operate (EDO) techniques [96]. These techniques increase system adaptation through community participation [97]. Such systems are widely known for their ease of assembly, deployment and capacity to be repaired (e.g. home furniture and appliances) without the need of professionals. They also include aspects of leisure, work and education, and are used across a range of fields including engineering, medicine, emergency management, energy and occupational safety [98]. Importantly, some small-scale hydropower and solar energy projects are designed based on these techniques [99].

Such approaches offer advantages to humanitarian engineering while also supporting perceived 'ownership' within beneficiary communities [97], and would include the potential to minimise or eliminate reliance on external technicians and promote community-based skills centred on repair and ongoing maintenance. Community access and oversight of this kind could reduce the risk of technological failures. In order to increase endurance against weather extremes and other environmental impacts, the appropriate location of systems could be determined based on hierarchical flood risk models at the local level. This data could then inform community deliberations as to placement and use, as well as contributing to the resolution of other issues to be factored in regarding site selection.

CONCLUSIONS

This article has critically reviewed cases of communities using OGRES and EWS. It presented existing concepts and emphasised failure and success indicators and their reported sources using a combined tool for appropriate technology and sustainability evaluation. The wider aim of this study was to consider the feasibility of an integrated system supporting both the flood resilience and socio-economic development of remote communities. The study also explored how lacking capabilities in energy generation and flood resilience affect local populations. Vulnerable communities in low and lower-middle income countries are at higher risk, and external assistance is often needed to establish suitable protections. While humanitarian engineering interventions can provide such support, it is common for these interventions to fail over time, often because they are not designed in conjunction with the community, or with specific regard to the community's context and needs.

Recommended features for more appropriate design include: the input of community stakeholders; technology appropriateness for the consideration of local/traditional knowledge in the processes; scaling of community demands based on energy availability; and use of techniques such as the DIY and EDO in assembling and maintaining systems were highlighted.

Further research is needed to better understand how local knowledge can best adapt to these technologies in order to strengthen the feasibility analysis of hybrid systems. Such systems have the potential to support local ecosystems in sustainable ways, as well as provide vital services to remote populations.

Limitations and future work

Future studies could include databases and journals that are not considered in this scoping review. This would allow more comprehensive findings. Follow-up research should also focus on how the COVID-19 pandemic affected the sustainability of OGRES and EWS in remote communities, and how local energy and disaster response needs changed or escalated during the lockdown restrictions.

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APPENDIX

Table A1. Summary of case studies

Author/s (year)	Methodology	System type	Region(s), site(s) and/or population(s)	Findings	
				Failure and Issue indicators	Success indicators
Butchers *et al.* (2020) [100]	Mixed methods - maintenance assessment, and interviews with managers, operators and consumers	Micro-hydropower systems	Nepal, 24 sites [NE24]: 2 private, 2 co-operative and 20 community-owned	Pre and post-installation technical issues. In some cases, the collected income from tariffs was not sufficient to pay repairs.	Regular maintenance in most sites. Communities were paying tariffs. Communities were actively engaged.
Njoh *et al.* (2019) [101]	Mixed methods - primary data analysis via direct in-situ observations including site survey, data collection on homes and energy consumption, and project records; secondary data analysis via published and unpublished materials	Solar system	Cameroon, Esaghem village [CAES1]: Esaghem Solar PV Electrification Project	Prolonged or heavy rainfalls affected power efficiency. High equipment costs due to low densities and area inaccessibility. No previous/appropriate infrastructure for such renewable type in the village. Lack of pre and post installation/maintenance personnel. Insufficient funding from both community and non-community sources. Hydropower marketing and demand neglected solar solutions. Overall lack of interest in renewable energy systems. Authorities showed no high interest in renewables investing.	The village is located on a hill and exposed to sunlight - good conditions for solar installation. Community was willing to participate in the project.

Arnaiz *et al.* (2018) [46]	Mixed methods - evaluation of 17 remote communities (site/community visits, engagement with local developers, and community interviews)	Micro-hydropower systems	Bolivia, 9 communities in the regions of [BO9]: -Andean -Sub-Andean -Llanos	Television and refrigerators contributed to cultural changes and children's obesity according to the elderly.	Sense of empowerment, teamwork, general comfort. Job creation (e.g. system's operation and maintenance. personnel) and income increase Improvements in health and diet due to refrigerator uses (e.g. for prolonging medical supplies), reduced kerosene uses and increased lighting (e.g. lights at night reduced stumbling for the elderly). Power used in devices for emergency services (radio and phone). Improvements in children's education.
			Philippines, 8 communities in the regions of [PH8]: -Cordillera -Negros Island	No significant improvements in health and diet as the communities did not use refrigerator and emergency lines.	Sense of empowerment, teamwork, general comfort. Job creation (e.g. system's operation and maintenance personnel) and income increase. Improvements in children's education.

Ikejemba *et al.* (2017) [54]	Mixed methods - ethnographic approach (interviews with stakeholders and site visit observations)	Hydropower and solar systems (small and larger scales)	Sub-Sahara, several communities and sites [SUS8]: -Ethiopia -Gabon -Ghana -Kenya -Malawi -Mozambique -Nigeria -Tanzania South Africa – excluded from this research	Publicly funded projects presented prolonged timelines due to limited budget and multiple stakeholders. Poor management, maintenance and reparability in post-installation stages. Local communities hesitated to accept such systems due to insufficient benefits. Lack of technical know-how, supportive regulations, logistics and supply chain. Incidents of project completion failure or sub-completion (e.g. their scale is smaller than initially intended). Conflicts between landowners and project managers due to insufficient benefits. In some cases, ownership was not shared fairly. Local communities were unwilling to participate in processes (e.g. repair and maintenance) due to complicated tasks, lack of education/training, and insufficient benefits. Jealously, sabotage, theft and vandalism.	-
Shoaib and Ariaratnam (2016) [47]	Mixed methods - two-phase analysis: assessment of existing literature and technologies, and data collection via questionnaire development, pilot project selection, data collection and data analysis	micro-hydropower systems, windmills, and solar home systems	Afghanistan, 2 communities [AF2]: -Sheikh Ali -Shebar	No major improvements in economic conditions (i.e. limited job creation and no new/improved enterprises) possibly due to power delivery primarily to homes and not industries/production.	Improvements in well-being and daily activities. Improvements in health. Improvements in education and government services.

Crossland *et al.* (2015) **[102]**	Mixed methods – four week socio-technical field study using measured demand data, system surveys and semi-structured interviews	Off-grid solar systems	Rwanda, rural communities and sites [RW9]: -8 health centres, and -1 school	High power demand during night hours in all sites. Poor installation, maintenance, repair and monitoring due to high costs or lack of technical understanding and education. Power failure due to overloading. Consumers' perception that solar energy is unlimited. Solar panels were under-sized and battery could not fully charge. Systems were vulnerable to extreme weather events (e.g. lightnings). Power shortage during raining season.	Improvements in security, safety, lighting, communication, education and administration. Improvements in health services - prolonged conditions for medical supplies, and equipment sterilization. Improvements in health due to the reduced kerosene uses.
Kenfack *et al.* (2014) **[103]**	Mixed methods - data collection during implementation phase, literature survey, interviews with stakeholders in power sector, and field observations	Micro-hydropower systems	Central Africa, rural communities and projects [CEA4]: -Cameroon -Central African Republic -Chad -Republic of Congo	Unfitting size, design and construction. Lack of durable materials, second handed or wrong equipment. Pool local capacity in systems' design and development. Lack of maintenance. Lack of local infrastructure for manufacturing. Power failure due to weather extremes (e.g. during low or high-water levels). Circuit failure due to overloading. Poor community engagement. High cost compared to traditional energy sources (e.g. firewood, petrol and gas generators).	Systems operated well when communities participated in the processes and there were available technical solutions.

		Solar systems		Poor institutional management and regulations. Lack of know-how. Poor actors' capacity. Unfitting size, battery type, regulation and control of charger/discharger. High cost compared to traditional energy sources (e.g. firewood, petrol and gas generators).	Systems operated well when sizing and maintenance were proper. Popular renewable type due to sufficient promotion.
Hong and Abe (2012) [30]	Case study using multiple correspondence analysis	Centralised off-grid solar plant	Philippines [PH1], Pangan-an Island Solar Electrification Project	Monthly tariffs could not be paid, and this discouraged connections. Operational costs increased when connections reduced. Capacity development and maintenance required external funding. Plant's insufficiency resulted in people turning to conventional power sources.	Improvements in life quality. Improvements in education and daily activities.
Nfah and Ngundam (2012) [104]	Review of existing renewable energy applications	Solar and pico-hydropower systems	Cameroon, Djetcha-Baleng [CA1]: Health centre	Not all medical equipment could be used due to limited power rating of the inverter. Lack of funding and other support by local authorities. Local residents had to visit health centers in other areas for services that could not be delivered at this center due to the lack of power. Issues within the management committee as one of their members used energy for personal purposes.	Improvements in health services improved (e.g. prolonged life of medical supplies and medical operations during night hours). A non-governmental organization assisted the local community in the hydropower system's conceptualization, fund raising and problem solving in management committee matters. Community members assisted in the construction works of the hydropower system.

		Two wind turbines	Cameroon, Ndoh-Djutitsa [CA2]: Sub-divisional hospital	Power failure due to overloading – the inverter was linked to a greater capacity tank. Lack of skilled personnel for post installation management and maintenance. Lack of a proper management committee. Lack of funding and documentation for missing/broken parts replacement.	Two universities from Cameroon ad France initiated the procedures for funding and equipment purchase. Improvements in health – pumped water consumption reduced stream water related diseases. Reduced electricity costs for the hospital.
		Pico-hydropower system	Cameroon, Bangang [CA3]: African Center for Renewable and Sustainable Technologies	-	The system operated well during the wet season (excessive water amounts). The Center investigates the development of other renewable systems.
Gurung *et al.* (2011) **[14]**	Mixed methods - in-depth interview (213 households), key informant opinion (4 participants), focus group discussions (in Sikles and Pokhara), and site visit for observation	Micro-hydropower system	Nepal, 3 sites [NE3]: -Sikles, -Parche, and -Khilang	Insufficient power - system originally designed for Parche and Sikles villages; Khilang village included after some years. Two landslides caused damages - repairs occurred about one year later due to the lack of funding and skills. Incidents of power supply cheating and faulty monitoring.	Community-owned, equitable benefits. Improvements in life quality. Improvements in education, daily activities and communication. Improvements in health due to the reduced firewood and kerosene uses.

Sovacool *et al.* (2011) **[105]**	Mixed methods - primary data analysis via 36 semi-structured research interviews with government, banking, planning agencies, companies and consumers, site visits (3 provinces), field research (7 rural villages), and literature review	Solar home systems	Papua New Guinea [PA10], -Provinces: Goroka, Madang and Port Moresby -Rural villages: Akameku, Asaroka, Kundiawa, Lufa, Okifa, Simbu and Talidig	Lack of high-quality product availability. Lack or improper maintenance. Problems in logistics and distribution to rural areas. Insufficient income - local communities live in poverty. Lack of external funding. Poor institutional capacity. High cost compared to traditional energy sources (e.g. fossil fuels and main grid electrification). Consumers' perception that solar energy is unlimited Conflicts, jealously, sabotage, theft and vandalism. Local communities are unfamiliar with the system.	-
International Centre for Integrated Mountain Development (2018) **[95]**	Project report with description and function of the community-based flood early warning system	Community-based flood early warning system	Hindu Kush Himalaya [HKH4]: -Kunduz River, Afghanistan -Jiadhal, Singora and Ratu Rivers, India -Ratu, Gagan and Rangoon Rivers, Nepal -Gilgit River, Pakistan	-	Simple and low-cost system. Self-powered (by solar panels). Managed and operated by local communities. Increases collaboration between upstream and downstream communities.

Cools *et al.* (2016) [106]	Case studies	Flood early warning system	Egypt, communities in [EG1]: Red Sea Mountains	Flood management knowledge was limited in local communities. System's lead time was small (48 hours). The region was affected by flash floods (short-lived and destructive type of flood). The system was managed by professionals – system operators decide when to alert authorities which in turn, alert communities. System was not reliable as the operators did not work 24/7. Warnings dissemination was limited to local communities due to poor telecommunications in the area.	The system allowed emergency authorities to prepare and respond faster.
		Flood early warning system	Mali, communities in [MA1]: Niger Delta	Conflicts between different groups (e.g. fishermen and herders) due to the lack of water.	Flood management knowledge was substantial in local communities. System's lead time was long (2 weeks to seasonal). Floods were beneficial for local residents (fishery, agriculture). Both peak flood and floodwater retreat information was disseminated to the authorities and local communities. Information was broadcasted by radio in many languages and is available online. Community chiefs were responsible for planning important activities such as fishery and cattle river crossing.

Baudoin *et al.* 2014 [15]	Case studies	Multi-hazard and people-centred early warning system – CLIM-WARN Project, United Nations Environment Programme (UNEP)	Kenya, 4 sites/12 communities [KE12]: -Nairobi, 2 peri-urban villages, and an informal settlement -Kisumu, a peri-urban village, and 2 rural villages -Turkana, 3 rural villages -Kwale, 3 rural villages	Limited access to television, radio, phone, etc. in rural communities could make access to warnings difficult – chiefs/elders or other traditional institutions deliver such information. Low education in rural areas may affect response if the system is not flexible/ adjustable to local capabilities. Local urban communities had multiple sources of income, higher education and access to different warning devices – this reduced their need for additional early warning systems.	Early warning was essential for local rural communities with one form of income (monoeconomy) due to their dependency on weather conditions.
		Community-based flood early warning systems	Sri Lanka, 2 Districts [SR2]: -Matale -Nuwaraeliya	Ensuring active community involvement for longer periods in such programs was difficult. Only a limited number of national and international non-governmental organizations were engaged in community-based early warning programs. There was a need for more participatory community work involving all actors.	Local communities received education and training. Portable, plastic, color warning rain gauges were introduced as low-cost, low-tech warning equipment. Local residents monitored and read the gauges, and verbally informed nearby communities of the water level status. Community participation was important for the success of the system and effective community response.

Table A2. Appropriate technology and systems evaluation tool

FAILURE IDENTIFIED		DIMENSIONS OF SYSTEM SUSTAINABILITY		SUCCESS IDENTIFIED
CASE STUDIES		INDICATORS OF TECHNOLOGY "APPROPRIATENESS"		CASE STUDIES
PH1	Institutional	Autonomy (Community Self-Sufficiency)	Institutional	BO9, PH8
SUS8, CEA4		Co-Creation (Local and Professional Stakeholders)		CA1, CA2,
SUS8, SR2		Community Input (Engagement)		NE24, CEA4, CA1, CAES1, SR2, HKH4
SUS8		Community Controlled (Managed, Owned)		NE3, SR2, HKH4
SUS8, CEA4, CA1, CAES1, SR2		Legal and Regulatory		-
SUS8, CEA4, CA1, CA2, CAES1, PA10, SR2		Support (Technical, Administrative, Financing)		-
-	Environmental	Habitat Neutral	Environmental	-
-		Low Emergy		-
-		Low Emissions		all case studies
-		Renewable Energy		all case studies
-		Renewable Resources Availability		CAES1, SR2
RW9, CAES1		Scaled for Conditions (Resources, Weather, Land)		CA3, SR2
-		Waste Utilization and Reduction		-
SUS8, CAES1, KE12	Social / Ethical	Acceptability	Social / Ethical	KE12
-		Aesthetics		-
SUS8		Ease of Use		SR2
-		Gender Appropriate (e.g. women in staff/management)		-
-		Indigenous Techniques		MA1
RW9, NE3, SUS8, CEA4, CA1, CA2, PA10, KE12, EG1		Knowledge, Skills, Feedback		SR2, EG1, MA1
-		Social Entrepreneurialism		BO9, PH8
BO9, PH8, NE3, SUS8, CA1, PA10, MA1		Socio-Cultural -incl. health, education, harmony, etc.		BO9, PH8, RW9, NE3, PH1, CA1, CA2, AF2
RW9, NE3, PH1, SUS8, CEA4, CA1, CA2, CAES1, PA10	Economic	Affordability	Economic	NE24, HKH4
AF2		Income Generating		BO9, PH8, KE12, MA1
AF2		Job Creating		BO9, PH8
PH1, AF2		Money Saving		BO9, PH8, CA2
-		Labor Intensive		-
-		Resource Efficiency		-
SUS8, CAES1		Selling Appropriate		CEA4
CEA4, KE12	Technical	Adaptability	Technical	SR2, MA1
NE24, RW9, PH1, SUS8, CEA4, CA2, CAES1		Constructability and Replicability		CEA4
CA1, KE12		Compatibility		-
RW9, NE3, CEA4		Durability (e.g. against time or extremes)		-
EG1		Effectiveness		SR2, MA1
RW9, NE3, PH1, SUS8, CEA4, CA2, CAES1		Energy Efficiency		SR2
-		Low Power		SR2
RW9, PH1, SUS8, CEA4, CA2, CAES1, PA10		Maintainability		NE24
SUS8		Modification vs Invention		CA3
-		Multi-Purpose		CA2, KE12, MA1
CEA4		Open Source Manual and Design		CEA4, SR2
NE24, RW9, CAES1, PA10		Parts and Hardware		SR2
CEA4, PA10		Raw Materials Availability		CEA4, SR2,
SUS8, EG1,		Reliability		-
RW9, NE24, NE3, SUS8		Reparability		-
-		Reusability		-
SUS8		Scalability		-
SUS8, EG1		Simplicity		SR2, HKH4
EG1		System Independence		-

Region Keys	Country Keys			
CEA: Central Africa	AF: Afghanistan	CAES: Cameroon (Esaghem Village)	MA: Mali	PH: Philippines
HKH: Hindu Kush Himalaya	BO: Bolivia	EG: Egypt	NE: Nepal	RW: Rwanda
SUS: Sub-Sahara	CA: Cameroon	KE: Kenya	PA: Papua New Guinea	SR: Sri Lanka

Note: Region/Country keys detailed in Table 1