Solar Photovoltaic versus Micro -Hydroelectricity: A Framework for Assessing the Sustainability of Community-run Rural Electrification Projects

Mahmoud Kabalan
Electrical and Computer Engineering Department
Villanova University
Villanova, USA
mkabal01@villanova.edu

Benaiah Anabaraonye
Chemical Engineering Department
Villanova University
Villanova, USA
banabara@villanova.edu

Abstract— **One of the crucial steps in meeting the Millennium Development Goals (MDGs) is access to reliable and affordable energy. The majority of the people without access to clean and reliable energy sources live in rural areas. The advent of renewable energy technologies, such as solar photovoltaic (PV), wind and micro-hydroelectricity has allowed electricity to be generated independently of the national utility grid. The sustainability of such off-grid energy projects is crucial to foster socio-economic development of these local communities. Many studies have addressed the sustainability of rural electrification projects post-completion using indicators. However, these studies are fairly extensive and do not provide pre-implementation insights into the best rural electrification technology. In this study, we present a more holistic approach to decision making by analyzing two off-grid renewable technologies – solar photovoltaic (PV) and micro-hydroelectricity (MH) using a village in Ifugao Province in the Philippines as a case study. An analysis of social, technical, environment, economic and political (STEEP) dimensions that impact the success of the project is presented. A measure of the technology's potential to bring about positive change, termed total impact (TI), is estimated. Micro-hydroelectricity was projected to be a better alternative in this location.**

Keywords—sustainability; framework; rural electrification; community run systems;

I. INTRODUCTION

One of the crucial steps in meeting the Millennium Development Goals (MDGs) is access to reliable and affordable energy [1]. Studies have shown that there is a correlation between lack of energy access and poverty with most of the poor living in remote rural areas [1]. More specifically, recent findings strongly suggest that there is a clear connection between the human development index and energy development index [2]. Hence, rural electrification is an important factor in a government's policies to achieve sustainable development, necessitating a considerable amount of a country's resources [3]. Traditionally, governments' rural electrification policies relied on extending the national grid to remote communities. Grid extension requires significant initial investment costs to procure transmission and distribution equipment in addition to hiring skilled personnel [4]. However, with the advent of off-grid renewable energy technologies such as solar photovoltaic (PV), wind and micro-hydroelectricity, electricity could be generated independent of the grid extension. As a result, the expensive infrastructure investment can be leapfrogged while still bringing clean and sustainable energy to the most remote villages and communities. However, renewable energy systems face multiple challenges such as high initial costs, the limited range of choices and technological complexities. Nevertheless, the most complex problem for rural electrification is ensuring the social, technical and economic sustainability of these projects once the initial investment is made [5]. One particular issue of interest is finding the best rural electrification technology from a sustainability point of view in the absence of a grid extension plan.

Many studies have tried to address the sustainability requirements of such projects. The use of indicators has been proposed by multiple organizations and authors [6-10]. However, some of these studies address electrification project on a national level to guide governments and international organizations [6-9]. Consequently, there is a need for an approach to study the sustainability of local rural electrification projects. More specifically, a framework for assessing the sustainability of community-run rural electrification projects is needed. Ilskog [11] proposed a fairly extensive framework to study rural electrification projects. The proposed framework consists of 39 indicators that cover social, technical, economic, environmental and organizational dimensions. Furthermore, the framework required completing questionnaires that took about 20-40 minutes to complete and interviewing the local officials and community members. The authors' field work and experience in Ifugao, Philippines during 2010 and 2012 showed that using such an elaborate framework can prove to be challenging and potentially counterproductive. In essence, such frameworks require a considerable number of fieldworkers and financial capabilities to complete surveys and gather information and data. For example, the study by Ilskog [12] was completed with multiple research studies done by foreign researchers in collaboration with local fieldworkers spanning multiple years [13-16]. Local non-governmental organizations (NGOs) have limited financial capability and personnel to carry out such studies over an extended period of time. Therefore, there is a need for a simpler framework for local governments or NGOs that will serve as a guide in their decision making process for rural electrification projects. Such frameworks need to provide the best options for decision makers prior to the start of any project.

Studies that assess the sustainability of electrification projects after completion provide valuable lessons for national policy makers and the international donor community. However, from the perspective of the local governments and NGOs, a more valuable framework gives them insight into best options prior to project implementation. Thus, the aim of this study is to provide a framework that is targeted at local NGOs and/or governments to better guide their decisions in choosing rural electrification technologies. Inspired by the authors' work in the region, we present the application of this framework by using the village of Duli in The Philippines as a case-study.

II. Community Overview

Duli is a rural community in the province of Ifugao in northern Philippines. One of the authors visited the region in 2012 to work with a community-based organization to set up a micro-hydro power plant. Experiences gathered from these trips inspired further conversations regarding what other renewable technologies might be appropriate. In order to get a better understanding of the community, a survey was conducted in 2012. The survey was completed by interviewing locals, multiple officials, the community nurse/midwife and the school principal. The socio-cultural and socio-economic analysis of Duli has been documented [17, 18].

III. Technology Overview

Ifugao province is in the Cordillera Administrative Region (CAR) which is a mountainous area with abundant streams, rivers and waterfalls. Such a landscape provides a potential to develop micro-hydroelectric power stations in the province. Micro-hydroelectric systems are hydroelectric power systems that produce up to 100 kW using water flow. A study completed by JICA (Japanese International Cooperation Agency) showed that CAR has at least 50 sites capable of generating 25 kW or more of electric power [19]. As a result micro hydroelectric systems are well suited for that area as a rural electrification project.

During a 9 month assessment trip, the community of Duli was visited multiple times to study the water potential. A waterfall was located close to the village center and calculations showed that the site could generate 25 to 30 kW of electric power. Micro-hydro systems do not require advanced and complicated materials. Local wielding shops can maintain the turbine and rewire the generator if need be. Micro-hydro systems have the potential to run 24 hours a day and 7 days a week as long as enough water is available. Thus, micro-hydro systems can provide a consistent and steady source of electric power if designed and operated properly.

Solar PV is an extremely versatile technology and can be implemented in any location with consistent sunshine. Moreover, the technology does not require grid connection and can be used anywhere to provide a source for clean energy. Its disadvantage is that power is available only during daytime and energy storage devices are needed to provide energy during the night. Furthermore, energy storage devices, such as batteries, are expensive and need routine maintenance and replacement. Thus, for a rural development project with little or no steady maintenance fund, this presents a significant economic challenge.

In this study, we will compare a 30 kW micro-hydroelectric system against a 30 kW solar photovoltaic system. The authors realize that both MH and solar PV are not compatible when compared on total energy output (if both systems have same power rating). The energy output of the MH system would be higher than that of the solar PV. The solar PV system cost would be extremely high if the same level of annual energy output is required. Thus, real world constraints and costs dictate this comparison and make it more realistic.

It should be stated that Duli's prospect of being connected the national grid is very low in the foreseeable future like many communities in that region. Multiple talks with local and Department of Energy officials showed that Duli might not be connected till 2020 or 2025. Thus, the focus of this paper is to find the most sustainable method to electrify the community when grid extension is not an option.

IV. Approach and Methodology

A. Framework Development

A literature review of sustainability assessment frameworks showed a lack of standardized assessment methodology. However, five key sustainability dimensions keep re-occurring [11, 20, 21]. These five dimensions are: Social, Technological, Environmental, Economic and Political (STEEP). The analyses of projects through these dimensions provide a more holistic assessment of their sustainability profiles.

In this study, the STEEP model was adopted. The five dimensions were considered over the lifetime of the project unless otherwise specified. For each of these dimensions, we were interested in the following:

Social: This covers the effect of the project on the social status of the community such as community involvement, community development and effect on social structure. It also covers the complexity of the organization structure needed to manage the project

Technical: This focuses on the construction, maintenance and likelihood of survival of the project over the expected lifetime.

Environmental: Life cycle analysis (LCA) of each project was performed using SimaPro®.

Economic: This deals with the projects' initial costs, maintenance costs, job creation and indirect effect on economy.

Political: This covers the potential effect of the political environment on the project. Indicators such as resiliency to corruption, ease of legal issues and access to government funding or support were considered.

In order to gain a better understanding of these dimensions, an indicator-based approach was adopted similar to previous work [11] due to its simplicity and ease both an analysis and communication tool. The number of indicators was kept at an essential minimum to minimize the fieldwork required for rural electrification projects. We reckon this as vital since experience shows that local governments and small NGOs have few, if any, additional resources at their disposal. The indicators chosen for this study were inspired by the author's visit to the region in 2012. The importance of fieldwork cannot be overstated as a means of getting as much information as possible. Local partners can provide information about all dimensions of this framework drawn from their informal knowledge and experience of such settings. Such insightful ideas could save time and money but more importantly shed light on issues that could potentially derail a project.

Following the specification of the relevant indicators, a rating system was adopted. In this study, the indicators were assigned either 1 or 2, where 2 represents a higher positive impact and 1 a lower positive impact. The assignment of these scores were arrived at either through empirical data (where available), inferred from survey responses from the local residents or after several brainstorming sessions. In Table 1, we present the sustainability dimensions examined, the corresponding indicators used for assessment and the key questions asked during assessment. While STEEP dimensions have been explored in literature, it is obvious that the rating/assessment of these dimensions is dependent on the key question asked.

The cumulative impact for each of the STEEP dimensions is calculated in order to compare the relative performance of the technologies among themselves. Subsequently, the relative difference (RD) and total impact (TI) are defined and calculated.

B. Total Impact (TI)

To better compare the desired technologies, the total impact (TI) of each technology is calculated. In this study, the TI is a function of the relative difference (RD) between the two technologies and the weight assigned (Wi) to each of the STEEP dimensions. Relative difference (RD) calculates the change in impact between the two technologies for each of the STEEP indicators. These are obtained by the equations shown below:

If $S_{MH} > S_{PV}$; RD (PV) = 0

$$\mathrm{RD_i(MH)} = \frac{S_{MH} - S_{PV}}{S_{MH}} \quad (1)$$

When $S_{PV} > S_{MH}$; RD (MH) = 0

$$\mathrm{RD_i(PV)} = \frac{S_{PV} - S_{MH}}{S_{PV}} \quad (2)$$

where S_{MH} and S_{PV} represent the estimated cumulative impact numbers for each of the STEEP dimensions.

C. Weight Value

As addressed earlier, each of the STEEP dimensions is important in evaluating sustainability. However, the relative importance of these dimensions on the decision-making process could be location-dependent. Consequently, weighting factors are introduced to account for this variation. In this study, the weighting factors ranged from 1 to 3, where 1 has the least priority and 3 the highest.

TABLE I. STEEP ANALYSIS

Dimension	Indicator	Key Question
Social	Community Involvement	What level of community involvement is required to make the project a success?
	Community Development	What is the potential effect on community development (social services, etc)?
	Effect on Social Structure	Does this disrupt the current social structure of the community?
	Simplicity of organization structure	Does the project require a complex management structure?
Technical	Ease of Setup	How hard is it to construct the system?
	Ease of Maintenance	How accessible is the support infrastructure needed to maintain the system?
	Robustness	How susceptible is the system to breakdown/natural disasters?
	Reliability(Design, efficiency)	What is the amount of electric energy available?
Environmental	Several indicators	What is the overall impact on environment?
Economic	Total Cost	What is the initial capital cost?
	Jobs Created	Projected direct jobs created?
	Indirect effect on Economy	Does this spur income generating activities?
	Maintenance Costs (price /HH)	How much is the expected maintenance costs?
Political	Resiliency to Corruption	How vulnerable is this project to political corruption?
	Ease of Legal Issues	Are there any inherent liabilities associated with the project?
	Access to Government Funding/Support	How much funding is available from the government?

Consequently, the total impact (TI) is calculated by the equation below:

$$\boldsymbol{TI = \sum_{i=S}^{P} RD_i * W_i} \quad (3)$$

where TI is the total impact, RD is the relative difference and W_i is the assigned weighting value. Based on the above, a project with a higher TI value was judged to be a more sustainable alternative.

V. Impact Assessment

A. Social

The social dimension is the most complex aspect of sustainable development since it encompasses a broad area of study and is usually the least thoroughly investigated for development projects [11]. The following indicators for social sustainability were considered:

Community involvement: This indicator covers the extent of the community involvement required to successfully implement a project. We consider a cohesive and strong community involvement and engagement as a key indication that a project might be successful. We believe that an engaged community would do its best to protect and maintain a system. Moreover, an involved community would get a greater feeling of empowerment and confidence. We found that MH has the potential to engender more community involvement since it necessitates the participation of the entire community.

Community development: This indicator addresses the potential of the project to bring about community development. This was measured in terms of the availability of social services, possibility for street lights and share of population with electricity. Due to the intermittent nature of solar PV, it is rated lower than MH.

Effect on social structure: A system that would disrupt the status quo or social structure is considered to be negative if not dangerous. A sudden change in social structure might lead to tensions within the village/community and could prove dangerous and perhaps lead to conflicts. A possible problem for MH system is that if a certain section of the distribution system breaks down, households connected to that section would lose power. If the community fails to repairs the breakdown, tension could arise between people with power and people without it. The distributed nature of solar PV would lower the possibility of such a breakdown.

Simplicity of organization: A system that requires a simpler form of organization to run and maintain is preferred over a system that requires more complicated managerial and technical skills. Consequently, solar PV was rated favorably in comparison due to its distributed nature. Table 2 shows the scores of each technology.

B. Technical

This indicator addresses the technical aspect of the project. In this study, the following indicators were considered:

Ease of setup: The MH system is a fairly significant civil engineering project requiring the construction of a small dam, flow channels, piping and power house. On the other hand, a solar PV system with no battery storage would require the panels to be installed on rooftops and simple wiring to be done. Overall, the solar PV project is a simpler to set up.

Ease of maintenance: This indicator addresses the availability of local support infrastructure such as wielding shops in order to provide routine or unexpected maintenance when needed. From our field study, we assess that the presence of welding shops in nearby villages makes the repair of broken MH parts a possibility. However, proper wielding of the turbine or generator requires specific technical skills and certain technological sophistication. The presence of several moving parts makes MH subject to more wear and tear especially the gears and belts. Replacing these parts would require a trip to the nearest town. Similarly, solar PV maintenance would require professional and skilled labor that is currently not available in Ifugao. Consequently, MH and solar PV are similarly rated.

Robustness: The distributed nature of solar PV makes it more robust towards failure and weather patterns while a MH system is more sensitive to parts failure and natural disasters. Thus, solar PV is rated better than MH.

Reliability: This indicator addresses the reliability of these technologies. The MH system has the possibility to run all day if enough water is available while solar PV can only function when the sun is shining and its operation can be extended for few hours during the night if batteries are charged during the day. However, this stored energy would only be useful for space lighting or cell phone charging. Thus, the MH system is favored. The MH system would be able to integrate easily into any future grid expansion plans since the MH system would generate AC voltage and distribution lines would be installed. Solar PV, on the other hand, would not integrate so easily unless necessary inverters are used to convert the DC power of solar into AC. Moreover, as with any case of central generation of electricity, a significant amount would be lost in the MH system as transmission and distribution losses. The limited availability of electrical energy from solar PV can be detrimental to the sustainability of the system since it might cause locals to invest in their own generating sets [11]. MH systems can be, and have been, maintained by local wielding shops in nearby city.

C. Environmental

The environmental dimension is critical to maintaining long-term sustainability. In order to estimate the overall environment impact of these two technologies, life cycle assessments (LCA) were completed using the software SimaPro®. The following were accounted for in the analysis: mining, design, construction, usage and end of life. The environmental criteria of interest in this study include global warming, smog, acidification and eutrophication. Global warming and smog are

TABLE II. Social dimension analysis

	Community involvement	Community Development	Effect on social structure	Simplicity of organization	Total
MH	2	2	1	1	6
Solar PV	1	1	2	2	6

TABLE III. Technical dimension analysis

	Ease of Setup	Ease of Maintenance	Robustness	Reliability	Total
MH	1	2	1	2	6
Solar PV	2	2	2	1	7

measured to see the effect on air quality while eutrophication and acidification were measured to understand the effect on water quality. Water quality is important because the community relies on the local stream both for drinking and agriculture.

Table 4 presents the data obtained after the SimaPro® simulations on both systems. From the table below, it can be seen that solar PV has a more detrimental impact on the environment than MH on all the categories explored. This is appropriately reflected by the assigned scores.

While solar PV has a relatively low environmental impact during use, the greatest environmental impact associated with this technology lies in its production, especially, the purification of metal-grade silicon to solar silicon- an energy intensive process. This is consistent with the work done by Stoppato [22] and the assumptions made in this simulation are similar to the one presented in the paper. On the other hand, cement manufacturing is the most environmental intensive process in MH.

We understand that local NGOs or governments may not have access to the software. Moreover, their scope might be more local rather than global. This shift in scope would change the results of the environmental impact. Solar PV proved to be worse than Micro-hydro because mining and manufacturing of solar panels requires significant energy. However, solar PV might prove to be more environmentally friendly than MH if only the operation phase is studied. In any case, we reckon that both technologies will have a positive impact on air quality since they will offset the use of kerosene lamps for indoor lighting. On the other hand, we estimate that MH will have a larger water impact than solar PV since water is used to generate electricity, making the likelihood of water pollution higher.

D. Economic

Financial and economic sustainability is critical for rural electrification projects. Community-run systems should be self-sufficient and cover the operation and maintenance (O&M) costs independently. Traditionally, it was thought that these systems can be maintained by charging locals tariffs for electricity usage per household (HH). However, studies have shown that households are not capable of supporting such systems alone [23]. The tariffs per household (HH) proves to be too high for the locals to afford in the long run [20].

TABLE IV. ENVIRONMENTAL DIMENSION ANALYSIS

	Effect on water quality			**Effect on air quality**	**Total**
	Eutrophication (kg N eq)	***Acidification (Mole H+ eq)***	***Global Warming (kg CO2 eq)***	***Smog (kg O3 eq)***	
MH	17	11186	77293	1365	2
Solar PV	378	22800	100000	7270	1

Moreover, the amount of electric electricity consumed by households alone is negligible which keeps the capacity factor of the system very low. A system's capacity factor is the amount of consumed electric energy divided by the total energy produced. Consequently, it is vital to couple these rural electrification projects with income generating activities that are suitable for the local setting. These activities consume the electric energy produced, increase the system capacity factor and pay energy tariffs which bridges the gap between O&M costs and HH tariffs. During the field work, the people of Duli stated that they will be using the electricity to start wielding shops, bakeries, sugar cane processing plant and a sewing shop. This fact makes the community primed to receive electric power since its utility goes beyond lighting. Moreover, the locals demanded to have electric meters installed per households and pay for energy usage as opposed to a flat monthly rate. This highlights the importance of a lucrative income generating business even.

Table 5 shows the system component costs of MH and the solar PV systems. Contractors and suppliers located in Manila were contacted for pricing and quotes of required materials, systems and services. To calculate the cost/month/HH, we assume that both systems are grants or donations and have the same O&M costs. The O&M costs include management and technical personnel salaries and minor repair costs. The replacement cost is the cost to replace the entire system after the end of its lifetime.

Cost/month/HH = (monthly replacement cost + O&M cost)

Fig. 1 below compares the Cost/HH/month if both systems will only be maintained by tariffs for households. For a community with 100 HH, the solar PV will cost \$7.85/month/HH while MH will cost \$4.925/month/HH. Both these values are high with MH being twice what the community can pay while the solar PV is almost 4 times. The survey showed that the community can pay between 100-150 PhP/month for energy which is around \$2.2 to \$3.3/month. The gap between the household tariffs and needed fees must be covered from income generating activities within the community. Hence, it is important to tie rural electrification projects with income generating businesses within the community.

However, if energy meters are used to calculate the energy consumption per households, the tariff structure would become per kWh. Assuming that the entire energy of both systems is consumed by households, the cost/ kWh for solar PV would be \$0.345/kWh while MH would be \$0.035/kWh. However, these

TABLE V. COST ESTIMATES FOR BOTH TECHNOLOGIES

Solar PV components	**PV Panels**	**Inverters and wiring**	**Shipping and labor**	**Total**
Cost	\$65,000	\$26,000	\$27,500	\$119500
MH components	Construction materials	Electromechanical systems	Shipping and labor	
Cost	\$25,000	\$22,000	\$18,000	\$65,000

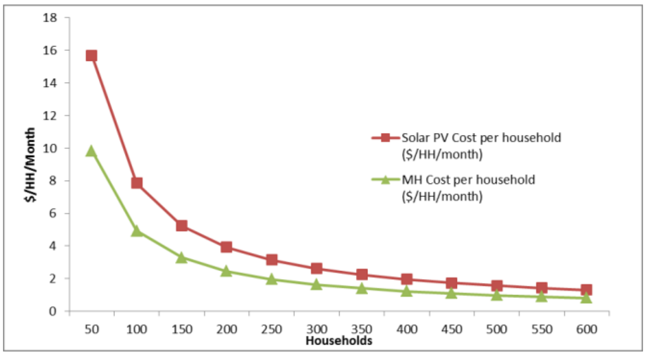

Fig. 1. *Cost per HH*

assumptions are not realistic since households are not capable of consuming all energy output. As mentioned previously, rural electrification projects have a much lower capacity factor. Fig. 2 presents the cost/kWh versus capacity factor. As can be seen, even for low capacity factors, the cost/kWh for MH is under \$0.7/kWh, however the solar PV cost/kWh is over \$1/kWh for capacity factors less than 0.35. We can see that on a flat rate basis the system costs for MH and solar PV are more comparable than on a per kWh basis. A kWh tariff scheme could be prohibitive for rural electrification projects involving solar PV, a flat rate for \$/kW/month is more favorable.

Next, the direct and in-direct effect of these systems on the economy is studied. First, the amount of jobs created is studied. Since MH is such an extensive civil engineering project, it would require significant man hours to construct. The authors estimated a need for about 400 man-day labor in order to complete the MH system. On the other hand, the solar PV would require labor for transportation and installation; however the need for labor would be considerably lower in this case. Once construction is complete, the authors estimate that MH would create more long term jobs for running and maintaining the system than what the solar PV might need.

Second, the indirect effect on the local economy of these systems is studied. During our field study, it was noticed that villages with a stable and reliable source of electricity had more economic activities than villages with no electricity. The simplest form of business observed was cell phone charging. Some of these businesses extended to charging flashlights

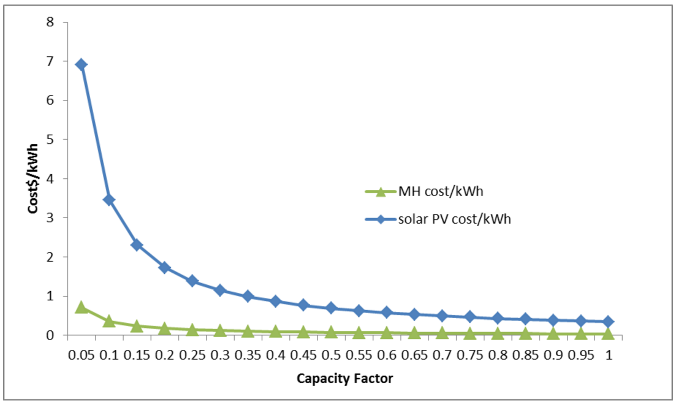

Fig. 2. *Cost/kWh of solar PV and MH systems*

and car batteries. Thus, a stable source of electricity could catalyze local economy and provide additional sources of income for entrepreneurs. Since MH is not limited to daytime, it was given a higher score in this category.

Finally, the maintenance cost for the MH is thought to be higher than solar PV. A system with a lot of moving parts is more susceptible to instrument breakdown, hence, the cost associated with fixing the several parts is likely to be higher. This is based on the assumption that all components are of good quality in both systems. Table 6 summarizes the economic scores of these systems.

E. *Political*

Undoubtedly, the political environment plays a major role in the sustainability of these projects. The role of governance in the successful implementation of a project cannot be overstated as it sets the legal framework from which other stakeholders would operate. In this study, we evaluated the following political indicators:

Resiliency to corruption: This indicator assessed the resilience of these technologies to political corruption. We found both projects to be equally susceptible to political corruption; consequently they were given similar ratings.

Ease of legal issues (land and water rights): While both technologies are subject to land rights issues, micro hydroelectricity is especially vulnerable to water rights especially in period of droughts. This is particularly critical in communities whose main source of income is agriculture which is the case in the Ifugao Province. Due to this, solar PV was rated more favorably in comparison.

Access to government funding: This indicator assesses the likelihood of financial support from the government. All things being equal, a more expensive project lowers the likelihood of full funding from the government. As shown earlier in the economics section, installation of solar PVs is more expensive than setting up a micro-hydroelectric plant. Consequently, micro hydroelectricity is rated better than solar PV installation in this category. Table 7 below summarizes the scores.

F. *Cumulative Analysis*

The cumulative assessment of the STEEP dimensions is shown in Table 8. As shown, both technologies were comparable in their impact on the social dimension. However, solar PV appeared more favorable when technical and political dimensions are considered whilst micro-hydroelectricity is preferred when economic and environmental factors are considered.

TABLE VI. ECONOMIC DIMENSION ANALYSIS

	Total cost	**Jobs created**	**Indirect effect on economy**	**Maintenance costs**	**Total**
MH	2	2	2	1	7
Solar PV	1	1	1	2	5

TABLE VII. POLITICAL DIMENSION ANALYSIS

Indicators	MH	Solar PV
Resiliency to Corruption	1	1
Ease of legal Issues	1	2
Access to government support/funding	1	1
Total	3	4

To achieve a more meaningful comparison, Equations 1 to 3 are applied to the data found in Table 8. As addressed earlier, every aspect of the STEEP model is important. However, the relative importance of these on the decision-making process can be adjusted by assigning different weighting values to each dimension. In this study, 1- 3 were chosen where 1 has the least priority and 3 the highest. We chose to weight the environmental aspect the highest (3) whilst the technical and political aspects were weighed the least (1). These weightings are justified by authors' fieldwork in the region. Table 9 shows the calculated TI values of the two technologies based on their cumulative impacts.

Based on the holistic analysis above, MH presents a more sustainable option for Duli. As shown in Table 9, the environmental (E_1) indicator had the most influence in determining the total impact. While both renewable technologies presented are overall favorable, the negative environmental impacts of the production and installation of solar PVs are much higher. Advances in solar cell production, energy efficient processing of silicon and nanotechnology could possibly make solar PVs comparable to MH.

As stated earlier, we seek to present a simple but straightforward method for decision makers. It is understood that whilst the weighting value is important, it is a flexible parameter that could vary as a function of the location. For instance, decision makers in a politically unstable community would assign a higher weight to the political indicator (P). Similar scenarios can be imagined for each of the remaining STEEP indicators.

VI. DISCUSSIONS

The challenges associated with assessing the sustainability of rural electrification projects are documented in literature [11]. Simplifying such a complex problem presents major challenges. This study is no exception. Some of these challenges are subsequently discussed.

First, the proposed electrification project is yet to be implemented. Consequently, analyses were largely based on past experience and previous studies. In addition, there is some subjectivity in the quantification methods. In the absence of empirical data and standardized analysis methods, the presented analyses are based on past experience and information obtained from community residents during the author's trip. In addition, assigned weights (W) that formed the basis for the calculation of the total impact (TI) used are values that can easily be manipulated. This feature cuts both ways. On one hand, it gives the decision maker the ability to customize the impact calculations to incorporate the peculiarities on ground. On the other hand, it makes the model vulnerable to individual biases. While individual and community biases cannot be eliminated completely, some steps could be taken to minimize this. Inputs from relevant stakeholders should be sought in order to identify the appropriate sub-indicators for each of the STEEP dimensions. Following that, the assignment of scores as shown in Tables 2 to 9 should be open for debates and agreed upon after thoughtful deliberation.

TABLE VIII. CUMULATIVE IMPACTS OF BOTH TECHNOLOGIES

Dimensions	MH	Solar PV
Social	6	6
Technical	6	7
Environmental	2	1
Economic	7	5
Political	3	4

TABLE IX. IMPACT ASSESSMENT SUMMARY TABLE BASED ON STEEP ANALYSIS OF THE TWO TECHNOLOGIES

	RD (MH)	RD (PV)	Assigned Weight
S	0	0	2
T	0	0.14	1
E_1	0.50	0	3
E_2	0.28	0	2
P	0	0.25	1
Total Impact	2.06	0.39	

Furthermore, combining the different dimensions of sustainability together could be problematic. The process of simplification dictates combining and eliminating several factors altogether. Such a process blurs the difference across indicators and valuable information might be lost. Also, this combination can lead to a loss of certain details within each dimension. If a certain dimension is deemed more important than another, the weighting system can be adjusted appropriately to reflect that.

Finally, this study is specific to a location. As much as possible, the indicators and their corresponding scores have been made to reflect the reality on ground in Duli. Consequently, it is important to note that these could differ from one location to the other. It is consistent with the goal of this study to present a framework from which decision makers can discriminate among different technologies and configurations. Thus, the whole-systems thinking presented in this study could be extended to several rural communities. The strength of the proposed framework is that it can give a quick overview of competing technologies for rural electrification. Thus, certain technologies can be either eliminated or kept when an NGO or government is studying various technologies. Moreover, having an NGO or government think holistically about a project can lead to insightful ideas and further discussions.

A holistic approach that is both comprehensive and realistic is needed to help NGOs and governments realize the most sustainable technology for rural electrification. An excessively complex approach might cause the NGO to allocate a lot of valuable time and resources that could have been used elsewhere. On the other hand, an overly simplistic approach would not provide the needed analysis that could help the NGO to a better decision. We believe that this study has struck the right balance.

VII. Conclusion

We have presented in this study a framework for comparative analysis of two renewable technologies: solar photovoltaic and micro-hydroelectricity using Duli as a case study. The framework is aimed at local NGOs and governments that are not capable of realistically completing the more complex frameworks suggested in literature. Those frameworks require considerable time and effort from fieldworkers in order to complete them. The framework presented here aimed to achieve a balance between workload and depth of analysis. Based on the analysis presented in the report, micro-hydroelectricity presents a more sustainable option for this location. While we realize the elements of subjectivity present in the analysis, we reckon that this framework presents a simple yet comprehensive decision-making tool for stakeholders interested in setting up a sustainable rural electrification projects. A delicate balance between complexity and accuracy needs further exploration.

Acknowledgment

The work done in this paper was funded by Halloran Philanthropies. The authors are grateful for that financial support.

References

[1] IEA., I.E.A., Energy poverty: how to make modern energy universal. 2010.

[2] IEA, I.E.A., World Energy Outlook 2012. 2012.

[3] World Bank, Rural electrification and development in the Philippines: measuring the social and economic benefits, 2002, World Bank Energy Sector Management Assistance Program: Washington, DC.

[4] Mahapatra, S. and S. Dasappa, Rural electrification: Optimising the choice between decentralised renewable energy sources and grid extension. Energy for Sustainable Development, 2012. 16(2): p. 146-154.

[5] Rahman, M.M., J.V. Paatero, and R. Lahdelma, Evaluation of choices for sustainable rural electrification in developing countries: A multicriteria approach. Energy Policy, 2013. 59(0): p. 589-599.

[6] UN, Indicators of Sustainable Development: Guidelines and Methodologies, 2001: New York, USA.

[7] OECD/IEA, Towards a Sustainable Energy Future, 2001: Paris, France.

[8] World Bank, A User's Guide to Poverty and Social Impact Analysis, 2003: Washington, DC, USA.

[9] IAEA, Energy Indicators for Sustainable Development: Guidelines and Methodologies, 2005: Vienna, Austria.

[10] Ilskog, E., Rural Electrification Sustainability Indicators—Manual for Field Workers. TRITA-STH Report 2008, Royal Institute of Technology: Stockholm, Sweden.

[11] Ilskog, E. and B. Kjellstrom, And then they lived sustainably ever after? Assessment of rural electrification cases by means of indicators. Energy Policy, 2008. 36(7): p. 2674-2684.

[12] Ilskog, E. and B. Kjellström, And then they lived sustainably ever after?—Assessment of rural electrification cases by means of indicators. Energy Policy, 2008. 36(7): p. 2674-2684.

[13] Gustavsson, M. and A. Ellegård, The impact of solar home systems on rural livelihoods. Experiences from the Nyimba Energy Service Company in Zambia. Renewable Energy, 2004. 29(7): p. 1059-1072.

[14] Gustavsson, M. and D. Mtonga, Lead-acid battery capacity in solar home systems—Field tests and experiences in Lundazi, Zambia. Solar Energy, 2005. 79(5): p. 551-558.

[15] Gustavsson, M., Educational benefits from solar technology—Access to solar electric services and changes in children's study routines, experiences from eastern province Zambia. Energy Policy, 2007. 35(2): p. 1292-1299.

[16] Gustavsson, M., With time comes increased loads—An analysis of solar home system use in Lundazi, Zambia. Renewable Energy, 2007. 32(5): p. 796-813.

[17] Kabalan, M. , Tamir, D., Singh, P., Community Engagement for the Development of a Micro-hydroelectric site in Ifugao, Philippines. IEEE-IHTC. 2014. Montreal, Canada.

[18] Kabalan, M. , Tamir, D., Singh, P., Failure Analysis of Microhydroelectric sites in the Province of Ifugao, Philippines. IEEE IHTC. 2014. Montreal, Canada.

[19] JICA, The Study of Micro-hydropower Development for Unenergized Barangays in Northern Luzon, 2003.

[20] Hong, G.W. and N. Abe, Sustainability assessment of renewable energy projects for off-grid rural electrification: The Pangan-an Island case in the Philippines. Renewable & Sustainable Energy Reviews, 2012. 16(1): p. 54-64.

[21] Ilskog, E., Indicators for assessment of rural electrification - An approach for the comparison of apples and pears. Energy Policy, 2008. 36(7): p. 2665-2673.

[22] Stoppato, A., Life cycle assessment of photovoltaic electricity generation. Energy, 2008. 33(2): p. 224-232.

[23] ITDG, BEST PRACTICES FOR SUSTAINABLE DEVELOPMENT. OF MICRO HYDRO POWER FINAL SYNTHESIS REPORT