Using Experts' Opinions and Multi-Criteria Decision Analysis to Determine the Weighing of Criteria Employed in Planning Remote Area Microgrids

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***Abstract*—Electrification of remote areas with the help of standalone power supply systems, also known as islanded microgrids, is a complex and multi-dimensional problem. This problem needs to address and consider diverse factors such as economic, technical, environmental, social and political. This study has used an analytical hierarchy process-based multi-criteria decision-making approach to obtain a more robust and universally convincing plan for remote area microgrids. To this end, a survey has been conducted from worldwide academics, industry experts and consultants. The study reveals that the economic criterion is the most important factor versus other factors.**

***Index Terms*—Analytical hierarchy process (AHP), Multi-criteria decision analysis (MCDA), Remote area islanded microgrid, Optimal planning**

I. Introduction

Around 1.2 billion people living in the remote and rural areas worldwide are deprived of electricity access [1]. This not only adversely impacts their lifestyle but also obstructs the social growth that hinders the advancements of the United Nations' sustainable development goals (SDGs) [2]. Energy, the key enabler in achieving SDGs, has to be affordable, reliable, sustainable and based on modern-day technologies [2]. The primary target represent three pillars of sustainable energy, i.e., ensuring access to clean and modern energy, increasing the share of renewable energy, and improving energy efficiency.

Electrification of remote and rural areas around the world has always been economically and technically challenging due to the long distances between the load centers and the nearest power grid lines or substations, low load density and challenging topography [3]. Off-grid or standalone solutions are thereby deemed as an integral part of the remote areas' power supply systems, also referred to as islanded microgrids [4-5]. Diesel-driven synchronous generators are primarily chosen to electrify these areas due to low capital cost and consolidated supply chain in the regions [6-7]. However, the reduced capital cost of renewable systems, their low or zero ongoing costs, as well as low or zero emissions, have made them comparable and sometimes competitive with diesel generators in such areas [8-10].

In recent years, tremendous effort has been put worldwide to develop methods for harnessing energy more effectively from renewable sources. Introduction of these technologies plays a significant role in the lifestyle of the local habitats as these impacts the social and economic aspects of their lives. Therefore, optimal planning is required for these islanded microgrids to satisfy the technical requirements of the local community whilst addressing non-technical issues, such as economic, social, environmental and political. Such a holistic approach can provide the decision makers with a tool to be used for achieving robust planning for islanded microgrids in remote and rural areas.

Most literature focus on mathematical modeling and power systems simulation for the optimal planning of remote area electrification which briefly portrays the consideration of mono-objective optimization via simple linear programming and enumerative optimization [11]. This approach helps the system planners to propose a technically sound system. However, it does not consider the non-technical issues, and thus, lacks practical features. As an example, [12] and [13] discuss the insufficiency of considering only economic indicators such as cost-benefit analysis or net present cost.

Literature [14-15] demonstrate that an in-depth understanding of the local concerns and conditions are necessary for planning, implementing and managing microgrids. The study also reveals that all of the five dimensions of microgrid planning (i.e., social, technical, economic, environmental and policy) need to work together to overcome the barriers. This will result in achieving the desired sustainable energy development, which is beyond the scopes of the traditional techno-economic planning. For example, if social awareness is not addressed within the community where the microgrid is to be implemented, the lack of knowledge will affect the people's way of maintaining the technology and thus using energy [16]. Therefore, social challenges have direct impact on the technical success and the environmental benefits of microgrid in remote areas [14]. The lack of community engagement, lack of proper education, lack of practical preliminary survey and insecurity of the infrastructure are some of the factors, which may create adverse impressions of microgrid among communities. Hence, this research tries to address these non-technical issues. If the social aspects are ignored, then the overall planning will lack inputs that come from the local stakeholders. Without addressing these challenges, implementing a microgrid in a remote community is an incomplete solution.

Planning for remote area microgrids not only depends on the socio-economic and technical factors but also depend on some environmental factors. Environmental factors must be addressed for a long-term viability when designing a cost-effective system for the respective community [14, 17]. The current solution of fossil fuel-based electrification in most of the remote areas worldwide is facilitated by the lower capital cost and lower expectation of system reliability. However, this solution lacks long term sustainability characteristics. Installing renewable energy-based power systems lowers the consumption of fossil fuel, and thus, leads to lowering the fuel dependency, the transportation and storage costs, as well as the associated risks, which are essential long-term benefits in terms of environmental sustainability. Renewable energy integrated systems make remote communities self-reliant for its electricity, and thus, assist in creating new jobs and lowering the health impacts coming from burning fossil fuels. Hence, it is a matter of concern to assess the degree of interest on environmental sustainability among the experts working in the power systems and renewable energy sector. Failure to address such non-technical aspects may lead to a disappointment to the community, which will outshine the benefits of microgrid. Some of the key features of a well-designed and planned microgrid that addresses both technical and non-technical planning factors are [14, 18-20]:

- Proper and practical design of the grid/network
- Standard equipment maintenance techniques
- Use of quality machines and materials
- Proper use of monitoring system
- Ensuring system reliability and energy sufficiency
- Financial incentives by the government or local authority
- Financial involvement by the local community
- Effective environmental impact assessment
- Educating the local consumers
- Effective community awareness and participation
- Effective pre design survey and study
- Creation of local jobs, and
- Ensuring proper management system that mitigates the major remoteness factors

On the other hand, communities of remote and rural areas are usually considered as the underprivileged society in terms of educational and cultural growth [21]. It is a common concern of the utilities and contractors operating in these areas to consider some factors those may create social turmoil while introducing power system equipment, which are modular and flexible to use [22]. Personal work experience of the authors convey that, residential rooftop PV panels are often become targets of vandals due to market demand and presence of black market. Often electrical devices; for example, batteries get damaged and stops providing adequate support due to poor or lack of safety rules and regulations knowledge of the remote community. This creates a misconception regarding that technology, and people become demotivated to invest on it in future. Another obstructive factor is that, many governments tend to amend the renewable energy policies and regulations depending on the respective political and financial interests. A country's renewable energy policy dictates the interest towards renewable energy based microgrids for the development of that country's remote and rural areas. If the policies do not support enough incentives or withdraws the facilities provided for uptake of renewable energy technologies, remote and rural communities get demotivated to uptake those technologies, which may cause higher upfront cost that result a lengthy payback period.

It is challenging to come up with an optimal plan for a remote area islanded microgrids as some criteria, for example, job creation, social acceptance and impacts on physical and mental health cannot be measured by monitory values. Some criteria also have a rebound effect on others, and they may not offer the best solution without cogitating. Therefore, there is a need to develop a comprehensive and rational planning process that is appropriate for remote off-grid communities, which considers all criteria to address the SDGs. In this context, multi-criteria decision analysis (MCDA) is an efficient, timely and prudent approach, and is helpful when a decision-making dilemma arises from multiple and probably conflicting objectives [23-24]. This technique provides a reliable methodology for ranking several options or alternatives, considering the objectives and constraints. It assists the stakeholders to compare choices across several dimensions. Many stakeholders are involved in this process of planning including academics, industry experts, consultants, policymakers, as well as environmental and public interest groups. All of these stakeholders share divergent viewpoints and interests. Thus, a systematic approach is required that can combine all the trade-offs from these diversities and settles the results. This is because no single source can satisfy all the criteria at the same time. MCDA is the process that can combine all the diverse view-points to propose a comprehensive solution. Mardani et al. [25] has reviewed a range of techniques for MCDA and finds it an essential and realistic method to solve energy-related problems, which deal with multiple objectives associated with multiple numbers of resources. The study reveals that, from 2004 to 2015, there has been continuously increasing interest in MCDA methods for solving renewable energy technology-based problems [25]. Around 29% of all the methodologies used in planning or operating electric supply system of rural and remote areas follow the MCDA approach [11, 26-27].

The key question for which this research aims to find an answer is: What are the primary concerns among various groups of worldwide experts on planning a remote area islanded microgrid? The study considers photovoltaic (PV) and battery-based electrification options in the microgrid as additional sources to the existing diesel-driven synchronous generators. To this end, a survey has been conducted from the worldwide academics, industry experts and consultants. First, they are requested to provide feedback and opinion on integrating PV and battery energy storage systems into diesel-driven synchronous generator-based islanded microgrids of remote and rural areas. Then, the MCDA approach has been applied to the replies provided by the experts. The only reason for focusing on PV systems among various types of renewable energies is that they are currently playing a significant role in hybridization of the electric networks in remote areas on a global scale [28]. The battery energy storage systems are also focused on this question as they can enhance the microgrid's dynamic performance versus the unexpected and variable output variations of PV systems [29-31].

II. Methodology

This study investigates the prioritization of decision-making criteria and sub-criteria for islanded microgrids. Fig. 1 depicts the followed methodology in this study, which includes an analytical hierarchy process (AHP) technique for the MCDA. The AHP technique has been employed as it has the best value measurement model, and thus, it is one of the most commonly used techniques for MCDA [32-34].

In this research, first, the problem is structured into a hierarchy model. The objective of the study is to define the criteria and sub-criteria for optimal electrification of the remote area islanded microgrid. These criteria have been chosen based on extensive literature review. Most of the researchers have mentioned four broad criteria of economic, environmental, technical and social to be considered when evaluating a remote area microgrid. To make the decision-making more comprehensive and robust, each criterion is also divided into several sub-criteria, as listed in Table I [35].

The second step is to obtain the weighing of each criterion and sub-criterion of the hierarchy. Each criterion has a relative importance, which can be identified by their weightings (scores) [36]. A survey questionnaire was prepared for collecting the relative importance and score and circulated to the experts around the world. The experts provided the relative weightings of all the criteria and sub-criteria following a comprehensive guideline. The minimum sample size required for this survey (denoted by N_{survey}) is calculated from [37].

$$N_{\text{survey}} = Z_{\text{score}}^2 \times SD \times \frac{1 - SD}{E_{margin}^2} \quad (1)$$

in which $Z_{\text{score}}^2 = 1.645$ when the confidence level is considered as 90%; the standard deviation (denoted by SD) is 0.5 and the error margin (denoted by E_{margin}) is ±10%. From (1), the minimum sample size required has been calculated as 68 for this study. However, the total number of participants took part into the survey exceeded the minimum sample size. The considered expert groups are the 'Academics', 'Industry Experts' and 'Consultants' engaged in various sectors related to electric power systems, renewable energy technologies, microgrids and rural electrification. All experts who took part in the survey were categorized into one of these three groups. The experts are asked to rate all criteria and sub-criteria individually using the Saaty scale (i.e., the numerical scale shown in table II [34]).

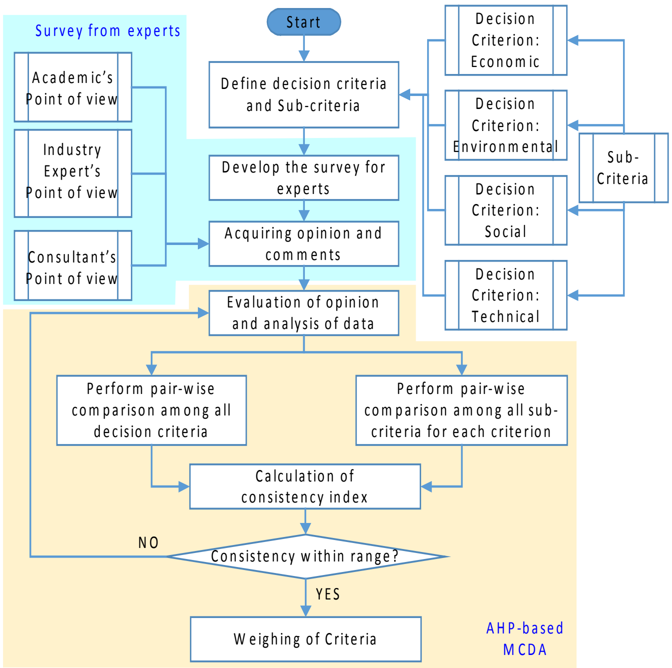

Figure 1. Typical methodological approach.

TABLE I. CONSIDERED CRITERIA AND SUB-CRITERIA.

Criterion	Sub-criterion
Economic	Net present cost, Capital cost, Operation and maintenance cost, Fuel price
Environmental	CO_2 emission, Noise pollution, Land use
Technical	System reliability, Renewable share, Peak shaving, Generator efficiency
Social	Job creation, Social acceptance, Remoteness factor

TABLE II. SAATY SCALE USED IN THE AHP TECHNIQUE [29-30].

Rating	Definition
9	Extreme importance
7	Very strong importance
5	Strong importance
3	Moderate importance of one over another
1	Equal importance
2, 4, 6, 8	Intermediate values between two adjacent judgements
Reciprocals	If action 'i' has one of the above rating assigned to it and then compared to another action 'j', then 'j' has the reciprocal value when compared with 'i'

The third and the final step is to evaluate each expert group's comparative prioritization and determine the weightings for all criteria and sub-criteria (universal data set). The technique consists of three principles: decomposition, comparative judgments, and synthesis of priorities [38]. First, the vector of weightings has to be computed for all criteria followed by computing the weighting vectors for sub-criteria. To compute the weightings of any criterion, the AHP technique generates a pairwise comparison matrix in which the Saaty scale is used. All criteria and sub-criteria are used for pairwise comparisons. More information on the used AHP technique can be learnt from [33].

TABLE III. CRITERIA PAIRWISE COMPARISON MATRIX FOR THE ACADEMIC, INDUSTRY EXPERT AND CONSULTANT GROUP

Criteria	Academic				Industry Expert				Consultant			
	Economic	Environmental	Technical	Social	Economic	Environmental	Technical	Social	Economic	Environmental	Technical	Social
Economic	1	4	1	7	1	5	3	x	1	7	7	8
Environmental	1/4	1	1	1	1/5	1	1	1	1/7	1	x	1
Technical	1	1	1	x	1/3	1	1	3	1/7	1/x	1	1/6
Social	1/7	1	1/x	1	1/x	1	1/3	1	1/8	1	6	1

III. SURVEY RESULTS AND DISCUSSION

A total of 71 participants responded to the submitted survey. Fig. 2 presents the diversity of the respondents and shows 63% of the respondents belong to the Academic group, 30% to the Industry Expert group and the rest 7% to the Consultant group. Moreover, 54% of the respondents have either work experience or currently working in developed countries while the rest belong to the developing countries. Furthermore, a total of 38% of these respondents are belong to Asia followed by 32% from Oceania and 14% from America, 13% from Europe and 3% from Africa. The survey asked the experts to take part in an online questionnaire and rank or rate the comparative and pair-wise importance of all criteria and respective sub-criteria among each other, using the scale provided in table II. The authors also sought through the survey, experts' views and comments on selecting these criteria for planning of a remote area microgrid. The results of this survey are unique because of the participation of multinational experts with multicultural background and experience from around the world.

Table III presents the pairwise comparison matrices obtained for each criterion, for all the expert groups. The information in this table has been then used to determine the weighting of each criterion using the AHP technique. These weightings are depicted in Fig. 3 for all expert groups. As seen from this figure, the weighting of the economic criterion outweighs other criteria by all expert groups. The intensity of importance for the economic criterion is respectively 48.7, 58 and 69.9% for the Academic, Industry Expert and Consultant groups. It is also seen from this figure that experts are less concerned about the environmental criterion when planning a remote area islanded microgrid.

Fig. 3 also shows that the Consultant group has ranked both environmental and social criteria more important than the technical criterion, making the technical criterion the least important factor and social criteria being the second important criterion. Usually, in practice, Consultants try to follow a conventional or safe-sided approach for advocating. The findings of this study also support this statement. However, as seen from Fig. 3, the social and environmental factors are less important than the technical criterion for the Academic and Industry Expert groups. According to [38], reliability and cost constraints are the primary considerations in power system planning process, and the findings of this study reveal that the Academic and Industry Expert groups agree with the claims of [39].

For each expert group, the weightings of all sub-criteria falling under each criterion are also computed. Fig. 4 presents the radar charts portraying the weightings of every sub-criterion marked by each expert group. As seen from this figure, from the perspective of the Academic and Industry Expert groups, the sub-criteria with the highest weightings are the capital cost, CO_2 emissions and the system reliability respectively for the economic, environmental and technical criteria.

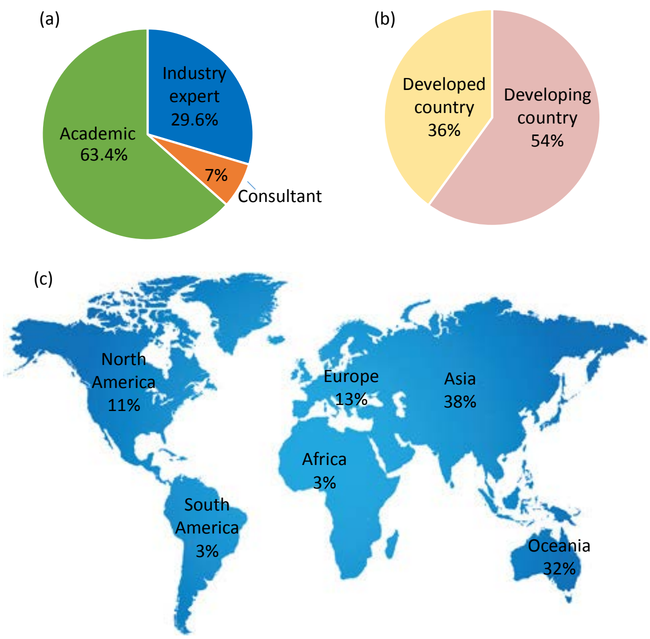

Figure 2. Diversity of the survey respondents; (a) percentage of respondents belonging to each expert group, (b) distribution of participants between developed and developing countries and (c) continent-wide distribution of respondents.

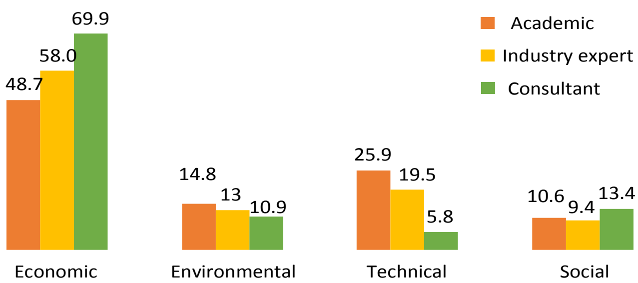

Figure 3. Overall weightings of all criteria scored by each expert group (in percentage).

Interestingly, within the social criterion, the Academic and Industry Experts have given the same weighting to all listed sub-criteria. The Consultant group has equally marked the net present cost and fuel cost sub-criteria as the highest weightings followed by CO_2 emission, system reliability and the remoteness factor respectively for the economic, environmental, technical and social criteria.

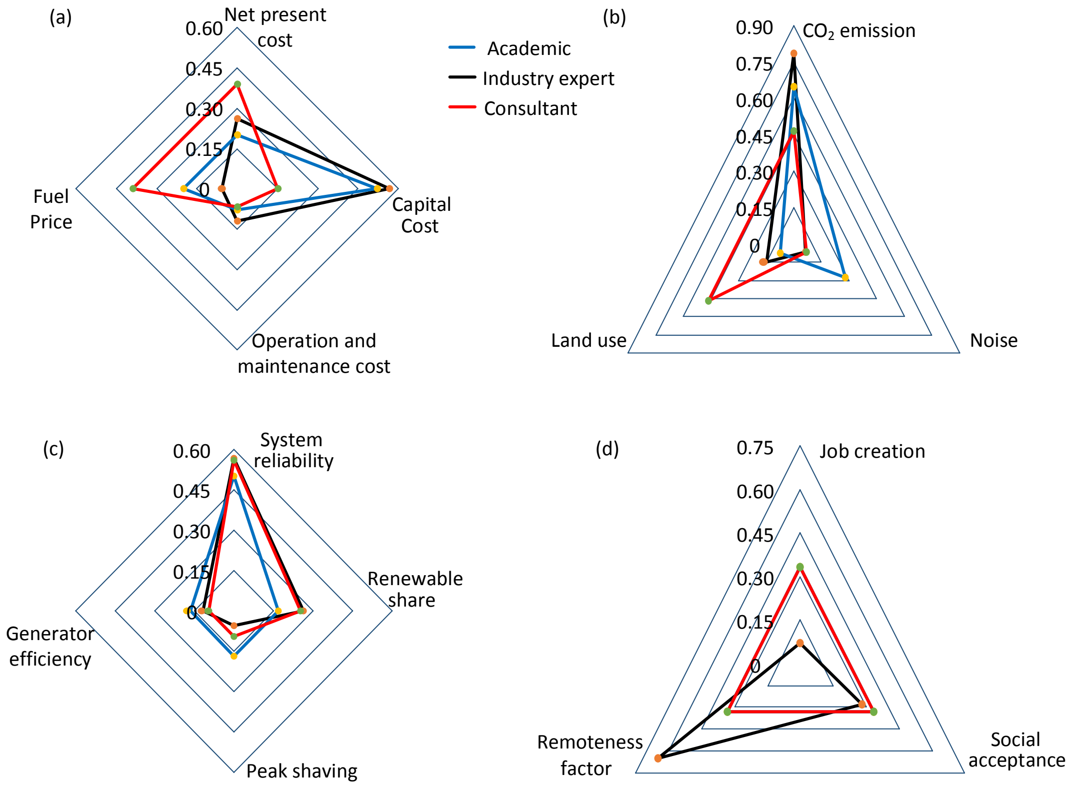

Figure 4. Weightings of each sub-criterion scored by various expert groups for criterion: (a) Economic, (b) Environmental, (c) Technical, (d) Social.

The experts were also asked about the importance of knowledge acquired through literature study over hands-on experience from fieldwork while planning microgrids. 31.1% of the participants from the Academic group had viewed the literature study has higher importance over hands-on experience, whereas 31.1% of them believe literature study and hands-on experience are equally important. 42.9% of the Industry Experts believe that literature study has weaker importance than the hands-on experience, as only 4.8% of them judged that literature study is strongly important. Among the Consultants, no one rated both these activities as equally important. 60% of the consultants believe that, literature study is moderately important than that of hands-on experience for planning remote area microgrid. Fig. 5. shows the percentage of this importance for each expert group.

The survey also asked the experts to rank the obstructive features which are generally posing discouraging impacts on microgrid implementations in remote and rural areas. Three options provided to rank were: a) vandalism; b) equipment safety rules and regulations, and c) frequent change of government policies. Among these options, vandalism was ranked the highest by the Consultant group, whereas the Academic experts ranked this option as the lowest one. Equipment safety rules and regulation was also ranked the highest by the Consultant group, whereas the Academic and Industry Experts ranked this option as second and third, respectively. Interestingly, both the Academic and Industry Experts group selected the 'frequent change in government policy' as the most discouraging factor (highest rank) among all selected factors. Fig. 6 portrays the hierarchy of importance of the obstructive factors. When considering all experts' opinion cumulatively, the research finds that 37.5% experts recommended the equipment safety rules and regulations as the highest ranked obstructive factor, whereas 33.9 and 28.6% of experts ranked frequent change in government policy and vandalism as the highest ranked obstructive factor. 44.1 and 39.8% of the experts ranked the frequent change in government policy and the vandalism as the second ranked and third ranked among the three options, respectively. Fig. 7 represents the experts' perceptions on ranking the obstructive factors.

The survey also requested additional comments and personal observation on the planning and operation issues of a diesel-PV-battery based microgrid in remote areas. According to the respondents, it is essential to know the type of energy demand (electricity and heat) and their proportion before planning a power supply system. Residential energy needs is an important factor for designing diesel-PV-battery capacity. One of the respondents mentioned that, *"Steps to be followed at planning stage: site selection, pre-survey to identify and quantify the present energy demand, demand forecasting, availability of energy efficient equipment, willingness to pay and co-operate, income and education level, suitability of installing decentralized power generation units at different combinations of diesel, and/or PV, and/or battery which will be interconnected."* while another respondent mentioned that, *"System sizing is very important - particularly the size of diesel generators. Allowance for future demand growth and use of best practice technologies are important as well."*

Respondents also expressed their view on economic, social and environmental issues on microgrid developments. Some participants mentioned that although diesel-PV-battery systems are economically more viable than diesel only systems, but considering the negative impacts on environment, PV-battery system is the future solution. Some concerns were raised regarding the land usage issues for PV installment, if it is not rooftop PV system: "*PV is better for environment. Now, the key is to choose the good location for PV harvesting. Then, PV becomes suitable.*"

Social factors were also mentioned as one of the important issues to be considered by the respondents. According to the participants, these type of hybrid systems are able to create job scopes in the local areas. One respondent comments that "*Hybrid system is expected to create more jobs than the diesel-only system.*"

IV. CONCLUSION

This study aimed to identify the most important and common universal criteria and sub-criteria for optimal planning of remote area islanded microgrids, consisting of diesel-driven synchronous generators, PV and battery energy storage systems. Four main criteria of economic, environmental, technical and social and fourteen sub-criteria have been considered. The weightings have been determined based on the Academic, Industry Experts and Consultant expert surveys from all over the world using an AHP-based MCDA technique. The survey results present interesting views and observations, which reflect various mindsets and areas of concerns of different groups of experts.

The study reveals that the economic criterion is the most important factor when planning the microgrids. The Academic and Industry Expert groups have coherence in their decisions, whereas the Consultant group has different opinions. The experts also emphasize the importance of collecting household energy use information from the field before finalizing the design of the microgrid systems. It was agreed by the experts to consider social factors while planning such systems. The study also reveals the concerns of experts regarding the importance of hands-on experience over literature studies for planning of microgrids. Experts have also ranked some of the demotivating or obstructive factors those may lead to fewer uptakes of renewable energy-based microgrids by communities, if not addressed properly. The findings of this study suggests that, the traditional concepts of using only technical or only techno-economic factors for planning of remote area islanded microgrids are becoming weaker or even outdated these days. The environmental and most importantly, the social factors that involve the local stakeholders, must be taken into consideration.

The outcomes of this research can be applied along with the techno-economic results, determined by power system simulation and optimization software tools. This will make the plan of renewable energy-based remote area microgrid more comprehensive, logical, translucent and location-specific.

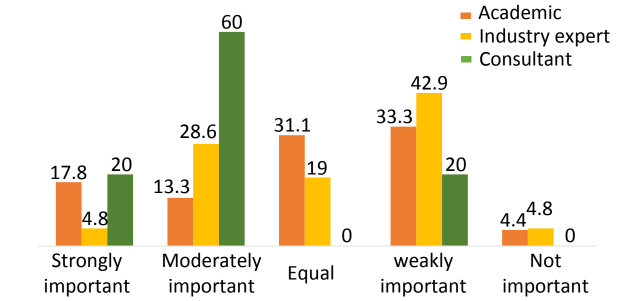

Figure 5. Experts' view on importance level of literature studies over hands-on experience for planning of microgrids (in percentage).

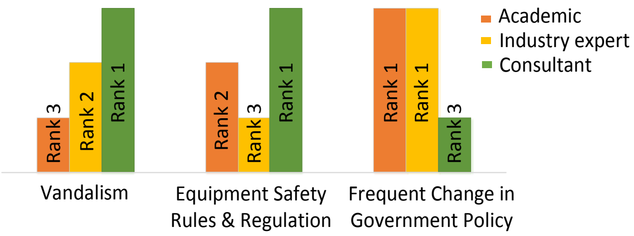

Figure 6. Hierarchy of obstructive factors for planning of remote area microgrids.

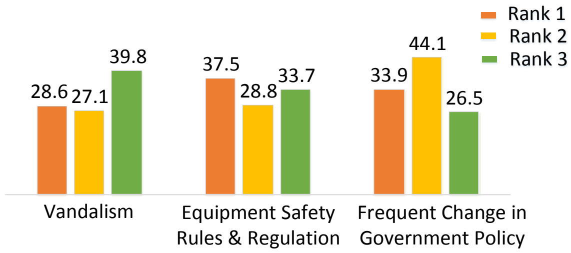

Figure 7. Experts' perceptions on various obstructive factors for planning of remote area microgrids (in percentage).

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