Hybrid assessment for a hybrid microgrid: a novel methodology to critically analyse generation technologies for hybrid microgrids

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Abstract

Eighty per cent of the people without access to electricity live in rural areas. Due to high investment costs in the grid, the solution to providing electricity to these people will mainly rely on the installation of islanded hybrid microgrids. Designers need to consider a variety of factors for the optimal design of hybrid microgrids. However, many of these criteria are qualitative or uncertain. This paper provides a novel methodology to assess the influence of such criteria in the design of a Hybrid Microgrid of Renewable Energy Sources (HRES). The method combines context analysis, literature review and the Analytic Network Process (ANP) through panels of experts and surveys. The methodology ranked the criteria and helped to design a HRES in an isolated Honduran rural community in the Mesoamerican Dry Corridor. The study presents a review and classification of the main criteria and energy technologies considered for the design of HRESs in rural communities. The most influential factors turned out to be the institutional support, the possible expansion of the grid to the community and the availability of local energy resources. Regarding energy technologies, photovoltaic and wind power ranked as the preferred followed by a biomass gasifier as backup.

Keywords— Hybrid Microgrids, Renewable Energy, ANP, Rural Electrification.

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1. Introduction

Access to clean electricity is a key factor in fighting energy poverty and promoting sustainable development. Organisations such as the World Bank or the International Energy Agency state that access to electricity improves socio-economic conditions such as the poverty ratio, health, education, environment and income [1]. The UN Sustainable Development Goal 7 (Affordable and Clean Energy) plans to achieve the electrification of the world's population by 2030 [2]. However, around 0.86 billion people remain without access to it [3]. Among them, 80% live in rural areas mainly located in sub-Saharan Africa, Southeast Asia and South America. Commonly, vast and/or, steep lands separate these rural communities from the central power grid, resulting in high investment costs to connect them. Electrification is understood to cover the basic human demands and community needs [4,5] and this is normally beyond the supply of the common pico-solar and individual home power systems [6,7].This situation makes islanded microgrids an optimal solution to securely cover electrical demand [8]. In fact, the International Energy Agency foresees that microgrids will provide almost 50% of projected electrification worldwide [9]. Microgrids tend to rely on the different renewable energy sources available in the communities, supported by back-up systems [10]. These microgrids combine several technologies and the literature refers to them as Hybrid Microgrids of Renewable Energy Sources (HRES) [11–13].

A broad range of studies analyse the feasibility of Hybrid Microgrids of Renewable Energy Sources (HRES) to electrify remote rural areas. Oduo *et al.* study the techno-economic viability of an HRES in a village of Benin [14]. Their research shows that a hybrid solar PV system with a battery and the support of a diesel generator provides the lowest cost option. Ayodele *et al.* present an HRES optimisation model applied to a village in Nigeria. Wind and solar PV resources supported by conventional generators and batteries power the HRES [15]. Das and Zaman show a viable performance of an HRES based on solar PV, diesel and batteries in a remote community in Bangladesh bearing in mind economic parameters such as cost of energy and net present cost [16].

Nowadays, experts accept the feasibility of HRESs for electrifying rural areas. Nevertheless, to our knowledge no research deals with how to optimally select the technologies prior to the design based in a diversity of both quantitative and qualitative interrelated criteria. Drivers like energy resources, climate conditions, project specific viability or energy demands condition the decision [17]. Despite the undeniable importance of these factors, basing technology selection only on these criteria jeopardises the long-term sustainability of the project, which also requires social acceptability and community appropriation of it. For instance, Ilskog proposed a set of 39 indicators for rural electrification analysis grouped into five different dimensions, which contained not only technical or economic sustainability, but also social/ethical, environmental and institutional sustainability criteria [18]. Ilskog and Kjellstrom completed this study by scoring 31 of these indicators [19]. Katre and Tozzi [20] and Purwanto and Afifah [21] also assess the sustainability of HRES regarding these last five dimensions. The first ones proposed a list of 12 measures and 31 indicators [20]. While Purwanto and Afifah [21] highlighted the important role that rural communities play on electrification projects. Lillo *et al*. [22] shed light on this statement, and incorporated a Human Development approach to evaluate hybrid electrification projects. This approach relies on four principles: equity and diversity, sustainability, empowerment and productivity, emphasising the importance of social and communitarian indicators. Besides, Lhendup rank ordered different criteria related to rural energy supply based on a score method [23]. These studies show how non-commonly assessed factors such as institutional regulations and environmental and social aspects may largely affect HRES projects' feasibility. Among these factors, authors identify the social acceptance of the community as a critical factor to ensure the success of these projects, which cannot take acceptance for granted [24].

Despite all this research, the way these criteria should inform the selection of HRES technologies remains unclear [22,25]; particularly how trade-offs among different objectives in conflict occur. These competing objectives require an assessment on how each criterion influences the selection of alternative technologies. Prioritising alternatives based on their performance on multiple criteria is the purpose of Multi Criteria Decision Making (MCDM) methods. Multi Criteria Decision Making (MCDM) have been able to successfully prioritise renewable energy alternatives at a system scale. Authors use the method ELECTRE III to select among seven energy strategies for the island of Crete (Greece) [26]; or to conduct an energy resources selection in France [27]. Researchers use another MCDM method, PROMETHEE II, to perform a decision-making process about four geothermal energy development scenarios for Chios island in Greece [28]; or to select from among fourteen renewable energy technologies in a German case study [29]. These and other MCDM methods demand quantitative, certain and complete information. However, this is not the case of the social, institutional and other criteria influencing at the first stage of the HRES configuration previous to its design.

To overcome incompleteness, a series of MCDM methods exist to manage situations of incomplete, qualitative and uncertain information that may produce disagreements among decision makers. These MCDM have dealt with social, institutional and other criteria, although without considering quantitative data [30]. The Analytic Hierarchy Process (AHP), and its development: the Analytic Network Process (ANP) [31] derive ratio-scale measurements to allocate resources according to their ratio-scale priorities. Then, ratio-scale assessments, in turn, enable prioritisations based on trade-offs. Noble uses the Analytic Hierarchy Process (AHP) to decide among five energy policy scenarios in Canada [32]; besides, Chatzimouratidis and Pilavachi apply AHP in another research to select energy technologies considering quality of life and socio-economic aspects of the beneficiaries [33]. The AHP drawback is the need to model the reality by means of independent factors or criteria, although social, economic and technical factors are normally mutually dependent.

ANP is a development of AHP that allows for complex inter-relationships among the factors at different decision levels. For that reason, ANP models the prioritisation problem as a network of criteria and alternatives, grouped into clusters. This provides an accurate modelling of complex settings and allows handling of the usual interdependence among elements, as in the selection of technologies for an HRES. Different studies present successful cases of ANP used to assess energy related issues. Aragonés-Beltrán *et al.* [34,35] present an ANP model to decide over investment variables in both solar PV and solar thermal plants. ANP methods have also ranked decisions over renewable energy planning [36], national renewable portfolios [37], wind farm [38] or solar PV locations [39]. Finally, another ANP study rank ordered the barriers to the deployment of renewable energy sources in Colombia [31]. To the best knowledge of the authors no research has performed such a holistic approach as to consider all influential and interrelated factors, both qualitative and quantitative, of the HRES design, nor applied ANP to decide energy technologies in this context.

This paper provides a novel methodology to assess the influence of the different criteria to predesign an HRES that combines context analysis, literature review and the Analytic Network Process (ANP) through a series of panels of experts and surveys. The authors apply the methodology to a case study based on a real HRES in the Honduran rural community of El Santuario. The study presents a review and classification of the main criteria and energy technologies considered in the design of HRESs for rural communities. Moreover, the ANP proves itself as a viable tool to assess the influence of the criteria and to choose suitable technologies for the implementation of HRESs in rural contexts. Finally, the paper presents the main findings of the case study that can provide valuable conclusions to similar projects in the area.

The rest of the paper's structure is as follows. Section 2 presents the methodology. Section 3 provides the information on the case study, the stakeholders and the criteria analysis. The results and discussion arise in section 4, and section 5 concludes.

2. Methodology

The proposed methodology contains three main phases: i) a literature and context review, ii) the selection of a panel of experts and, iii) the application of the ANP method. The first two phases are part of the ANP method but require special analysis and need to be case specific. In this regard, Figure 1 presents the rest of the sub processes and outputs of the methodology, including the feedback loops with the panel of experts in several stages of the method. It is important to remark the methodology applies after the full identification of the project has been carried out. This identification sets the reference terms that will be the boundaries of the problem: beneficiaries' own resources, culture, energy demand, social structure… and most importantly, their agency. This is undergone mainly by the beneficiaries themselves and the rural development agents, with the support of other actors like policy makers or project designers. Hence, when applying the methodology to the early design of the project, each reference term must be met, or consensually changed.

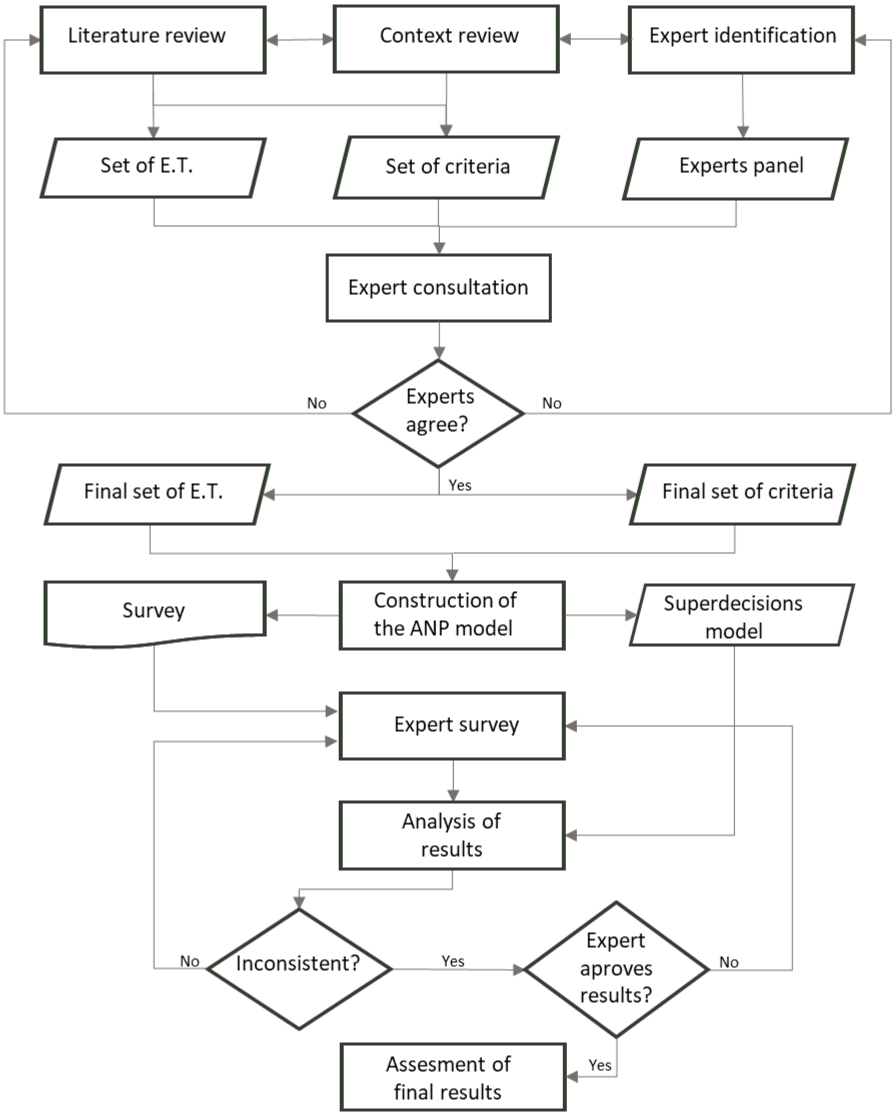

Figure 1. Methodology proposed. Note: E.T. means Energy Technologies.

2.1 Literature review and context analysis

This phase has the purpose of identifying all eligible energy technologies and all the relevant criteria for the assessment. This comprises participatory processes with the community, which hasto agree the project's terms of reference (including energy needs [40]), and it will participate in the selection of the possible technologies. As introduced, different approaches exist to study the optimal design of an HRES [41]. Besides, some authors have developed an extensive literature review in the field focusing on rural communities' applications [42–45]. Table 1 presents the combination of the results of these works, a starting list of 23 initial criteria and 7 different energy technologies for rural communities. Initial criteria are classified into 5 main clusters: economic, environmental, institutional, social and technical [46].

Table 1. List of criteria and energy technologies.

Cluster	Criteria	Description	In final selection (see section 3.3)	Research
Economic	Investment cost	Cost associated with capital-intensive uses at the start of projects, related to materials, technologies, civil engineering, etc.	Included	[47]
	Operation and maintenance cost	Cost associated with the day-to-day management and maintenance of the installation.	Included	[48]
	Levelized cost of energy (LCOE)	Power source measurement to allow comparisons among different electricity generation procedures.	Considered with the previous two	[49] [50]
	Institutional support	Existing public policies to subsidise installations costs or administration exemptions to accelerate projects' implementation.	Included including fiscal policies	[51] [52]
	Custom tariff	Tax of import/export components of the microgrid from one country to another.	Considered with institutional support	[53]
Environmental	Greenhouse emissions	Emissions gases into the earth's atmosphere. They contribute to global warming.	Included as environment	[54] [55]
	Impact on forests	Forest disturbances due to natural phenomena or human actions	Included as local environment	[56]
	Noise pollution	High levels of noise which disturb people and other environmental conditions.	Included as local environment	[57]
	Visual impact	Change in the landscape due to microgrid, so it would not be in line with the environmental context anymore.	Included as local environment	[58] [59]
	Waste	Residues produced during operation, or that remain after the main processes have finished or the main parts have been used.	Included as local environment	[60]
Institutional	Unclear legal framework	The ambiguity of policies or the absence of them regarding renewable systems.	Considered in institutional support	[61]
	High level of corruption	Dishonest conducts carried out by the Public Administration or private companies mainly due to bribes or extortions.	Included	[62] [63]
	Political will to expand the grid	Probability of expansion, in the short or medium term, of the electric grid up to where the microgrid will be sited.	Included	[14] [64]
Social	Employment generation	Job or business opportunities creation due to the operation and maintenance tasks of the new equipment.	Included in equal distribution	[65] [66]
	Capacity building	Individual and communal knowledge and tools provided to the inhabitants in order to ensure correct system management.	Included	[67] [66]
	Equal distribution of impacts	Electricity arrival should provide equal opportunities to all the inhabitants irrespective of their gender, race or age.	Included	[68] [69]
	Social acceptability	A proper assessment and involvement of the community should be carried out. Otherwise, people can reject the project.	Included	[70] [24]
	Cohesion to local activities	Renewable energy projects should be in line with the local activities of the community.	Included in social acceptability	[71] [72]
Technical	Local energy resource availability	Quantity of natural resources and their electricity conversion potential such as wind speed and frequency, solar irradiation, wood availability…	Included	[73] [74]

	Technical feasibility	Development of technical equipment and knowledge to ensure a correct and safe operation, and also long-term durability of the installations.	Included	[11] [75]
	Total energy generation	Total energy that should be provided by the system, directly related to the community`s electricity demand.	Included	[76]
	Technological maturity	Widely proven technologies, whose initial problems have been solved.	Included	[77]
	Security of supply	Guarantee of electric supply due to the different combination of renewable sources and back-up systems.	Included in total energy	[78] [79]
Energy Technologies	Batteries	Back-up technology that allows electric power storage due to a chemical process.	Included	[80] [81]
	Biomass digestor	Renewable technology used to generate biogas from anaerobic digestion (breakdown of organic materials in the absence of oxygen). This gas is then utilised as combustible in power generators.	Discarded	[82]
	Biomass gasifier	Renewable technology used to generate synthesis gas from dry biomass gasification. This gas is then used as combustible in power generators	Included	[83] [84]
	Diesel	Traditional power generators that use diesel petroleum derivate as combustible. Although it is not a renewable source of energy, designers occasionally use it as a backup system in HRES.	Included	[85] [86]
	Small hydro	Renewable technology that uses water potential energy to generate electricity.	Discarded	[82] [87]
	Solar PV	Renewable technology that uses solar radiation to generate electricity.	Included	[88] [89]
	Wind	Renewable technology that uses wind to generate electricity.	Included	[90][81]

2.2 Panel of experts

Once the boundaries of the problem are set by the community and the rural development agents, the method involves the collaboration of a panel of experts who represent different approaches to the problem to prioritise the selection of technologies. As ANP is a semi-qualitative technique, and in view of to the available kind of information, the quality of experts is mandatory and more important than the number of them. ANP is not a survey that requires large sample sizes as discussed in [24] and the results from different experts provide different and valuable viewpoints. The methodology demands three main rules, starting by the selection of experts based on their broad experience in the model issues, their personal research on the topic and their involvement as a specific type of key actor. This leads normally to indirectly include the community representatives in the panel, i.e. to ask the rural development agents who work with them to speak on their behalf (consulting them if need be). Normally, in cooperation projects, the beneficiaries lack the specific knowledge on many of the model's criteria, and neither the schedule, nor the budget, allow to train them on these in the early stages of the project's design.

The second rule is feasible inclusivity. i.e. an as complete and balanced as possible panel of experts. Based on the literature and the authors' experience, normally three key actors with holistic views exist in the supply of electricity by means of off-grid HRES to isolated energy-poor rural communities: project designers, rural development agents (promoters and managers) and policy makers. Representatives of the beneficiaries must be added to the panel if they have the required expertise. Other stakeholders only relate partially or indirectly to the HRES design and deployment. Anyhow, above-mentioned key actors know other stakeholders' views and can reflect them in the process. Furthermore, each experts' group can include one or more different profiles and one type of profile can be part of different groups. For instance, local or regional public institutions can either act as policy makers or rural development agents. Non-Profit Organisations (NPO) normally act as development agents but, in particular, public universities can also design microgrids or provide regulatory or strategic advice. Private companies tend to play the role of project designers but can also be rural development agents, etc. For a complete and balanced design of the experts' panel, all those roles and profiles must be studied and considered in the panel.

The third rules is to avoid unidentified bias. For this, it is recommended to involve more than one expert by type, in order to contrast their opinions [24]. Finally, the method relies critically in the expert knowledge and commitment to the project of the participants, which needs to be reviewed periodically. Due to this, the stage can be said to be the most difficult of the methodology, although not the most laborious, which is the literature review.

2.3 Analytic Network Process

ANP is a method proposed by Saaty [91] that enables a framework for decision making under complex contexts. In [92], Saaty provides the main characteristics and its mathematical formulation. ANP performs the ranking of elements by deriving ratio-scale measurements based on their ratio-scale priorities, which enable trade-off considerations. These network comparisons among elements grouped in clusters provide an accurate modelling among interdependent elements. The main steps of the ANP are the following:

1. Identification of the elements of the network and their relationships.
2. Pairwise comparisons of both clusters and elements using Saaty's 1-to-9 scale.
3. Construction of the unweighted supermatrix, which represents the interrelationships of all elements in the network.
4. Construction of the weighted supermatrix, which considers the cluster comparison to weigh the elements.
5. Obtention of the limit supermatrix by raising the weighted matrix to limiting powers until the matrix converges.
6. Obtention of the prioritisations of the elements given by the limit supermatrix.
7. Interpretation of the results.

The importance of each element is a non-dimensional value. According to the questions made to feed in the method, the ANP considers the influence of the criteria on the other criteria and on the energy technologies.

3. Case study

This section presents the case study in which we applied the proposed methodology. The section explores the context of the selected rural community, the criteria and the technologies considered in the proposed method and the ANP model obtained.

3.1 A rural community in the MesoAmerican Dry Corridor

The rural community of El Santuario is in the department of Choluteca at the south west of Honduras. This region is part of the Mesoamerican Dry Corridor, which covers large parts of central America from Mexico to Panama. The area experiences the El Niño-Southern Oscillation (ENSO), which causes extreme drought periods followed by heavy rains and floods. The frequency of these events has increased due to the effects of climate change, worsening the socio economic vulnerability of the area [93]. FAO recognised these conditions and designated the area as one of the most affected by the effects of climate change, which generate major climate migration movements [94].

El Santuario has a topography characterised by steep slopes and it is surrounded by a dry forest of pines and oaks. The main water sources are streams running during approximately six months of the year and water wells during the rest of the year. Temperatures and sunlight are stable due to its equatorial location.

However, rainfall concentrates in the wet season. The community has a population of approximately five hundred people that inhabit eighty houses. Economic activity is predominantly based on subsistence agriculture with almost no production surplus and the inhabitants migrate to nearby areas to occasionally work in agriculture. Just like 30% of the Honduran rural population [9], El Santuario does not have access to electricity. The community is fifty kilometres away from the state's capital, but a complex set of valleys and mountain trails hinder most communications. As with many other communities, the government has no projects to build power line infrastructures to connect the community with the main grid in the coming years and the electricity access of these communities will mainly come from HRESs.

3.2 ANP experts' profile

As previously discussed, three profiles normally represent the key stakeholders in the development of HRESs for rural development; project designers, rural development agents and policy makers. The first ones are key to understand the robustness of the preferred solution and the demand needs of the community as well as fulfilling the national energy policy. Rural development agents are the main intermediaries between the project and the community. Their main objective is to help the community's agency ensuring the long-term sustainability of the project by transferring the necessary knowledge to use the system. Policy makers have expertise in the system as a whole and promote policies to diminish the lack of modern energy, understanding budgets needs and program designs. For the case of El Santuario, and based on the stakeholders' project analysis, three experts per category formed a panel of 9 experts. In order to prevent biasing the results, the same number of experts formed each group. All the experts know the community and the project, some rural development agents indeed performed the previous participatory processes with the community, and all fulfil the expected requirements. Finally and, just as important, they all are willing to participate in the research. Actors that did not meet all the requirements were not selected as the method relies critically in their expert knowledge. Acknowledging the inherent uncertainty of such a decision, based on their performance, this paper research authors believe the panel was sufficiently complete and balanced.

As for the sub profiles that play a key role in this project, they are listed in Table 2, alongside a small description of them.

Table 2. List of stakeholders.

ID	Affiliation	Stakeholder group
PD1	Associate professor with vast experience in designing isolated microgrids	Project Designer
PD2	Researcher specialised in hybrid renewable systems	Project Designer
PD3	Engineer in a private utility company with experience of rural microgrids	Project Designer
RD1	Director of an energy research institute with experience in rural electrification projects	Development agent
RD2	Project coordinator of rural electrification projects	Development agent
RD3	Technician in a cooperation and development agency	Development agent

PM1	Energy consultant in a public international organisation	Policy Maker
PM2	Former environment secretary of state and project officer in a public international organisation	Policy Maker
PM3	Researcher specialised in energy policy	Policy Maker

The research team played the role of the ANP facilitators during the decision-making process; that is, assisting the experts in the evaluation and discussion of results throughout the entire procedure.

3.3 Selection of criteria

A literature review nourished the first set of criteria and energy technologies presented in Table 1. This set of criteria acts as a starting set of factors and energy technologies to consider in all projects of rural electrification, mainly in energy poor communities, by means of islanded HRESs.

The field work for this specific project determined which of the selected criteria were not influential. Thus, the panel of experts, in coordination with the research team, reduced the criteria from the initial set of 23 to a set of 14 criteria grouped in 5 different clusters: economic, environmental, institutional, social and technical (see Table 3). This process aimed to avoid repetition of criteria, which are directly or partly included in another criteria or group of them. For instance, the levelized cost of energy criteria depends on T4. Total energy, as well as on Ec1. Investment cost and Ec2. Operation and maintenance criteria [95]. Cohesion to local activities directly depends on S3. Social acceptability criteria as only the projects in line with local activities of a community could achieve from their social acceptance [71].

Furthermore, the panel eliminated two of the seven initially selected energy technologies. Since mini hydro and biomass digestors need considerable water inputs, experts excluded these energy technologies as inviable solutions in a region characterised by a six-month dry season and growing indicators of water stress and droughts. Table 3 presents the final selection of both criteria and energy technologies for the analysis.

Table 3. List of criteria.

Cluster	Criteria	Description
Economic	Ec1. Investment cost	[a]
	Ec2. Operation and maintenance cost	[a]
	Ec3. Institutional support	Existing public policies to subsidise installation costs or administration exemptions to accelerate projects' implementation.
Environmental	En1. Global environment	Impacts perceived at a global scale, mainly related with climate change.
	En2. Local environment	Impacts perceived at a local scale such as noise, fuel spills, land use change, waste generation, deforestation or visual impact.
Institutional	I1. Expansion of grid	[a]
	I2. High level of corruption	[a]

Social	S1. Capacity building	[a]
	S2. Equal distribution	[a]
	S3. Social acceptability	[a]
Technical	T1. Local resources	[a]
	T2. Technical feasibility	[a]
	T3. Technological maturity	[a]
	T4. Total energy	[a]
Energy technologies	A1. Batteries	[a]
	A2. Biomass gasifier	[a]
	A3. Diesel	[a]
	A4. Solar PV	[a]
	A5. Wind	[a]

[a]: As previously described at Table 1.

3.4 ANP model

Once the experts agree on the clusters of criteria and alternatives, the panel fills in the unweighted supermatrix to represent the interrelationships of all the elements in the network. This phase is divided into two sub steps. First, the dependence matrix shows the model elements in rows and columns. Later the criteria's relationships fill in the matrix with data (a_{mn}) that can be 0 or 1. If a_{mn} = 1 the criterion in the row *m* influences the criterion in the column *n.* Otherwise, there is no influence. For this, the Pareto Principle was applied to identify the small set of relationships that accumulate the biggest influence. Experts were asked if variations of one criterion would influence the performance of another, pairwise analysis, and only those cases were there was a clear agreement on the existence of an influence, were included in the matrix. Secondly, each expert answers a questionnaire to determine the level of influence that each element has on the rest of the elements that it is related to. The matrix below presented shows a series of key aspects regarding the influences among criteria. On the one hand, Ec3. Institutional support influences most criteria from other clusters while Ec1 and Ec2 do not. En 2 Local environment and I1 Expansion of the grid influence all three economic criteria. On the other hand, En1 Global environment, T1 Local resources and T4 Total energy have low dependencies as they are only related to the alternatives and one or none criteria. Finally, in contrast to what was expected from the literature review S3: Social acceptability was not a very influential criterion. The ANP results show that the social cluster was found not to be very influential in the model and thus, S3 was not influential either. We assume this contradiction with the literature since the community acceptance of all alternatives is almost guaranteed with the previous participatory process and the agreed reference terms, diminishing the possibility to social unacceptability. Regarding the alternatives, they influence and are influenced by all criteria, but normally do not influence each other, according to the methodology presented by Saaty [92].

Table 4. Dependence matrix of all elements of the network.

	Ec1	Ec2	Ec3	En1	En2	I1	I2	S1	S2	S3	T1	T2	T3	T4	A1	A2	A3	A4	A5
Ec1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	1	1	1
Ec2	0	0	0	0	0	0	0	0	0	1	0	0	1	0	1	1	1	1	1
Ec3	1	1	0	0	1	0	1	1	1	1	0	0	1	0	1	1	1	1	1
En1	1	0	1	0	1	0	0	0	0	0	0	0	1	0	1	1	1	1	1
En2	1	1	1	0	0	0	1	0	0	1	0	0	0	0	1	1	1	1	1
I1	1	1	1	0	0	0	1	0	0	1	0	0	0	0	1	1	1	1	1
I2	1	0	1	1	0	1	0	0	1	1	0	0	1	0	1	1	1	1	1
S1	0	1	1	0	1	0	0	0	1	1	0	0	1	0	1	1	1	1	1
S2	0	0	1	0	0	0	0	1	0	1	0	0	1	0	1	1	1	1	1
S3	0	0	1	0	0	1	0	1	1	0	0	0	1	0	1	1	1	1	1
T1	1	1	0	0	0	0	1	0	0	0	0	1	1	0	1	1	1	1	1
T2	1	1	1	0	1	0	0	0	0	1	0	0	1	1	1	1	1	1	1
T3	1	1	0	0	0	0	0	1	1	1	0	0	0	0	1	1	1	1	1
T4	1	1	1	0	0	0	0	0	0	1	0	1	1	0	1	1	1	1	1
A1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
A2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
A3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
A4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
A5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0

Figure 2 shows the ANP model obtained from the dependence matrix. The software Superdecision® serves as a tool to include the dependences among elements and clusters in the ANP model. Clusters containing criteria and energy technologies represent the model. These relate with each other through arrows that represent the dependencies among elements of the model. An arrow represents that an element of a cluster exerts influence over one or more elements in another cluster. Bidirectional arrows express influences among criteria in both directions and feedback arrows indicate influences between elements of the same cluster.

The model serves afterwards to include the expert's pairwise comparison and calculate the ANP results for each of them. The software also provides the inconsistency ratio of each group of judgments and the unweighted, weighted and limit supermatrices associated with the model.

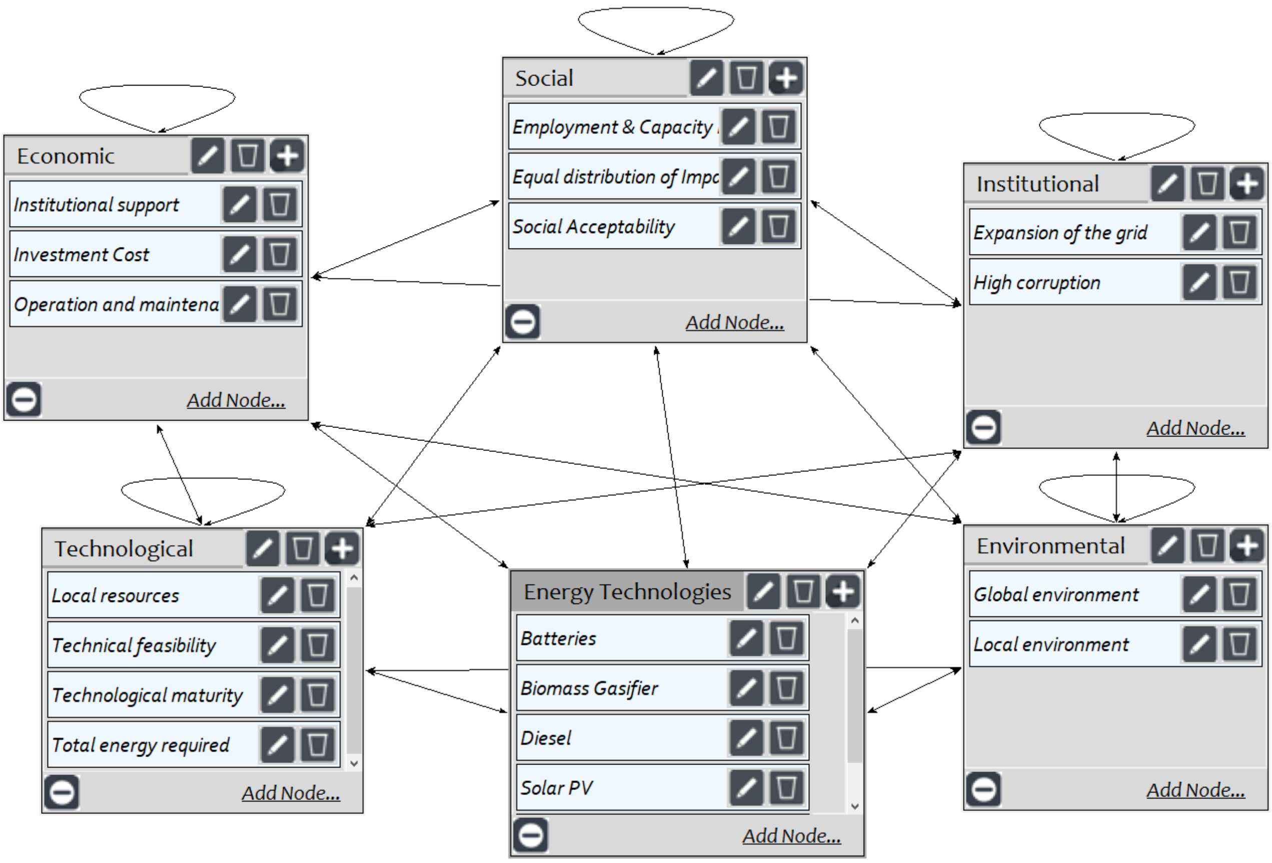

Figure 2. ANP network of the case study obtained by means of the software Superdecisions®

4. Results and discussion

The first result of the research is the list of the various influential factors that a project should analyse prior to the design of HRESs for energy poor rural communities (see Table 1). On the one hand, this list applies to all such projects regardless of the region or the size or the promoters. The same applies to the methodology, which is also universal. On the other hand, the particular application is specific in the field-work and social assessments of each project. Thus, the project stakeholders should trim the list of criteria discarding those factors that are not influential. The eligible technologies are also site specific and different from one project to another. The experts will vary consistent with the stakeholders' analysis of the project and, finally, the relationships among the elements of the model may be different, and also their influences.

4.1. Influential factors for the assessment of technologies in an HRES

After the selection of the influential factors, the assessment criteria, and their arrangement in an ANP network, experts compare the importance of the various elements by means of an ANP questionnaire that is introduced in Superdecisions® to obtain the different Matrices of the method. The ANP procedure captures these judgements and the Limit matrix gives the results of Figures 3, 4, 5 and 6 following the procedure developed by Saaty [92]. The figures place the factors with axis values and grouped by clusters. The levels show the relative importance of each criterion given by the experts; for example, all the criteria add one for one expert.

The study groups experts by their role and, logically, they tend to agree on their judgments, although they present some significant differences. Figure 3 shows how project designers tend to consider as most important criteria I1: Expansion of the grid, Ec1: Institutional support, T1: Local resources and En2: Local environment. In contrast, criteria Ec2: Investment costs, Ec3: Costs of operation and maintenance and T4: Total energy are the least influential.

The latter may come as a surprise because those factors are normally among the first criteria a project designer considers. However, during the feedback loops the experts considered energy supply to be a strategic business sector subject to extensive regulation with a large control by the public institutions. Besides, economies of scale do apply for energy supply and small installations cannot be economically affordable for energy poor communities without public support. Therefore, the Honduran project and the alike greatly rely on public funding and support. Finally, ANP makes comparisons among elements of the same cluster. And based on the judgments it assigns a greater or lower fraction of the weight of the cluster to its elements. When reviewing the answers by the experts, they gave more influence to follow the requirements and preferences of the public administration supporting the project (in this case the foreign affairs ministry of Spain) than to optimising the capital expenditure (Ec2.) or the operational expenditure (Ec3.).

Based on the discussion of results with the experts, factor T1: Local resources contribute more to prioritising one energy technology over another than T2: Technical feasibility or T3: Technical maturity, and hence their lower influence. Asked about T4: Total energy demanded by the community, the experts explained its low importance was due to that, whichever the alternative, the early design will cover the basic energy needs according to the project's terms of reference agreed with the community. All stakeholders consider a dramatic change to move from no energy to the agreed energy. Therefore, variations on the total amount of energy did not help to prioritise among technologies as much as variations of local energy resources. Local energy resources are critical to ensure the endogenous and autonomous development of the community and accumulated most of the preferences of the Technical cluster.

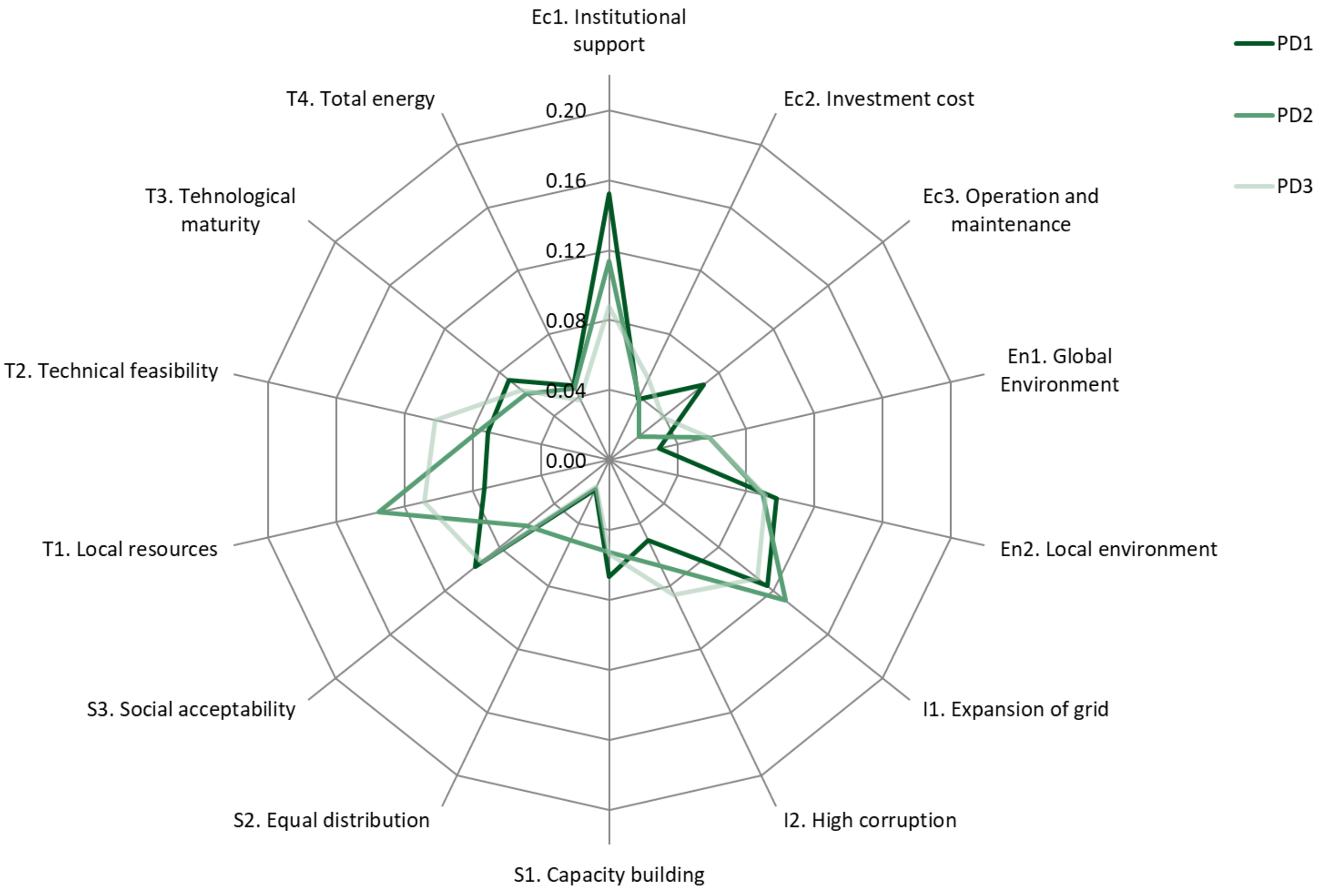

Figure 3. Relative importance of the criteria for the project designers

Figure 4 shows that rural development agents present a similar profile to project designers, with higher importance assigned to criteria T1: Local resources, I1: Expansion of the grid, Ec1: Institutional support, and En2: Local environment. According to the development agents, in this project the least influential criteria are Ec3: Operation and Maintenance costs, S2: Equal distribution, and T3: Technological maturity. Besides, overall, agents showed more agreement on the influence of the criteria than project designers.

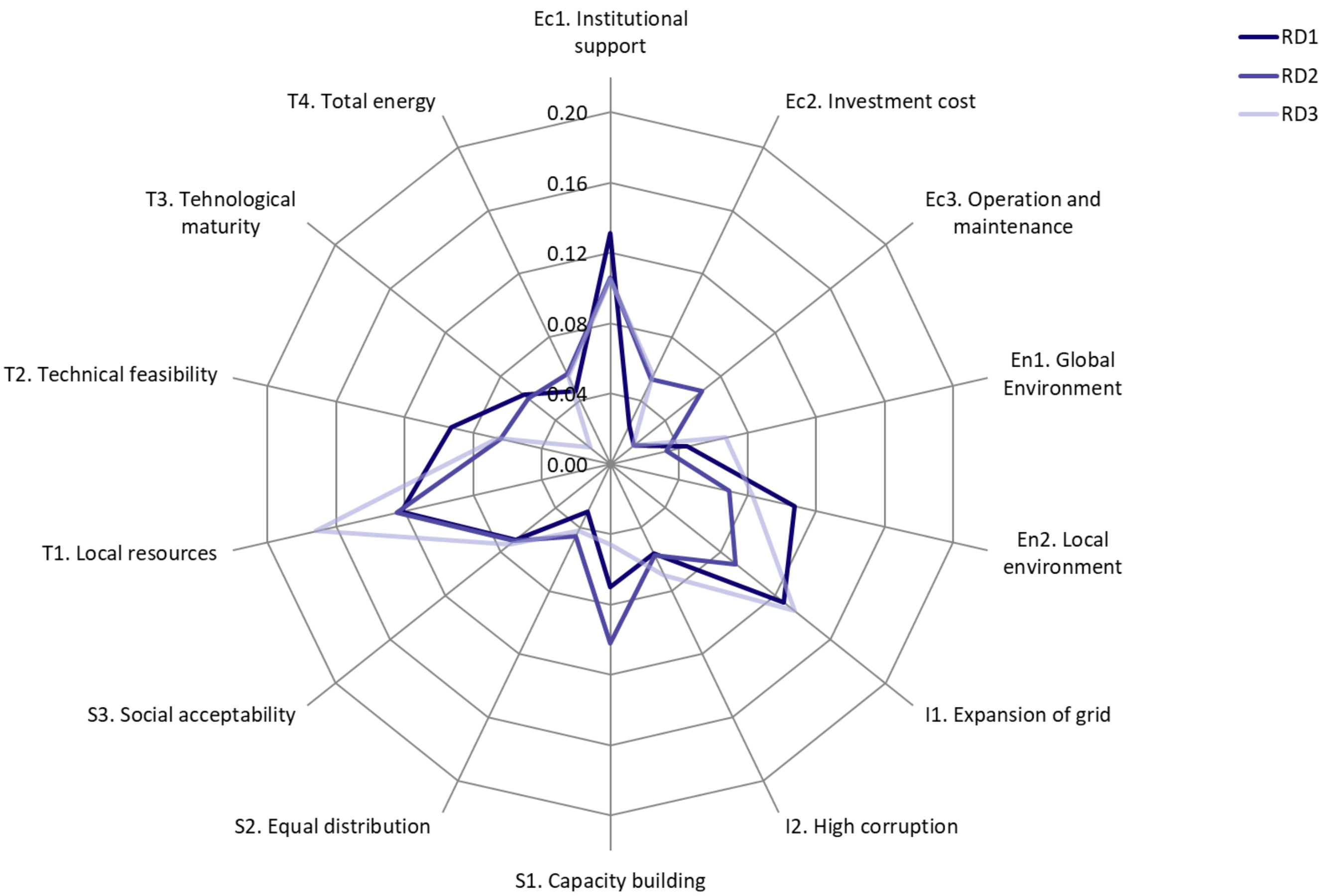

Figure 4. Relative importance of the criteria for rural development agents

Again, it is interesting to discuss why development agents gave such little importance to the social factors, which could be a priority for them. Actually, all experts have considered social aspects to be more related to the distribution of the electricity than to the generation of the electricity. The decision problem of this case study was mainly the generation and backup technologies, while grid topology did not change in any case. Therefore, rural development agents considered the cluster of social criteria less influential than the other clusters; and its elements have less influence to share.

Policy makers in Figure 5 also rank order Ec1: Institutional support and I1: Expansion of the grid and T1: Local resources as the most influential, but they clearly value the rest of criteria less. Again, S2: Equal distribution and Ec3: Costs of operation and maintenance have less importance in El Santuario project. In this group, one of the experts presented significant differences from the others, both in the criteria and the alternatives. Later, differences among alternatives are discussed.

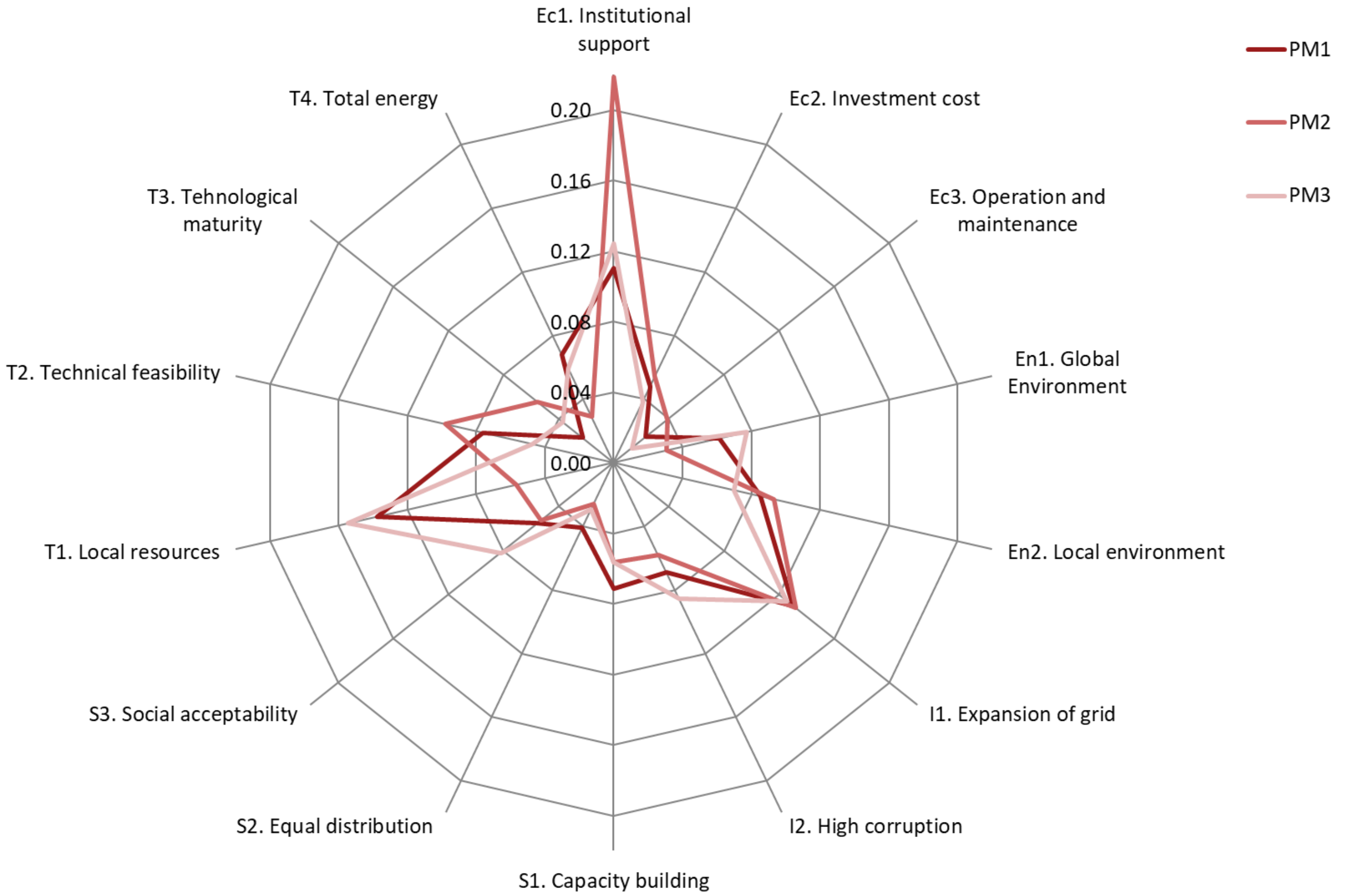

Figure 5. Relative importance of the criteria for the policy makers

When asked why the institutional factor I1: Expansion of the grid was so influential, the experts argued similarly for the importance of criterion Ec1. The institutional decisions are relevant for the prioritisation of the alternatives. And then, between the probability of the expansion of the grid up to the community and the possibility of corrupt public officers, the former contributed clearly more than the latter to prefer some technologies over the others.

Also, the comparison between the elements of the cluster Environment yields some interesting discussion. The project presents alternatives that are respectful with the environment, with the exception of the diesel generator, and the project is sensitive to the local community. In this context, all experts agreed on assigning more influence to the combination of local environmental impacts (En2.) than to the combination of global environmental impacts (En1.), even if the latter included the worrying Climate Change. Indeed, almost all technologies have low global environmental impacts, but they potentially have different local environmental impacts that establish clear differences among them. For example, diesel generators produce noise and emissions while photovoltaic panels pressurise land availability.

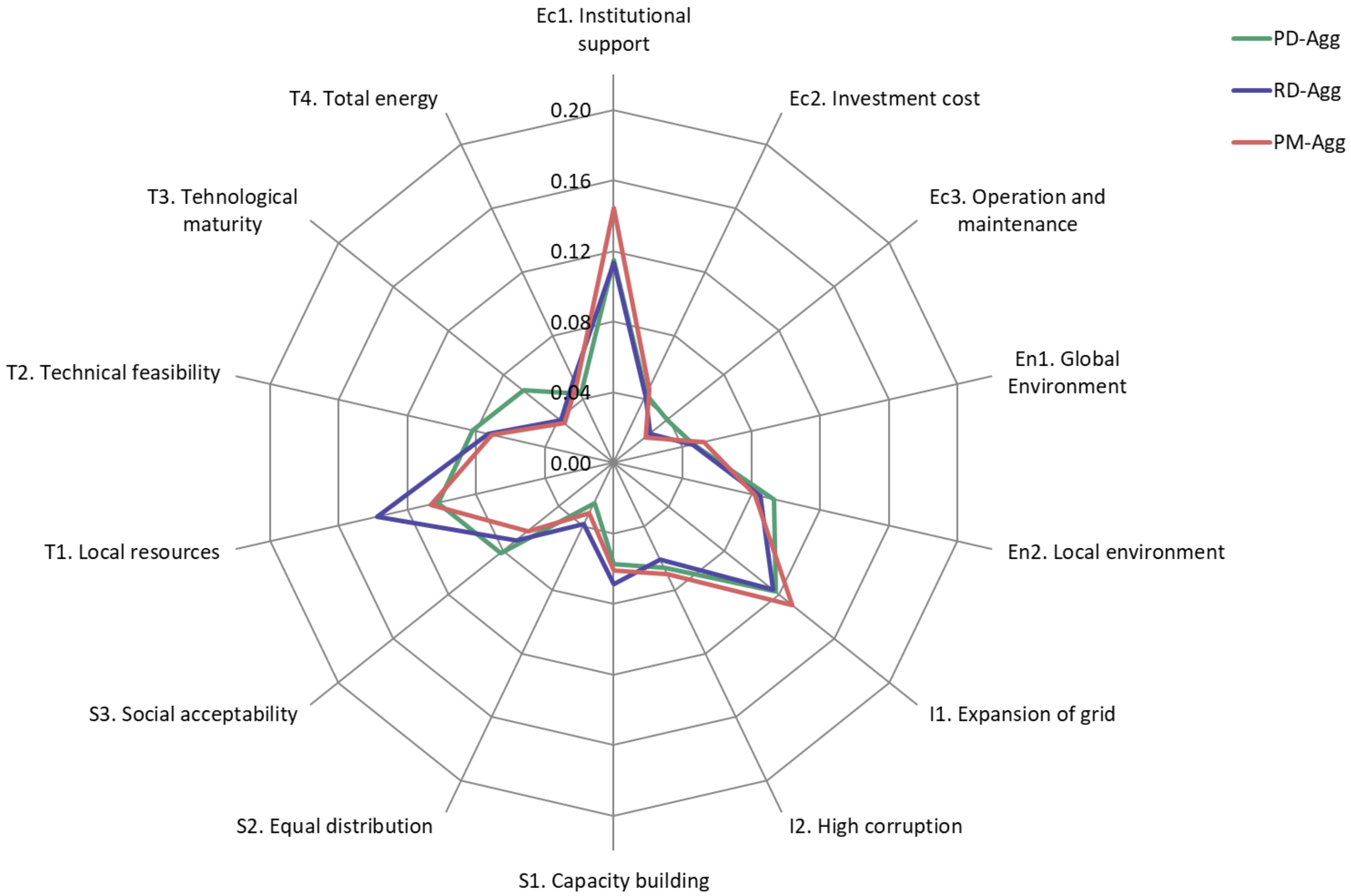

Figure 6. Aggregated relative importance of the criteria by stakeholders' group

To end this section, Figure 6 shows the results of entering in the ANP calculations the aggregation of the judgements of all experts of each role. For that, aggregation uses the Geometric Mean as prescribed by Saaty [92]. The differences among experts compensate and the average numbers are more moderate. Besides, the profile of the three groups coincide considerably, and this is not usual, and we associate it with the particular characteristics of the project.

4.3. Prioritisation of the energy technologies.

Figure 7 shows the preferences for alternatives after aggregating all the experts' judgments. Therefore, in the HRESs for El Santuario, Honduras, the preferred energy technology is solar PV, followed by wind generation and the gasification of biomass. All three clearly differentiated in preference. For the dispatchable technology in the HRESs, the biomass gasifier is preferred to the diesel generator and the batteries, which both score similarly.

Indeed, the final solution opts for Solar PV as the main energy source against wind, selecting among the two non-dispatchable technologies. Batteries accompanied with a biomass gasifier as the preferred back up since they provide emissions free electricity compared with the diesel generator. Moreover, and in agreement with the community, the low preference of batteries lead to a design were the gasifier plays a more active role than a mere back up. The community prefers to rely on a sustainable consumption of local dry biomass to an intensive use of batteries that will shorten their lifespan, or to devote a higher share of the investment to such a sensitive asset.

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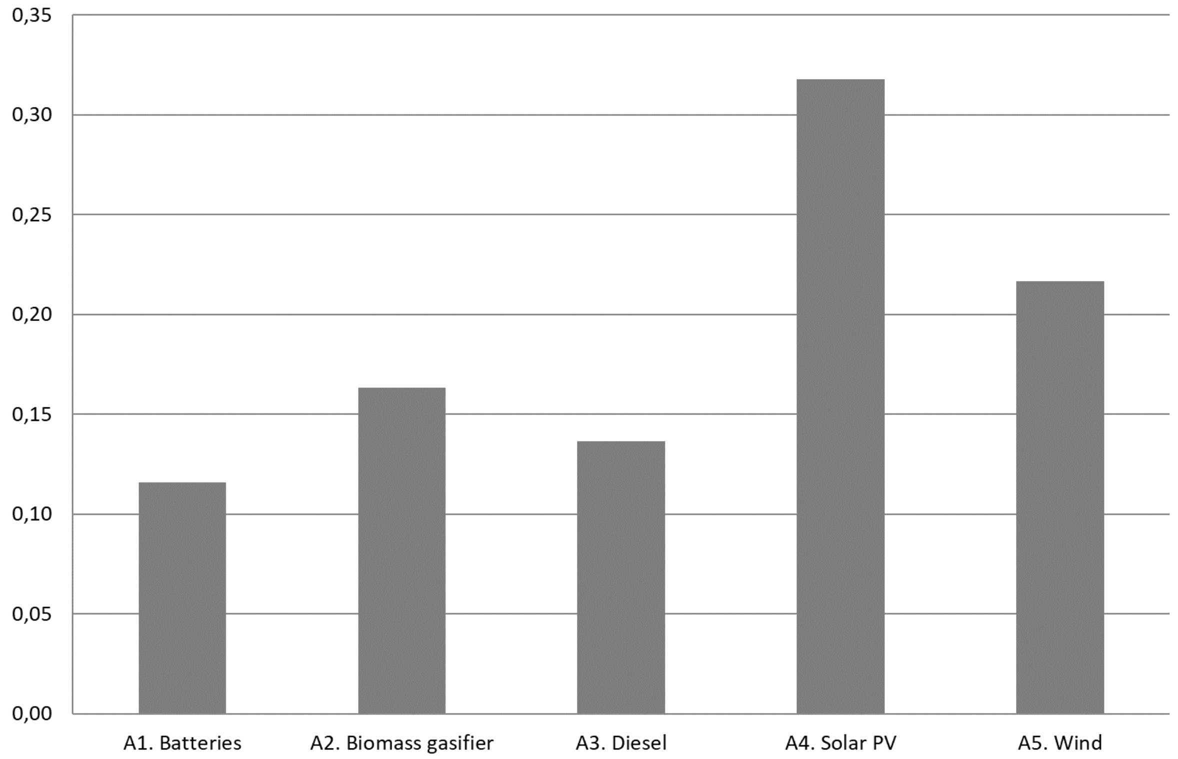

Figure 7. Aggregated relative importance of the energy technologies

Figure 8 shows the rank order of alternatives by expert, again grouped by role. The bars show the relative importance of each alternative, all the values add one for a particular expert. Again, experts tend to agree with their group members, but there is a policy maker that clearly disagrees. This is due to the great difference among the profiles of policy makers. While two of them have a wide experience with biomass systems and have supported them in the past, the other has mainly worked with solar PV plants and he presents bias towards this option. In conclusion, an adequate panel of experts must include not only representatives of all the important stakeholders, but also experts of the different profiles and disciplines involved. The discrepancies among all representatives of a certain stakeholder are relevant, as figure 8 shows.

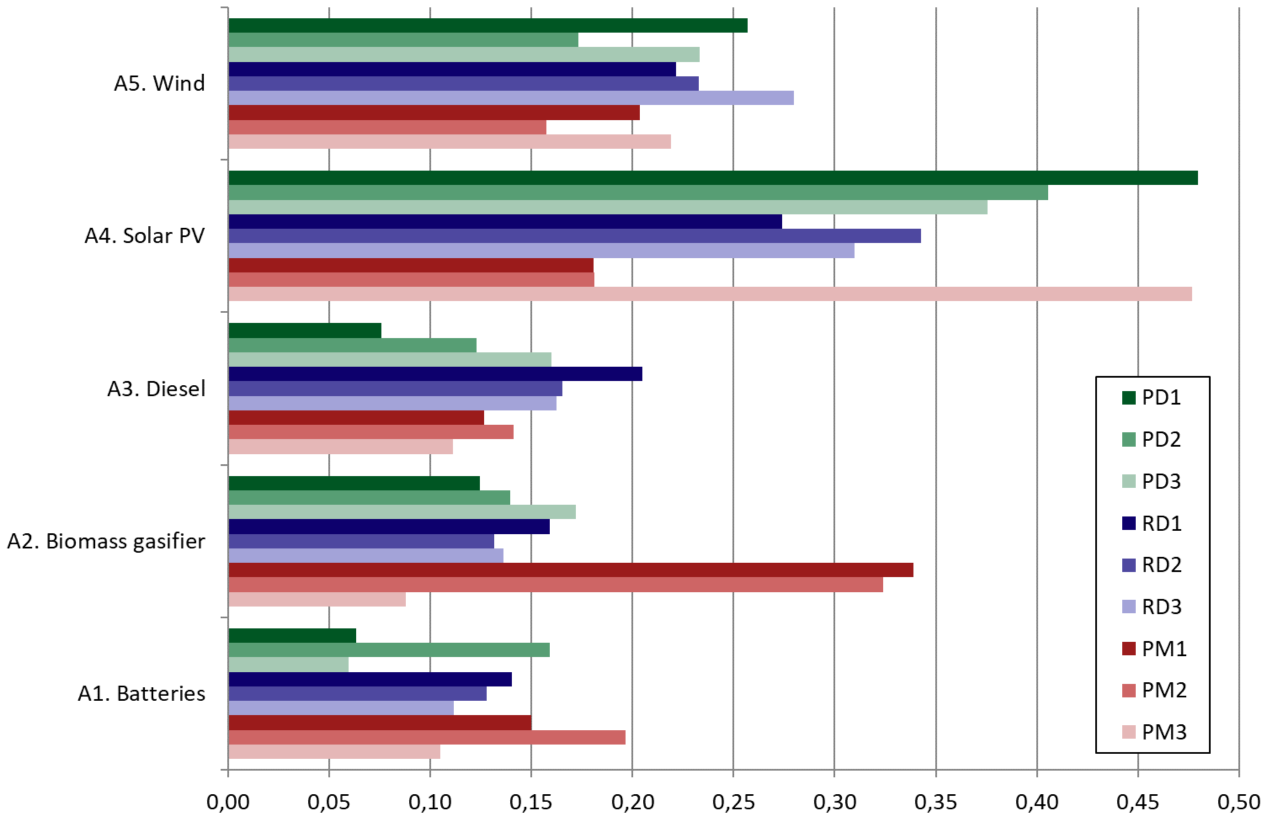

Figure 8. Relative importance of the energy technologies

4.4. Partial analysis. Influence of the criteria on the alternatives.

ANP also allows partial studies, for example how the criteria influence each alternative. Figure 9 shows the weighted supermatrix of the procedure, which presents these influences. For the analysis, again the ANP procedure introduces the aggregation of the experts' judgments. This partial analysis allows us to understand the general results better. Starting with what Figure 9 shows, Ec3: Operation and Maintenance costs are very influential for Diesel Generators, En2: Local environmental impacts is very influential in the case of the biomass gasifier, Batteries are the most expensive technology by investment (Ec1), and factor T1: Local resources have little influence on batteries and the diesel generator.

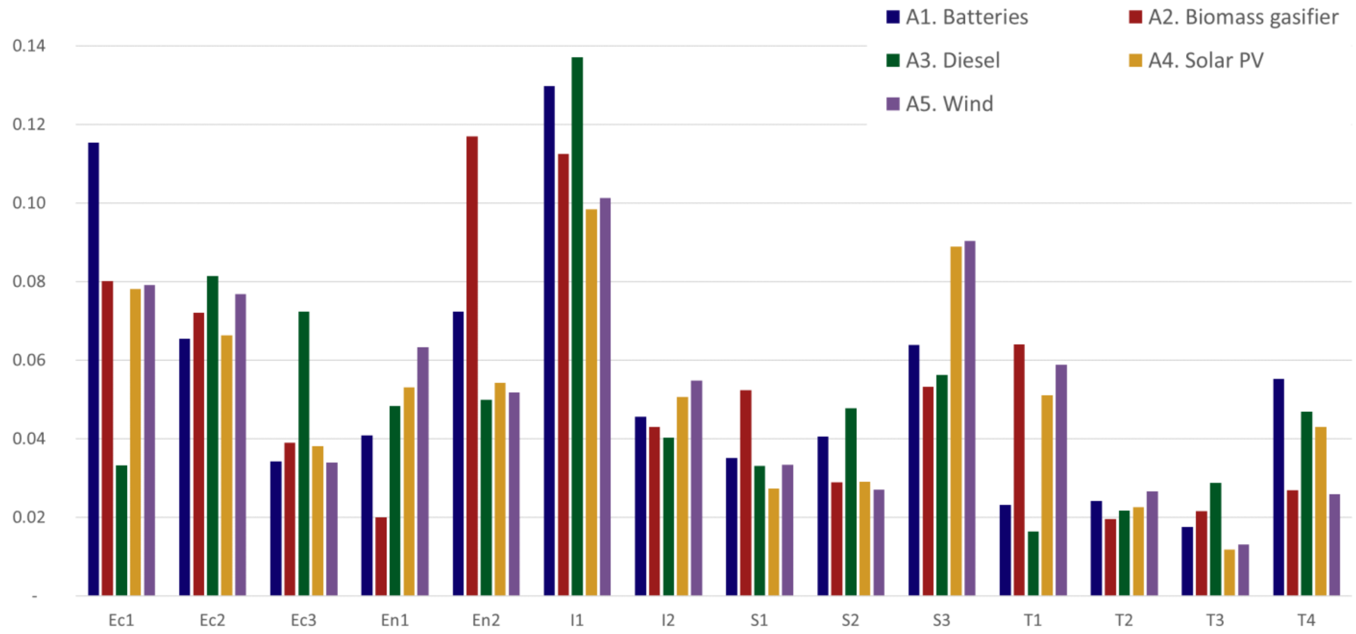

Figure 9. Relative importance of criteria by energy technologies

However, it came as a surprise that factor S3: Social acceptability shows a higher influence on alternatives than the importance experts gave this factor. When we checked the influences among factors in the weighted supermatrix, S3 may be influential as regards alternatives, but itself is a factor with little influence on the others. The contrary happens with T1: Local resources, that shows a somehow lower than expected overall influence on alternatives, although it influences many other criteria.

Figure 10 shows another ANP partial analysis, how experts rank ordered alternatives by criterion. If applied to the more influential criteria, it shows what are the preferred alternatives for those criteria and contributes to their assessment.

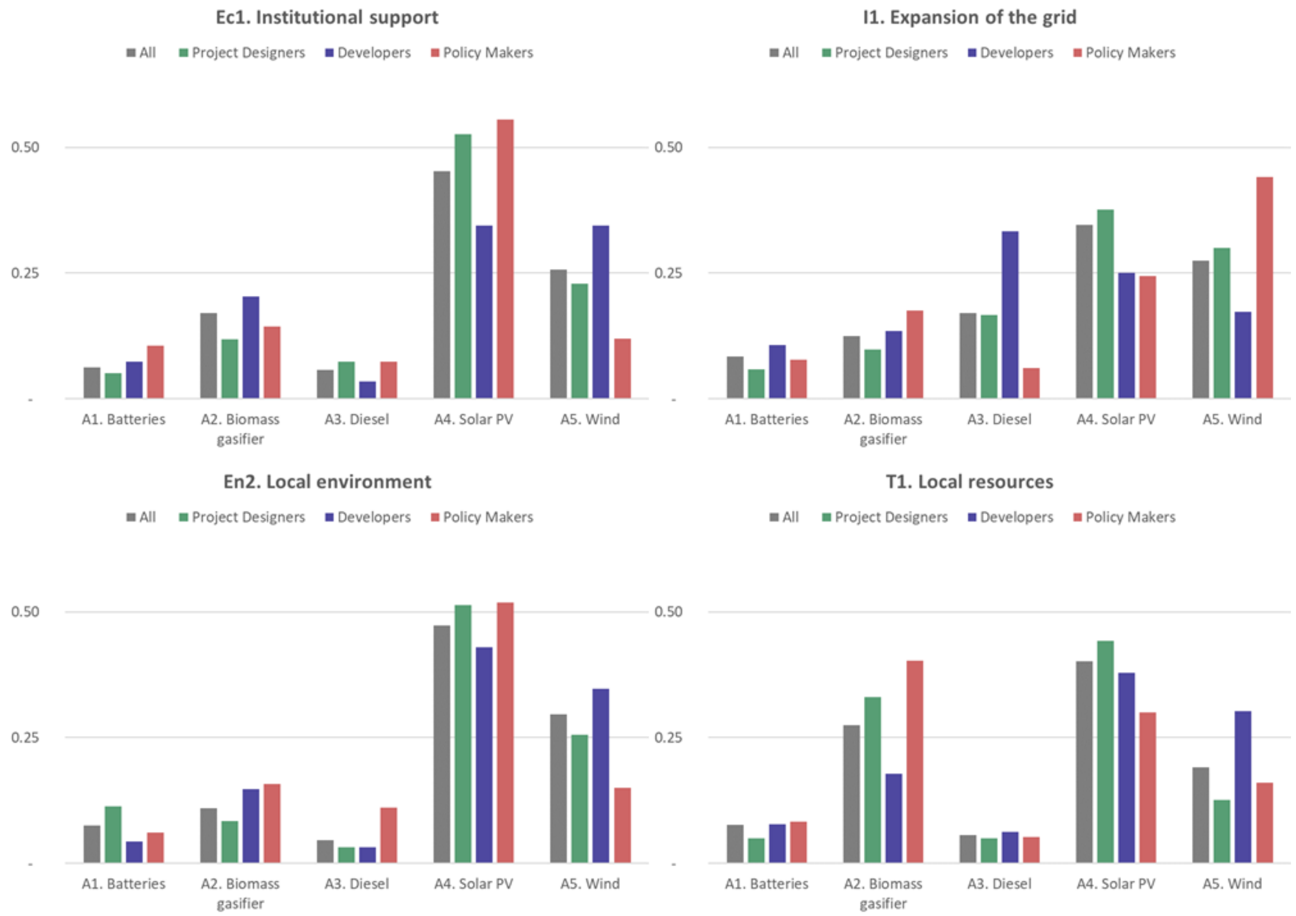

Figure 10. Relative importance of energy technologies by most relevant criteria

As expected, experts generally prefer the solar photovoltaic to the others for each influential criterion. Wind generators follow, except from the point of view of the availability and use of local resources, where the gasifier scores higher. Criteria Ec1., En2. and T1. penalise the diesel generator, which becomes interesting for experts only if the institutions plan to develop the electric grid to reach the community in the short term.

5. Conclusion

To fulfil the UN's Sustainable Development Goal 7 by 2030, millions of inhabitants of isolated rural areas will likely opt for islanded microgrids. Furthermore, these microgrids must be sustainable and for that, they should rely on local renewable energy resources. A combination of different dispatchable and non-dispatchable energy technologies can ensure a reliable continuous supply of energy. This complex technical design must be combined with a thorough social analysis. However, the outcomes of such work are normally qualitative, may be uncertain and frequently debatable without agreement among the stakeholders. This work proposed a methodology to bridge and combine the two realms. By means of ANP and the expert knowledge of representatives of the main stakeholders, the technical and social factors can be combined, informing the selection of technologies before the detailed design of the HRESs.

On the one hand, ANP is a valid methodology for decision making in situations of qualitative and uncertain information, where variables relate to each other. Nevertheless, to the knowledge of the authors, no research has applied ANP to designing the configuration of an HRES. On the other hand, it remains unclear how designers combine the two realms of information in their HRES design. Too often, technical and economic factors are the only influential ones and designers overlook social or institutional factors. Hence, this research aims to strengthen HRES design practice, mainly in its first and critical steps. ANP also allows us to carry out partial analysis to better understand experts' judgements. These analyses include the partial influence of criteria on Alternatives, the influence among criteria or the scores of alternatives for certain criteria. This information feeds a discussion about the particularities of the outcomes with experts.

The first and general findings of the research are the following. First, a complete list of 23 influential criteria for the configuration of an HRES to deliver electricity to poor communities based on an extensive literature review. Experts and stakeholders of these projects should initially consider these factors. However, they must be adapted to each case. Second, the proposed methodology explained in Figure 1, which experts may use with the necessary adaptation to each project and context.

To illustrate the viability of the methodology and the need to adapt it to each context, the article presents a case study of an energy poor community in the Honduran Mesoamerican Dry Corridor. The methodology guides the decision over the design of an islanded HRES to supply electricity. Three panels of experts, one per each main project-design stakeholder group provided, their opinions throughout the project. Each panel itself, included three experts with the same role but different profiles. In our case, experts mainly agreed on their conclusions. However, in other cases this might not happen and a decision must be taken about which experts' opinion should be followed. Based on the initial list and the field work, the experts agreed on a final list of 14 influential criteria grouped in 5 clusters: economic, environmental, institutional, social and technical. The number of viable energy technologies was 5, which formed a new cluster of the ANP model. The outcomes of the method state that the most influential criteria by order of importance are institutional support, the possible expansion of the grid and local energy resources. The preferred energy technologies in the case of El Santuario are Solar PV, wind power and a biomass gasifier.

Currently, the HRES for El Santuario includes a solar PV power plant as large as the energy demand, the local sun radiation and the foreseen budget allow. To combine it with a dispatchable energy technology, a biomass gasifier that will use the local biomass resource is also part of the system. The wind power alternative and the diesel generator have been discarded in accordance with the outcomes of the method in favour of Solar PV and a Biomass gasifier. Finally, a bank of batteries will also be added as the gasifier needs an electric supply to be turned on and off. Batteries will be as reduced as possible based on the case study results.

Acknowledgements

We really appreciate the help of our four experts in the field. Without them, we could not have carried out the research.

This is an extended and updated version of a paper originally presented at the 14th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES 2019) held in Dubrovnik, Croatia over the period 1st to 6th October 2019 (denoted then as paper SDEWES2019.0565 - Choosing the best configuration for a hybrid microgrid of renewable energy sources by means of the analytic network process).This work was supported in part by the Spanish public administration under grant FPU2016/00962, by the regional public administration of Valencia under grant ACIF/2018/106, by the Food and Agriculture Organisation under the Letter of Agreement (PO number: 332412). And finally, by the Cátedra de Transición Energética Urbana (Las Naves-UPV).

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