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Methodology for the evaluation and design of projects considering multiple criteria and uncertainty. Application to the development of energy projects in rural areas.

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Contents

ABSTRACT

In 2015, the United Nations defined the Sustainable Development Goals in a transition towards a world without poverty and where human rights, equity and sustainability are prioritized. In particular, modern energy services are considered crucial not only to achieve universal access to energy by 2030, but due to their contribution to alleviate chronical poverty, reduce food insecurity, promote the access to modern information in schools and enhance the start of productive activities. However, the aim of global access by 2030 is still far from being complete, with more than 700 million people living in rural areas without access to electricity and using firewood and other polluting traditional biomass for cooking and heating. Decentralized energy systems are gaining attention as a more feasible solution than grid extension to provide energy to rural and inaccessible areas. The evaluation and design of decentralized systems is a complex process that needs to take into account multiple alternatives and criteria to ensure a long-term sustainability, but usually available studies in literature focus exclusively in technical and economic aspects. Also, the minority of studies following a multicriteria decision-making approach underestimate the effect of the potential lack of confidence of the experts and users consulted to weight the importance of each criterion or to evaluate a specific alternative.

In this context, the objective of this thesis is to develop multicriteria procedures considering uncertainty to increase the robustness of the results. These procedures are applied to projects that foster access to energy services and promote therefore the development of rural and underprivileged areas. The thesis begins with two multicriteria procedures presented for the evaluation and the design, respectively, of rural electrification projects. These procedures are applied to two real case studies in Peru and Nigeria. Both applications provide valuable insights, for local authorities and other promoters of electrification systems in similar contexts, regarding which technologies and configurations to use in determined circumstances. At the same time, the analysis carried out enable an improvement regarding the robustness of results through the consideration of the lack of confidence of the opinions collected about the importance of the criteria and the evaluation of the alternatives.

In this regard, A Methodology for Multicriteria Decision-making considering Uncertainty (MIMDU) is then developed based on fuzzy numbers to include the lack of confidence experts and users might have when weighting a criterion or evaluating an alternative. The methodology designed includes a novel procedure to quantify human opinions with non-pre-defined fuzzy numbers and a systematic process to calculate diverse rankings of alternatives and provide complimentary information that leads to a more robust decision-making. Indeed, the potential of the methodology is illustrated with an example case that shows how the lack of confidence can affect the alternatives ranking and the subsequent decision. Finally, the methodology is applied to a real case study in Colombia to select the best alternative for digestate post-treatment before its application to agricultural soil as a fertilizer.

The use of MIMDU presents three major beneficial outcomes for multicriteria decision-making to foster rural development. First, the consideration of the lack of confidence of the respondents can reduce the pressure they might feel when providing an answer without complete knowledge. Second, it allows a more accurate quantification of the opinions given, turning, for example, more hesitant answers into less reliable evaluations of an alternative, that worsens its final ranking. And third, more robust decisions can be taken due to the major precision in the modelling of opinions and the possibility of comparing crisp and fuzzy-based rankings of the alternatives.

RESUM

El 2015, l'Organització de les Nacions Unides va definir els objectius de desenvolupament sostenible en una transició cap a un món sense pobresa i on es prioritzen els drets humans, l'equitat i la sostenibilitat. En particular, els serveis energètics moderns es consideren crucials no només per aconseguir l'accés universal a l'energia el 2030, sinó per la seva contribució a pal·liar la pobresa crònica, reduir la inseguretat alimentària, promoure l'accés a la informació moderna a les escoles i permetre l'inici d'activitats productives. Tot i això, l'objectiu d'accés mundial per al 2030 encara està lluny d'acomplir-se, ja que més de 700 milions de persones viuen a les zones rurals sense accés a l'electricitat i utilitzen llenya i altres biomasses tradicionals contaminants per cuinar i escalfar. Els sistemes energètics descentralitzats guanyen pes respecte l'extensió de la xarxa per proporcionar energia a zones rurals i inaccessibles. L'avaluació i el disseny d'aquests sistemes és un procés complex que ha de tenir en compte múltiples alternatives i criteris per garantir una sostenibilitat a llarg termini, però els estudis de literatura disponibles generalment se centren exclusivament en aspectes tècniques i econòmiques. A més, la minoria d'estudis que segueixen un enfocament multicriteri subestimen l'efecte de la manca de confiança potencial dels experts i usuaris consultats per ponderar la importància de cada criteri o avaluar una alternativa específica.

En aquest context, l'objectiu d'aquesta tesi és desenvolupar procediments multicriteri considerant la incertesa per afavorir l'obtenció de resultats robustos. Aquests procediments s'apliquen a projectes que afavoreixen l'accés als serveis energètics i promouen, per tant, el desenvolupament de zones rurals i desfavorides. La tesi comença amb dos procediments multicriteri presentats per a l'avaluació i el disseny, respectivament, de projectes d'electrificació rural. Aquests procediments s'apliquen a dos casos pràctics reals al Perú i Nigèria. Ambdues aplicacions proporcionen informació valuosa, per a les autoritats locals i altres promotors de sistemes d'electrificació en contextos similars, sobre quines tecnologies i configuracions a utilitzar en determinades circumstàncies. Al mateix temps, les análisis realitzades permeten una millora en quant a la solidesa dels resultats mitjançant la consideració de la manca de confiança de les opinions recollides sobre la importància dels criteris i l'avaluació de les alternatives.

Per fer-ho, es desenvolupa una metodologia per a la presa de decisions multicriteri que té en compte la incertesa (MIMDU) basada en nombres difusos per incloure la manca de confiança que els experts i usuaris podrien tenir quan ponderen un criteri o avaluen una alternativa. La metodologia dissenyada inclou un nou procediment per quantificar opinions humanes amb nombres difusos no predefinits i un procés sistemàtic per calcular diversos rànquings d'alternatives i proporcionar informació complementària que condueix a una presa de decisions més robusta. De fet, el potencial de la metodologia s'il·lustra amb un cas d'exemple que mostra com la manca de confiança pot afectar el rànquing d'alternatives i la decisió posterior. Finalment, la metodologia s'aplica a un estudi de cas real a Colòmbia per seleccionar la millor alternativa per al post-tractament del digestat abans de la seva aplicació a sòl agrícola com a fertilitzant.

L'ús de MIMDU presenta tres grans beneficis per a la presa de decisions multicriteri per fomentar el desenvolupament rural. En primer lloc, la consideració de la manca de confiança dels enquestats pot reduir la pressió que podrien sentir al donar una resposta sense coneixement complet. En segon lloc, permet una quantificació més precisa de les opinions donades, convertint, per exemple, respostes més dubtoses en avaluacions menys fiables d'una alternativa, que empitjora la seva classificació final. I, en tercer lloc, es poden prendre decisions més robustes a causa de la precisió en la modelització d'opinions i la possibilitat de comparar rànquings deterministes i difusos de les alternatives.

RESUMEN

En 2015, la Organización de las Naciones Unidas definió los Objetivos de Desarrollo Sostenible en una transición hacia un mundo sin pobreza y donde se priorizan los derechos humanos, la equidad y la sostenibilidad. En particular, los servicios energéticos modernos se consideran cruciales no solo para lograr el acceso universal a la energía en 2030, sino por su contribución para aliviar la pobreza crónica, reducir la inseguridad alimentaria, promover el acceso a la información en las escuelas y permitir el inicio de actividades productivas. Sin embargo, el objetivo de acceso global a la energía para 2030 aún está lejos de ser completo, con más de 700 millones de personas viviendo en áreas rurales sin acceso a electricidad y utilizando leña y otra biomasa tradicional contaminante, para cocinar y calentar. Los sistemas de energía descentralizados están ganando peso respecto a la extensión de la red para proporcionar energía a áreas rurales e inaccesibles. La evaluación y el diseño de sistemas descentralizados es un proceso complejo que precisa considerar múltiples alternativas y criterios para que sea sostenible a largo plazo, pero los estudios disponibles en la literatura generalmente se enfocan exclusivamente en aspectos técnicos y económicos. Asimismo, la minoría de estudios que siguen un enfoque de toma de decisiones multicriterio subestiman el efecto de la potencial falta de confianza de los expertos y usuarios consultados para ponderar la importancia de cada criterio o para evaluar una alternativa específica.

En este contexto, el objetivo de esta tesis es desarrollar procedimientos multicriterio considerando la incertidumbre para aumentar la robustez de los resultados. Estos procedimientos se aplican a proyectos que fomentan el acceso a los servicios energéticos y, por tanto, promueven el desarrollo de zonas rurales y desfavorecidas. La tesis comienza con dos procedimientos multicriterio presentados para la evaluación y el diseño, respectivamente, de proyectos de electrificación rural. Estos procedimientos se aplican a dos estudios de casos reales en Perú y Nigeria. Ambas aplicaciones pueden proporcionar información valiosa, para las autoridades locales y otros promotores de sistemas de electrificación en contextos similares, sobre qué tecnologías y configuraciones utilizar en determinadas circunstancias. Al mismo tiempo, los análisis realizados permiten una mejora en cuanto a la robustez de los resultados a través de la consideración de la falta de confianza de las opiniones recogidas acerca de la importancia de los criterios y de la evaluación de las alternativas.

Para ello, se desarrolla una Metodología para la toma de decisiones multicriterio considerando la incertidumbre (MIMDU) basada en números difusos para incluir la falta de confianza que los expertos y los usuarios pueden tener al ponderar un criterio o evaluar una alternativa La metodología diseñada incluye un procedimiento novedoso para cuantificar opiniones humanas con números difusos no predefinidos y un proceso sistemático para proponer rankings de alternativas y brindar información complementaria que conduce a una toma de decisiones más robusta. El potencial de la metodología se ilustra con un caso de ejemplo que muestra cómo la falta de confianza puede afectar el ranking de alternativas y la decisión posterior. Finalmente, la metodología diseñada se aplica a un estudio de caso real en Colombia para seleccionar la mejor alternativa para el digestato post-tratamiento previo a su aplicación al suelo agrícola como fertilizante.

El uso de MIMDU presenta tres importantes beneficios para la toma de decisiones multicriterio en contextos de desarrollo rural. En primer lugar, la consideración de la falta de confianza de los encuestados puede reducir la presión al dar una respuesta sin un conocimiento completo. En segundo lugar, permite una cuantificación más precisa de las opiniones emitidas, convirtiendo, por ejemplo, respuestas más vacilantes en valoraciones menos fiables de una alternativa, que empeora su clasificación final. Y tercero, se pueden tomar decisiones más sólidas debido a la mayor precisión en el modelado de opiniones y la posibilidad de comparar rankings deterministas y difusos de las alternativas.

1. INTRODUCTION

This first chapter defines the context and research interest of this PhD thesis (1.1), leading to the main objectives and research questions tackled (1.2). Finally, the content of the whole document is summarized (1.3).

1.1 PRESENTATION AND RESEARCH INTEREST

In 2015, the United Nations agree in a set of initiatives that aim to eradicate poverty in a transition towards a world where human rights, equity and sustainability are prioritized [UN, 2015]. These initiatives conform the 17 Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development, finally adopted in January of 2016 [UN, 2016]. In particular, universal access to reliable and affordable energy services is a key aspect of SDG7, and has a strong connection with all the other goals [McCollum et al., 2018]. Thus, modern energy services, such as electricity, clean cook-stoves or high-quality lighting have direct implications to other sustainable goals. For example, they contribute to:

- Alleviate chronic poverty (SDG1) and release resources (i.e. time, money) for productive activities development (SDG5 and SDG10) [Akter et al., 2017];
- Improve food security by enhancing agricultural productivity through mechanization and a more efficient use of resources (SDG2 and SDG15) [Winter et al., 2015; Das, 2017];
- Reduce the depletion of natural resources, such as coal, oil or natural gas (SDG12) [Ham & Lee, 2017], and the associated respiratory diseases (SDG3) through the utilization of renewable energies [Cherian, 2015];
- Promote thermal comfort and modern information and communication technologies in schools (SDG4) [Collste et al., 2017];
- Reduce water scarcity through pumping, purification and desalination systems (SDG6) [Parkinson et al., 2016];
- Allow the development of new energy-related productive activities (SDG8) and organizations providing them with financial and technical support (SDG9) [Goldthau, 2014].

However, the goal of global access to energy services are still far from being completed, particularly in rural areas of developing countries. In detail, 840 million people live without access to electricity [IEA, 2019a], 87% of them (730.8 million) in rural and underprivileged areas [IEA, 2019b], mainly in Africa, Latin America and South-Asia [Eras-Almeida, 2020]. When rural areas achieve electricity access, its main application is for lighting and television, since their poor economic situation usually make other appliances, such as fridges, unaffordable [Khandker et al., 2013; Banal-Estañol et al., 2017]. On the other hand, a lack of high-quality energy access is also observed for cooking or heating the houses, leading 3 billion people to still rely on solid fuels like firewood or other biomass [World Bank, 2018; Pizarro-Loaiza et al., 2021]. The incomplete combustion of biomass in traditional cooking stoves release toxic emissions, such as carbon monoxide (CO) nitrous oxide (N_2O) methane (CH_4)

and other compounds [Bhattacharya et al., 2002], that cause serious impacts in human health and the environment nearby [Miah et al., 2009].

Traditional plans to extend energy access usually involve centralized generation systems and large infrastructures for distribution [Ferrer-Martí et al., 2012; Zheng-Yang et al., 2021]. This strategy has technical and economic limitations when it comes to reach rural and remote areas due to hilly terrain, scattered communities and low consumption levels [Ferrer-Martí et al., 2012] that make the investment in infrastructure non-profitable [IRENA, 2019]. Alternatively, off-grid decentralized energy systems are increasingly being used due to different reasons [IRENA, 2013; Lucas et al., 2020]: i) improved technologies that can be tailored to meet users' particular needs for electricity, cooking and heating; ii) sharp reduction of the costs that result on a greater affordability; and iii) greater knowledge about local resources and renewable energies which usually powers them. Focusing on electricity extension, off-grid systems may include individual systems for each user or microgrids (MGs) that connect part or the whole number of households in a shared-equipment situation. On the one hand, individual systems are a cheap and easy option but may arise inequalities within the community and are not easily adaptable to potential increases on demand [Ferrer-Martí et al., 2011]. On the other hand, MGs are able to provide a greater equity and flexibility in consumption, and cost savings through economies of scale [Ustun et al., 2011; Blechinger et al., 2019a]. Microgrid-based systems can also operate in on-grid mode and ensure a more reliable supply [Khodayar, 2017] if constraints due to terrain or other techno-economic factors are overcome.

Decentralized energy systems can use renewable and non-renewables technologies. In particular, solar photovoltaic (PV) is the most popular technology for decentralized electricity generation, followed by wind, micro hydro and diesel [López-González et al., 2018a; Duran & Shainyazan, 2021]. Solar PV allows a cheap extension of the electricity access thanks to the decrease of the price during the last 10 years [Gandini & Almeida, 2017]. Wind systems have been intensively studied during the last years [Gabra et al., 2019] since they offer attractive investment/production areas in windy areas [Ferrer-Martí et al., 2012]. Micro-hydro is an excellent option, where potential exists, as it is capable to provide a continuous supply with a small impact on the nearby environment [Chaujan & Saini, 2015]. Despite the global commit to renewable energy, diesel generators are still predominant in rural electrification projects in Africa [APP, 2017] and its use within the poorest regions is expected to grow in order to fulfill universal access to electricity in 2030 [Narula et al., 2012; López-González et al., 2018a]. Moreover, hybrid systems that combine two or more technologies are increasingly being used [Ranaboldo et al., 2014], such as solar PV and wind [Domenech et al., 2015], as they are able to complement each other and overcome the supply intermittency of electrification systems based on a single technology [Bertheau & Blechinger, 2018].

For cooking and heating, liquefied petroleum gas has been quantitatively proved to improve health in rural household when compared to traditional biomass, but still needs a gas station to be close to the communities [Twumasi et al., 2021]. To overcome such infrastructure barrier, local authorities and international organisations have pushed the implementation of small biogas digesters [Thu et al., 2012], since it is a simple and clean technique capable of meeting daily energy needs in remote and agricultural areas [Iannou-Ttofa et al., 2021]. Also, the digestion of organic manure in these biogas digesters not only produces biogas, but a liquid effluent called digestate which can be used as a highly efficient fertilizer to improve agricultural productivity [Garfi et al., 2016]. Thus, this technology contributes to the simultaneous generation of both energy and food, and enables therefore a more sustainable use of the available resources. Indeed, such interaction is identified as key for a global sustainable development by the Food and Agriculture Organisation of the United Nations (FAO) in its report about the water-energy-food nexus [FAO, 2014]. However, the direct application of the digestate to agricultural soil may not be safe, since it can contain pathogens and other harmful substances for the crops [Chong et al., 2022] and release greenhouse gas emissions, which is frequently regulated by law. Thus, digestate must be properly treated before application to soil in order to prevent health risks [Garfi et al., 2016] and improve its quality as a fertilizer.

Multiple and diverse factors have to be taken into account when designing decentralized systems providing energy access to ensure long-term sustainability [Rahman et al., 2013]. Despite the cost of the system is essential in such budget-limited projects, several studies are increasingly remarking the importance of considering other issues, such as the reliability of the system components [Adefarati et al., 2017], the existence of an institutional support through a solid regulation and public investment [Moreira et al., 2019] and the final users' acceptance [Domenech et al., 2015]. However, most of the tools and studies present in literature still focus only in cost-related indicators for designing energy systems. Thus, economic indicators are given major priority in commercialized tools widely used in developing countries, such as HOMER [Akella et al., 2007] and ViPOR [Lambert & Hittle, 2000; Williams & Maher, 2008], and in newer open-source tools, like OSeMOSYS [Howells et al., 2011] and Offgridders [Hoffmann, 2019]. At a regional level, recent example studies embedded in Blechinger et al., [2019b] and Corigliano et al., [2020] select the electrification plan according to the best levelized cost of electricity.

The consideration of multiple factors is more common when looking at studies that pretend to develop a procedure to assess the impact of already implemented electrification projects. Ilskog [2008] was the first to standardize a method to assess the overall promotion of rural development by defining 39 sustainability indicators grouped into five dimensions: technical; economic; social and ethical; environmental; and organizational and institutional. Other authors have also used the comparative dimensions in their studies. López-González et al. [2018b] evaluate environmental, technical, socio-economic and institutional aspects considered key for rural electrification projects based on renewable energies. Boliko & Ialnazov [2019] focus on the same dimensions to evaluate distinct systems distributions (mini-grids, individual systems, grid extension) to allow electric service. Ferrer-Martí et al. [2018] defined a three-level multicriteria methodology considering social, environmental, technical and economic aspects to prioritize the community in which a biogas digester should be implemented, and select the most appropriate model and design. Gómez-Hernández et al., [2019] defines a three-level methodology with ad-hoc criteria and indicators in each level. The methodology aims to assess rural electrification plans at a wider scale, focusing first on the general definition at a regional level, then on the technical design at local level and finally on the operation and maintenance management. Garfi et al., [2019] develops a life cycle assessment focusing on economic and environmental issues to assess the benefits of low-cost biogas digesters for small-scale farms in rural areas.

Multicriteria decision-making (MCDM) is a suitable approach to deal with multiple and diverse criteria aiming to reach a decision, either for the evaluation or design of projects to promote rural development [Opricovic & Tzeng, 2004; Domenech et al., 2015]. Specifically, MCDM establishes a framework for structuring decision problems and generating preferences from the available alternatives [Awashti et al., 2018] to ultimately ease the choice of the best one [Melvin, 2012]. Different methods and procedures have been developed in the framework of MCDM such as ELECTRE, TOPSIS, SURE or VIKOR [Cherni et al., 2007; Henao et al., 2012; Domenech et al., 2018], and are mostly used in order to reach a comprehensive and robust ranking of alternatives through mathematical formulations. The structure of such methods is similar [Wang et al., 2009]: first, a set of criteria is defined; second, the criteria are weighted according to their relative importance [Opricovic & Tzeng, 2004; Ferrer-Martí et al., 2018]; third, the alternatives are evaluated according to each criterion; and fourth, a global rank is calculated by aggregating the previous two steps [Wang et al., 2009].

Along this process, uncertainties can appear due to the difficulty of quantifying human reasoning [Zadeh, 1975] or the lack of confidence of experts when asked about the criteria weights or the alternatives evaluations. This lack of confidence can arise when the experts feel there is not enough information [Kim & Ahn, 2019] or due to limited knowledge [Garg, 2016]. Current MCDM methods in literature that take into account uncertainty deal suitably with the difficulty of quantifying human reasoning employing fuzzy linguistic scales (FLS). With FLS, an expert is required to choose from different terms (i.e. high or low, to rate the importance of a criterion), which are quantified through fuzzy numbers [Zadeh, 1965]. Such numbers allow a set of numerical values for each single linguistic term to be considered, overcoming quantification difficulties. However, the human reasoning process might be difficult to encompass in a single linguistic term without additional information [Rodríguez et al., 2012]. Also, FLS fail to consider the potential lack of confidence, since experts are required to solve their hesitance by themselves before answering.

In this context, the aim of this PhD thesis is to develop multicriteria procedures considering uncertainty in the criteria weighting and the alternatives evaluation to obtain robust results able to assist decision-making for the evaluation and design of energy systems for rural areas in developing countries.

1.2. OBJECTIVES

The main objective of this PhD thesis is to develop multicriteria procedures considering uncertainty to reach robust rankings of alternatives and provide reliable information to ease decision-making. These procedures are applied to foster the development of rural and underprivileged areas, assisting the evaluation and design of energy projects.

Two multicriteria procedures are first develop for the evaluation and design, respectively, of electrification projects for rural communities. The evaluation procedure embraces the experience of technical operators and final users of electrification systems based on different renewable energies and allows to identify advantages and disadvantages of each one as well as key aspects to ensure the sustainability of such projects. On the other hand, the design procedure presents a detailed framework to define numerous electrification systems for a rural community, including on-grid and off-grid systems and distinct technologies, and select the best one taking into account the opinion of experts in the field. These procedures are applied to two real case studies in Peru and Nigeria, respectively.

Lessons learned from those first two works regarding the data gathering method lead to the development of a methodology for multicriteria decision-making that considers uncertainty throughout its application. The methodology designed embraces a novel procedure to quantify human opinions employing non-pre-defined fuzzy numbers and states a systematic process to calculate complementary rankings of alternatives towards a more robust decision-making. The particular use of non-predefined fuzzy numbers allows both to more accurately model human opinions and to provide useful information to robustly take a decision. The whole potential of the methodology is first illustrated with an example case. Next, it is applied to robustly select the best alternative for digestate post-treatment before its use in agricultural soil as a fertilizer. This application is based on three small-scales farms in Colombia. The resemblance of the different rankings of alternatives calculated with a slight modification of parameters contribute to a robust decision of an alternative recommended for the three farms.

The specific objectives and the research questions that constitutes the motivation of this PhD thesis are now presented (Table 2.1). The chapter in which the sub-objective and research question is addressed is also stated.

Table 2.1. Specific objectives and research questions

Specific objectives and research questions	Chapter
Objective 1: Develop a multicriteria procedure to perform a long-term assessment of the adequacy of renewable-based electrification projects for rural areas	3
Question 1.1: Which criteria are relevant to consider when performing long-term evaluations of rural electrification systems based on renewable energies?	3
Question 1.2: Which factors clearly determinate the success of rural electrification projects over time?	3
Question 1.3: Which are the advantages and drawbacks of the generation sources and distribution configurations in renewable-based rural electrification projects?	3
Objective 2: Develop a multicriteria procedure to select the best electrification design to be implemented in a rural community	4
Question 2.1: Which alternative designs should be taken into account in the design of an electrification system for a rural community?	4
Question 2.2: Which criteria are relevant to consider in order to select a final design?	4
Question 2.3: In which conditions off-grid solutions should be fostered compared to on-grid designs?	4
Objective 3: Develop a methodology for integrated multicriteria decision-making with uncertainty to provide reliable information for the decision	5
Question 3.1: Which specific sources of uncertainty can influence responses in multicriteria decision-making?	5

Question 3.2: How questionnaires must be organized to model subjective opinions including all sources of uncertainty in an easy procedure?	5
Question 3.3: How should the information with uncertainty of such questionnaires be treated in order to rank alternatives?	5
Question 3.4: Which benefits can be expected of such treatment with uncertainty compared to a crisp multicriteria procedure?	5
Objective 4. Apply the developed methodology to perform a robust selection of the best alternative for digestate post-treatment in small-scale farms	6
Question 4.1: Which alternatives for digestate post-treatment in small-scale rural farms can be considered?	6
Question 4.2: Which criteria are relevant to consider to select the most appropriate option of digestate post-treatment for rural small farms?	6
Question 4.3: Which advantages offer the proposed robust multicriteria methodology in the selection of the best alternative for digestate post-treatment, compared to other techniques?	6
Question 4.4: Which are the advantages and drawbacks of each alternative and which can be recommended?	6

1.3 CONTENT

This PhD thesis is organized as a compendium of papers. Thus, the next chapters aim to first define the methodology followed throughout the thesis, then present the papers that sustain it, and finally conclude the work. The necessary references to literature are detailed at the end of each chapter.

The specific structure of the next chapters is the following:

- Chapter 2 presents the general scheme of the methodology followed for the development of this PhD thesis and link the papers included together.

- Chapter 3 contains the first paper of this thesis. A multicriteria evaluation of stand-alone electrification projects implemented in rural communities with different options for electricity generation and distribution is performed. The evaluation is concluded with a collection of advantages and disadvantages of each technology and the identification of key aspects to ensure projects' success. The reference of the paper is the following:

  M. Juanpera, B. Domenech, L. Ferrer-Martí, A. Garzón, R. Pastor. Renewable-based electrification for remote locations. Does short-term success endure over time? A case study in Peru. Renewable and Sustainable Energy Reviews 146 (2021) 111177. https://doi.org/10.1016/j.rser.2021.111177

- Chapter 4 contains the second paper of this thesis. A multicriteria design of electrification systems for rural communities is developed, taking into account renewable and non-renewable technologies for electricity generation and the potential connection to the national grid. Conclusions of the study identify the best options according to community features such as acceptance of the technologies, size, peak demand and distance to the national grid. The reference of the paper is the following:

M. Juanpera, P. Blechinger, L. Ferrer-Martí, M.M. Hoffmann, R. Pastor. Multicriteria-based methodology for the design of rural electrification systems. A case study in Nigeria. Renewable and Sustainable Energy Reviews 133 (2020) 110243. https://doi.org/10.1016/j.rser.2020.110243

- Chapter 5 contains the third paper of this thesis. A methodology for multicriteria decision-making considering uncertainty is developed to ensure robustness of the results. The methodology is based in fuzzy numbers and a novel procedure to model human opinions and rank the alternatives. The study is concluded with an example case to show the potential of the methodology to accurately model uncertainty and provide robust results. The reference of the paper is the following:

  M. Juanpera, B. Domenech, L. Ferrer-Martí, A. García-Villoria, R. Pastor. Methodology for integrated multicriteria decision-making with uncertainty: Extending the compromise ranking method for uncertain evaluation of alternatives. Fuzzy Sets and Systems (2021). https://doi.org/10.1016/j.fss.2021.08.008

- Chapter 6 contains the fourth paper of this thesis, to be submitted during the first term of 2022. The methodology developed is applied to robustly select the best alternative for digestate post-treatment before its use in agriculture. Specific recommendations are performed in this regard with a solid base due to the methodology employed. The reference of the paper is the following:

  M. Juanpera, L. Ferrer-Martí, R. Diez-Montero, I. Ferrer, L. Castro, H. Escalante, M. Garfí. A robust multicriteia analysis for the post-treatment and agricultural reuse of digestate from small-scale digesters. A case study in Colombia. To be submitted during the first term of 2022.

- Chapter 7 provides final conclusions on the overall work done and presents further lines of research to be developed during the following months.

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2. METHODOLOGY

This chapter presents the general scheme of the methodology followed for the development of this PhD thesis. The methodology includes three phases (Figure 2.1):

- Phase 1 (P1): This PhD thesis starts with two proposals based on multicriteria procedures to foster access to electricity of rural communities by first evaluating the impact on population of rural electrification projects and then designing systems taking into account distinct technologies. These two proposals correspond to two publishes papers (papers 1 and 2 of this thesis). Phase 1 is summarized in section 2.1 and presented in detail in chapters 3 and 4.
- Phase 2 (P2): In this phase, a methodology for multicriteria decision-making that takes into account uncertainty due to the potential lack of confidence when weighing the criteria and evaluating the alternatives is developed. The methodology allows to overcome limitations in the data acquisition found within the two proposals developed in phase 1 towards a major robustness of results. This phase lead to a publication of one paper (paper 3 of this thesis). Phase 2 is summarized in section 2.2 and presented in detail in chapter 5.
- Phase 3 (P3): This PhD thesis ends with the application of the developed methodology to robustly select the best alternative for digestate post-treatment before its use in soil as a high-quality fertilizer. This application originated the fourth paper of the thesis (to be submitted during the first term of 2022). Phase 3 is summarized in section 2.3 and presented in detail in chapter 6.

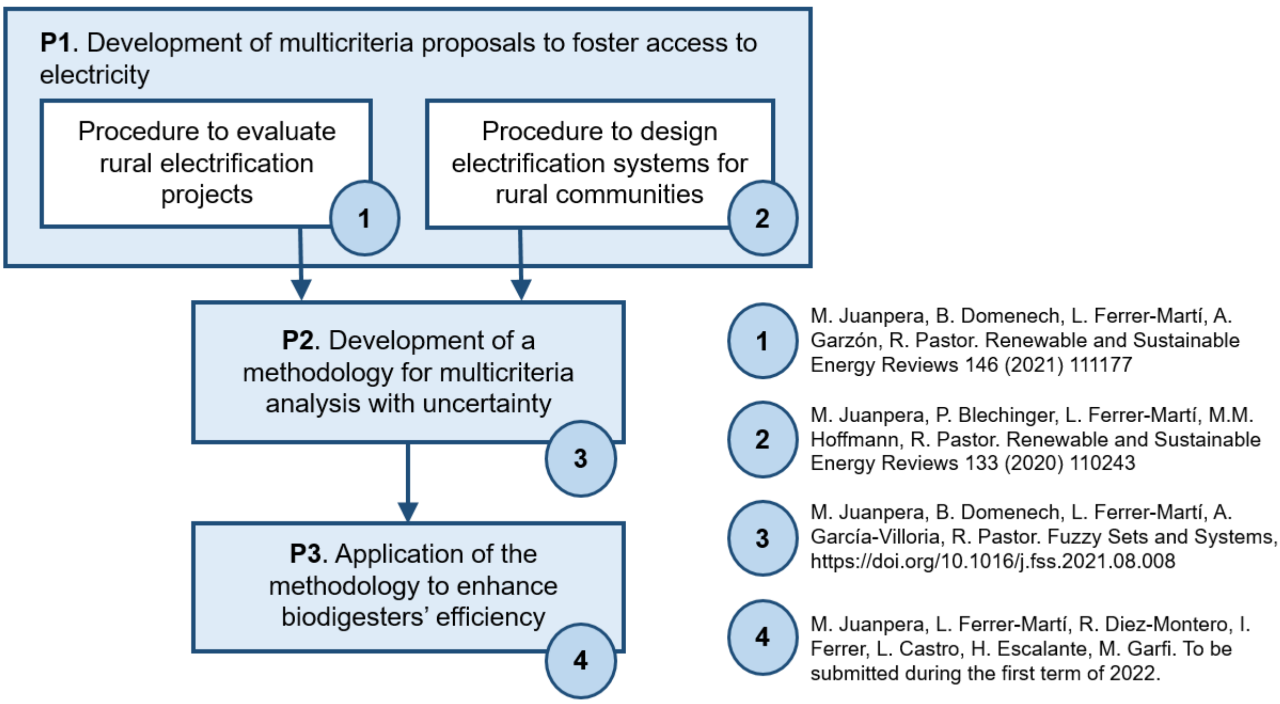

Figure 2.1 Methodology followed in this PhD thesis and papers written

2.1 P1. DEVELOPMENT OF MULTICRITERIA PROPOSALS TO FOSTER ACCESS TO ELECTRICITY

The first step of this thesis aims to develop multicriteria procedures to promote electricity access within rural and underprivileged areas. The common division between evaluation and design [López-González et al., 2018b] is followed to develop two procedures: one to evaluate already implemented electrification projects and the other to size and place new electrification systems for rural communities. Both procedures are based on a multicriteria approach that seeks global sustainability, involving economic, technical, social, environmental and institutional aspects into the assessment. On the one hand, the evaluation aims to comprehend the impact of the electrification projects on the beneficiary population. It pays therefore attention to the advantages of different options for electricity generation used (renewable or non-renewable) and other key aspects for the projects' sustainability, such as the management system established or the institutional effort given by public authorities. On the other hand, the design combines the information obtained from previous evaluations of electrification projects with quantitative methods to define a complete and sustainable system that is able to produce, store and distribute the energy needed to meet the demand and promote the community development. Therefore, the combination of both procedures provides with an overall picture of the strategies that should be followed when designing, implementing and operating a rural electrification program, which can be of great help to promoters and policy-makers in the sector.

Both procedures have been applied to real case studies. The evaluation procedure has focused on 9 renewable-based electrification systems installed around 2010 in 6 rural communities in the province of Cajamarca, one with the lowest electrification rates of Peru. Meanwhile, the multicriteria design procedure has been applied to the state of Plateau, in Nigeria, with more than 70% of people living in rural areas without electricity service [IEA, 2017]. Both studies involved gathering opinions both from experts and users of the electrification systems with an acquisition method that can be improved to include a potentially low level of confidence in the answer towards the achievement of more robust results.

The rest of the section aims to first, summarize i) the research need and objective, ii) the procedure followed and iii) the application and results obtained both with the multicriteria evaluation and design procedure (sections 2.1.1, paper 1 of this thesis; and 2.1.2, paper 2 of this thesis). Finally, the limitations observed in the data gathering method are detailed and the motivation for phase 2 of the thesis is consequently stated (section 2.1.3).

2.1.1 Multicriteria procedure for the evaluation of renewable-based electricity projects

The research need, objective, procedure and results of the first paper are now summarized:

Research need and Objective

Stand-alone electrification systems based on renewable energies have been proved to be suitable for electrifying isolated rural communities [Ferrer-Martí et al., 2011; Khan et al., 2018; García-Villoria et al., 2020]. After some years of operation, their impact on the development of beneficiaries must be evaluated in order to understand the strengths and weaknesses of each design option and to learn useful lessons for future projects [Ferrer-Martí et al., 2012; Domenech et al., 2014]. Current literature has studied the performance of different options for electricity generation and distribution in stand-alone systems, either alone [Chmiel & Bhattacharyya, 2015; Kudo et al., 2015; Mishra & Behera, 2016; Njoh et al., 2019; Wassie & Adaramola, 2021] or in combination of 2 or more [Millinger et al., 2012; López-González et al., 2017; Yadav et al., 2019], majorly after short time since implementation [Ferrer-Martí et al., 2012; Lillo et al., 2015]. However, it lacks of a unified study that compares the long-term impact on population of several projects combining different options for electricity generation (solar PV, wind and hydro) and distribution (microgrids and individual systems).

In this context, this study performs a two-phased assessment of 9 electrification projects using different technologies for electricity generation and distribution, located in 6 communities in Cajamarca (Peru), to reach global conclusions about the long-term adequacy of such electrification projects for rural areas.

Procedure

For this purpose, a set of objectives for sustainability evaluation is defined, grouped into technical, social, economic and environmental dimensions:

- The technical dimension includes the evaluation of the system performance to cover the family needs and the effectiveness of maintenance, either provided internally (for ordinary checks) or externally (for major failures).
- The social dimension evaluates the quality of supply perceived by the families and its impact in education and health, the collaboration among users to detect and solve potential conflicts and the institutional support that might be provided by a public administration.
- The economic dimension focuses on assessing the payment rate and the development or increase of productive activities that might be generated due to the electricity service.
- The environmental dimension considers the pollution generated, either on water or air, wastes at the end of lifetime and noise affections, as well as deforestation consequences of the systems' implementation.

The two-phased procedure involves two separate instances of field-work (2011-12 and 2016), as well as qualitative and quantitative information, to better encompass the relationships among the own community members and between the community and surrounding actors (i.e. local institutions and external technicians) or the electric equipment itself:

1. In phase 1, a qualitative comparison is performed of the fulfilment of sustainability objectives in 2011-12 and 2016 (with the information gathered in the corresponding field-works).
2. In phase 2, a quantitative assessment of the electrification projects and the development of the population is carried out through 28 indicators linked to the objectives and assessed from

the second visit, in which surveys were conducted with technical experts and beneficiary families.

During the visits, a technical expert in each community was interviewed and a total of 34 surveys were carried out to families, representing 139 beneficiaries, to observe their perception of the overall performance of the projects. These surveys were made 4 to 8 years after the projects' implementation, which reinforces the long-term evaluation of the 9 sustainability objectives divided in indicators. This long-term two-phase evaluation enables to identify the strengths and weaknesses of the projects, distinguishing their progression over time and what was (or was not) working previously.

Application and Results

The results obtained are useful for both rural electrification promoters and policy makers aiming to strengthen the extension of electrification through renewable-based stand-alone systems. These agents should take into account that:

- Regarding the technologies for electricity generation, micro-hydro is confirmed as permitting a continuous high-quality supply when effective organization can be maintained over time. Meanwhile, solar PV and wind systems are also technically viable options for expanding rural access to electricity and can perform successfully with a low frequency of technical revision. The ultimate choice of technology should be based mainly on the resource potential of the region and the investment capacity.
- Regarding the distribution option, microgrid-based projects encourage and require higher community involvement and stronger organization to cover maintenance tasks due to more complex designs. If achieved, they are flexible enough to allow long-term project expansions and start new productive activities. Meanwhile, individual systems are easier to install and maintain, and do not require as much community organization, although experienced technical operators and funding are still necessary to deal with big failures and repairs.
- Regardless of the generation or distribution options chosen, an effective management model involving both the community and local authorities is essential for long-term success. Particularly, the model should embrace a consensual tariff system that allows replacement of equipment and ultimately avoids discouragement among community members. Also, the alignment of the project with the long-term plans of the local and national institutions should be sought to ensure a more active support from the administration.

2.1.2 Multicriteria procedure for design of electrification systems in rural areas

The research need, objective, procedure and results of the second paper are now summarized:

Research need and Objective

Electrification with micro-grids is receiving increasing attention to electrify rural areas in developing countries [Ustun et al., 2011; Blechinger et al., 2019a]. However, determining the best local supply solution is a complex problem [Domenech et al., 2015] that requires considering different generation technologies (i.e. solar PV, wind or diesel) and different system configurations (off-grid or on-grid)

[Moner-Girona et al., 2019]. Most existing decision-aid tools to assess this design only consider economical and technical issues in a single optimization process [Akella et al., 2007; Lambert & Hittle, 2000; Howells et al., 2011; Hoffmann, 2019]. However, social and environmental considerations have been proven key issues to ensure long-term sustainability of the projects [Rahman et al., 2013; Moreira et al., 2019; Olówósejéke et al., 2020].

In this context, the objective of this work is to develop a multicriteria procedure to select the best electrification design from different ones considering both on-grid and isolated MGs and combining different technologies for electricity generation.

Procedure

This multicriteria procedure is integrated in a two-phased methodology to assist the design of the system to electrification promoters in a structured process. First, different electrification alternatives are generated with an open-source techno-economic optimization model; second, these alternatives are evaluated and ranked with the multicriteria procedure, which considers 12 criteria representing economic, technical, socio-institutional and environmental aspects:

- Economic criteria include upfront investment costs and operation and maintenance expenditures needed during the projects' lifetime.
- Technical criteria consider the autonomy factor of the system, the existence of small shortages on demand, the reliability of supply against forecasts and the likelihood of equipment failure.
- Socio-institutional criteria take into account the tariff for electrical service, the users' acceptance of the different technologies of electricity generation and the alignment of these technologies with the government's tendency to account for a more active institutional support.
- Environmental criteria embrace CO_2 emissions, the environmental impact of the project based on visual, noise impact and land-use, and wastes generation.

These criteria have been defined specifically to allow a comparison of electrification designs which might consider national grid extension and different generation technologies, and are particularized for each case study based on experts' opinions. The criteria evaluation through indicators is based on the outputs of the optimization model in phase 1. Thus, a perfect integration of alternatives generation and selection phases can be achieved. Consequently, decision-makers dispose of an integrated tool to determine different electrification designs and select the most appropriate guided by a comprehensive final ranking. The resulting procedure is expected to assist decision and policy makers in this complex process of determining the best electrification design within an integral approach.

Application and Results

The whole design procedure is validated with a real case study of 26 population settlements in Plateau State, Nigeria, which present different values of peak demand and distances to the closest national grid consumption point. Experts in rural electrification within the Nigerian context have been consulted to weight the criteria and assign a score to each generation technology considered according to their performance on the qualitative criteria. Four main electrification scenarios are considered for each community:

- An on-grid MG with only solar PV as generation technologies, with batteries as back-up.
- An on-grid MG with solar PV and diesel as generation technologies, with batteries as back-up.
- An off-grid MG with only solar PV as generation technologies, with batteries as back-up.
- An off-grid MG with solar PV and diesel as generation technologies, with batteries as back-up.

In addition, sub-scenarios are defined to determine the overall effect of considering small shortages on the supply of annual demand. Particularly, three levels of shortage are considered for each electrification scenario: 0% (complete fulfillment of demand), 2.5% and 5%. Therefore, 12 electrification alternatives are generated for each community (four electrification scenarios with three levels of shortage each).

Results are provided for the main steps of the methodology: alternatives calculation, criteria weighing and alternatives evaluation and ranking:

- Alternatives calculation: these results present the least cost size (power capacity) of the equipment for electricity generation and distribution that should be implemented in each particular electrification scenario to cover the electric demand of the community.
- Criteria weighting: defaults weights are given for the selected criteria based on the opinions of experts in the context of rural electrification in Nigeria. These weights can be reused in similar studies in different countries and contexts in case particularizing them for the other context is not possible due to a lack of information.
- Alternatives evaluation: The alternatives assessment takes into account the size of the equipment included in each alternative, the costs to implement it and the scores given by the experts on the qualitative criteria.
- Alternatives ranking: a ranking of the alternatives is computed in order to ease the selection of the one that better fits all criteria for the particular case study in Nigeria.

On the one hand, an on-grid alternative based on solar PV and batteries is recommended for 7 communities, with a distance to the national grid no bigger than 25 km. On the other hand, an off-grid solution based on solar PV and batteries is recommended for 19 settlements, for which an insufficient peak demand does not compensate the cost of extending the national grid. Finally, sub-scenarios defined show that a small shortage (2.5 - 5%) is attractive for off-grid scenarios, in order to reduce investment costs. Ultimately, the results obtained remark the adequacy of off-grid microgrids based on solar PV and batteries to electrify rural areas, which should be promoted and carefully regulated by the institutions involved.

2.1.3. Limitations observed in the data acquisition method

This first phase of the thesis concludes with valuable information for promoters of electricity access, both for design and implementation and management stage of the projects. However, some limitations observed in the data acquisition when performing both studies are now detailed and addressed within phase 2 of the thesis:

- Evaluation procedure (case study of Peru):
  The users of the electrification systems were required to answer a survey that focused on understanding the beneficiary perception of three items: i) quality of supply, ii) socioeconomic impact on their everyday lives, and iii) rational use of energy by the community and the corresponding negative effects on the own supply and the environment. These three items included different multi-choice questions. For example, 6 qualitative options were available to evaluate the quality of the supply: excellent, very good, good, bad, very bad and terrible; and 3 options allowed to evaluate the work of the community operators: very diligent, slightly diligent, and not diligent at all.

  Beneficiaries in rural areas, in most cases, are hesitant about the scope of the consequences of the electricity service in their lives. Thus, insecurities when choosing one option given are easily found, especially when more options are available in search of detecting nuances to enrich the evaluation.

- Design procedure (case study of Nigeria):
  Experts consulted were given a questionnaire that included two sections: section 1 required an evaluation of the importance of the 12 considered criteria on a scale from 1 to 5 (very low importance to very high importance). Then, section 2 asked to assign a score to the performance on the qualitative criteria of the three technologies of electricity generation considered (solar PV, diesel, and national grid extension) on a scale from 1 to 3 (low performance to good performance). In each particular question within both sections, a space was given for the experts' own remarks, encouraging especially the expression of doubts regarding the comprehension and evaluation of the specific question.

  The remarks of the experts allowed to distinguish distinctive levels of confidence between them. On the one hand, some experts provided notes that enrich the evaluation far beyond the mere score given, complementing the numerical answer with information such as new regulations approved or professional experiences on the topic. Meanwhile, other experts, despite providing a numerical answer on a certain question, recognized a high lack of knowledge on specific questions that makes them be uncertain about the validity of the answer given. The different information and confidence complimentarily shared by the experts allow to enhance the discussion of the evaluation, but has little effect on the quantitative results if only the crisp numerical answers are considered.

The limitations observed lead to think that a data gathering method that includes the level of confidence with which the provided answer is expressed can be beneficial in three particular ways:

1. It can reduce the pressure the respondents can feel when asked about a certain answer. Knowing in beforehand that a respondent can say whether he/she feels confident or not with

a particular answer can help to create a friendlier environment that can encourage the exchange of valuable information.

2. It can help to distinguish more confident and more hesitant answers when evaluating the alternatives. This level of confidence affects the reliability of a given evaluation, which should be taken into account in the alternatives rankings.

3. More valuable information can be obtained from the comparison of different rankings: i) considering only the crisp evaluations without uncertainty, ii) taking into account the lack of confidence of the respondents or iii) developing sensitivity analysis on the evaluations. A systematic process to compare the results from all rankings can lead therefore to more robust decisions.

The specific introduction of the level of confidence within the data gathering method, as well as its impacts in the quantitative decision-making process and the results obtained are summarized in section 2.2 and detailed in chapter 5.

2.2 P2. DEVELOPMENT OF A METHODOLOGY FOR MULTICRITERIA ANALYSIS WITH UNCERTAINTY

Phase 2 of the thesis aims to develop a methodology for multicriteria analysis taking into account the uncertainty generated in the processes of criteria weighing and alternatives evaluation. The appropriate consideration of this uncertainty can lead to more robust and informed decisions, since the more reliable alternative can be distinguished through the comparison of diverse rankings with more or less focus on the uncertainty detected. Such methodology is defined not only to decisions aimed to foster the access of basic needs in rural areas, but in a general way to be applied to any sector.

When analyzing closely the uncertainty that may arise throughout a multicriteria decision-making process, two factors can be detected: first, the difficulty of quantifying on a numerical scale answers commonly expressed in linguistic terms (such as: very good); and second, the lack of confidence in the response. The literature has widely accepted the use of fuzzy numbers to deal with the first factor of uncertainty, but lacks of a simple method for data gathering and treatment to efficiently encompass the lack of confidence towards a more robust decision. The work developed in this regard is embedded in the third paper of this thesis, which is now summarized and presented in detail in chapter 5.

The research need, objective, procedure and results of the third paper are now summarized:

Research need and Objective

Making a decision, either in promoting rural development or any other sector, usually means selecting one from different alternatives to solve a problem according to a set of criteria [Figueira et al., 2005; Butchart-Kuhlmann et al., 2018]. Multicriteria analysis offers a quantitative approach to ease decision-making by ranking the alternatives [Opricovic & Tzeng, 2004; Melvin, 2012; Awashti et al., 2018]. However, uncertainty can arise when rating the importance of criteria and the adequacy of each alternative for each criterion, due to two factors: first, answers are usually expressed in linguistic terms that do not have a unique quantification [Zadeh, 1975]; and second, there might be a lack of confidence in the response [Chen & Hong, 2014] due to limited knowledge [Garg, 2016] or the sense of not having enough information [Kim & Ahn, 2019]. Most multicriteria procedures combine fuzzy numbers and fuzzy linguistic scales to deal with the first factor, but underestimate confidence issues.

In this context, this work develops a Methodology for Integrated Multicriteria Decision-making with Uncertainty (MIMDU), which considers both factors of uncertainty through non-predefined triangular fuzzy numbers and focus on integrating the confidence level in the quantification of the response.

Procedure

MIMDU is structured in three phases:

1. In phase 1, experts' opinions are quantified with a novel procedure based on fuzzy rating scales that considers two steps. First, the experts rate the importance of criteria and the adequacy of alternatives according to the criteria on a 0-5 scale. Second, the experts express their confidence in the response among five options: *completely sure*, *sure*, *indecisive*, *unsure* and *very unsure*. The less confident the response is, the larger the support of the generated triangular fuzzy number is (in more intuitive words, the more values around the reference one from step 1 are included in the fuzzy number). As a result, the evaluation is adjusted to the level of confidence of the respondent, who can also undergo less pressure being able to complement the response by warning about his/her confidence.
2. In phase 2, a fuzzy formulation of the compromised ranking method (F-CRM) is standardized using the α-cut approach to deal with the triangular fuzzy numbers obtained in phase 1 and classify the alternatives according to their distance to the ideal solution.
3. In phase 3, a systematic procedure is presented to provide information to decision-makers in order to robustly choose the best alternative. This includes a comparison between a crisp ranking of alternatives (without considering confidence) and a fuzzy analysis (considering confidence). The fuzzy analysis includes pair-wise comparisons of the alternatives based on possibility and necessity measures which allows selecting or discarding alternatives under a certain threshold.

Application and Results

The methodology is illustrated with a generic example case, aiming to prove its potential application not only in decisions to foster rural development, but in any sector. Results show that the proposed procedure helps decision-makers to choose the most reliable alternative, which are significantly enhanced in the fuzzy analysis, which considers the confidence expressed.

Also, a sensitivity analysis is carried out to see the effect of a lower or higher confidence in the response. Results of this sensitivity analysis reveal that increasing the confidence when evaluating an alternative can significantly improve its performance in the final ranking, making the final selection of an alternative easier to a decision-maker.

Finally, the fuzzy multicriteria technique F-VIKOR is chosen, due to its resemblance with F-CRM in finding the most compromised solution, to be compared with MIMDU. This comparison proves the soundness of MIMDU to better capture confidence in responses and facilitate a more robust decision-making through numerous complementary indicators.

2.3 P3. APPLICATION OF THE METHODOLOGY TO ENHANCE BIODIGESTERS' EFFICIENCY

The last phase of this thesis aims to apply MIMDU to enhance the efficiency of biogas digesters as a technology for both energy and food production by improving the quality of one of their products, the digestate, before its use in agricultural soil. In detail, different options for digestate post-treatment are analysed according to their capacity of increasing the performance of the digestate as a fertilizer and its adaptation to the socioeconomic context of rural and small farms. The study is based on three real biodigesters located in farms of Colombia. The advantages of using MIMDU compared to other multicriteria procedures are also emphasized. The work developed in this regard is embedded in the fourth paper of this thesis, to be submitted, which is now summarized and presented in detail in chapter 6.

The research need, objective, procedure and results of the fourth paper are now summarized:

Research need and Objective

Small farms located in rural and underprivileged areas are increasingly relying on biogas digesters as a renewable source of energy (biogas) for cooking and heating [Thu et al., 2012; Iannou-Ttofa et al., 2021]. From the digestion of organic matter, a liquid effluent called digester is also produced, which can be applied to soil as a fertilizer [Ferrer et al., 2011; Ferrer-Martí et al., 2018]. However, its direct use in agriculture may not be feasible due to regulations or might not be efficient for too low quality [Kearney et al., 1993; Garfi et al., 2011; Surendra et al., 2014, Garfi et al., 2016; Chong et al., 2022]. Different studies in literature have focused on a specific technique of digestate treatment [EPA, 2011; Krishnasamy et al., 2013; Patil & Husain 2019; Sari et al., 2019; Arora & Saraswat 2021], but there is a lack of a comparative and simultaneous study of different alternatives.

In this context, the present study aims to define a robust multicriteria analysis to select the best treatment alternative for rural small-scale farms, among: degassing tank, sand filter, vermifilter, recirculation of the digestate, facultative pond, or combinations of them.

Procedure

For the selection of the best treatment alternative, 10 criteria and 21 sub-criteria of a technical, environmental and socio-economical nature have been defined:

- The technical dimension evaluates the suitability of the post-treated digestate and the adaptability of the own solution to the context of rural households in developing countries from a technical perspective.
- The environmental dimension focus on the effect of the considered alternatives on the natural resources located in the area, either for pollution or resources consumption.
- The socio-economic dimension evaluates the social and financial impact of the digestate post-treatment's solutions in the lives of the people working in the farm and living nearby.

MIMDU is used to include the potential lack of confidence when weighing criteria and evaluating alternatives towards a robust final ranking. Thus, the results obtained can be considered more reliable and applicable to small farms in rural areas of developing countries.

Application and Results

The multicriteria analysis has been applied to three small farms in Colombia. The alternatives have been designed according to real data of the biodigesters design and the digestate characteristics captured in-situ. 16 experts which count on several years of experience designing, implementing and evaluating programs involving biodigesters and solutions for digestate post-treatment have been consulted to weight the criteria in the framework of the MIMDU methodology. Also, a sensitivity analysis has been carried out to highlight the influence on the results of the different experts' profiles consulted, which are divided into technicians and academics. The results of the whole application include the following information:

- Alternatives design: these results present the correct definition of all important parameters in each of the alternatives, either common to some of them (such as their dimensions, hydraulic retention time or organic loading rate) or specific (such as the sand volume for the sand filter, the number of earthworms for the vermifiltration and the mass increasing factor of the recirculation alternative). Also, they include the specific materials, quantity and costs required for the implementation and operation of the alternatives in case of being selected.
- Criteria weighting: defaults weights are given for the selected criteria using the steps defined in MIMDU and considering the opinions of experts in the context of biogas digesters and digestate treatment in small farms in Latin America. These weights can be reused in similar studies in different countries and contexts in case particularizing them for the other context is not possible due to a lack of information.
- Alternatives evaluation: fuzzy numbers are assigned to evaluate each alternative-criterion employing an uncertainty margin around a base value, which is obtained from the captured data.
- Alternatives ranking: the most compromised design according to all criteria is selected and recommended for the three farms in Colombia.

The final results of the alternatives ranking state that vermicomposting is the most appropriate technique to post-treat the digestate before insertion to crop, followed by recirculation of the digestate and sand filter. These techniques, and specially vermifiltration, produce a high-quality digestate to be used as fertiliser, employ sustainable materials, generate no particles or gas emissions and can increase family's income due to a more efficient agricultural production and the possibility of revenues with vermicompost sales. Such results should orientate national and regional authorities, as well as international organisations, to foster vermifiltration, digestate recirculation and sand filters to increase the agricultural activity of rural areas.

Specifically, the consideration of uncertainty when capturing the numeric information and the combination of different crisp and fuzzy-based rankings within MIMDU has helped to identify vermifiltration, recirculation and sand filters as very robust techniques for digestate post-treatment in small-scale farms. Thus, decision-makers and promoters of such projects can be more certain on the suitability of such techniques than if only a crisp-based analysis was performed.

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3. PAPER 1. Renewable-based electrification for remote locations. Does short-term success endure over time? A case study in Peru

ABSTRACT

Stand-alone electrification systems based on renewable energies are suitable for electrifying isolated rural communities. After some years of operation, their impact on the development of beneficiaries must be evaluated; in order to understand the strengths and weaknesses of each design option and to learn useful lessons for future projects. The literature lacks a unified study that compares the long-term impact on population of several projects combining different options for electricity generation (solar PV, wind and hydro) and distribution (microgrids and individual systems). In this context, this work performs a two-phase assessment of 9 electrification projects combining different systems and located in 6 rural Peruvian communities. First, a qualitative analysis is performed to monitor the progress experienced by the communities, considering previous evaluations carried out shortly after the projects' implementation. Second, an in-depth analysis of the systems and the development of the communities is quantitatively performed through 28 indicators, evaluating 9 sustainability objectives organised into 4 dimensions: technical, social, economic and environmental. The results show that microgrid projects require and encourage community involvement to promote effective maintenance of the shared equipment. Conversely, individual systems can work for longer periods without as much regular maintenance, but still need an efficient management model to raise funds for repairs. Also, hydro is confirmed as providing continuous and high-quality supply, while solar and wind options allow more flexible designs. In all cases, a well-planned management model is essential for reducing the default rate, organizing effective maintenance and allowing the sustainable development of the community.

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Renewable-based electrification for remote locations. Does short-term success endure over time? A case study in Peru

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ABSTRACT

Stand-alone electrification systems based on renewable energies are suitable for electrifying isolated rural communities. After some years of operation, their impact on the development of beneficiaries must be evaluated; in order to understand the strengths and weaknesses of each design option and to learn useful lessons for future projects. The literature lacks a unified study that compares the long-term impact on population of several projects combining different options for electricity generation (solar PV, wind and hydro) and distribution (microgrids and individual systems). In this context, this work performs a two-phase assessment of 9 electrification projects combining different systems and located in 6 rural Peruvian communities. First, a qualitative analysis is performed to monitor the progress experienced by the communities, considering previous evaluations carried out shortly after the projects' implementation. Second, an in-depth analysis of the systems and the development of the communities is quantitatively performed through 28 indicators, evaluating 9 sustainability objectives organised into 4 dimensions: technical, social, economic and environmental. The results show that microgrid projects require and encourage community involvement to promote effective maintenance of the shared equipment. Conversely, individual systems can work for longer periods without as much regular maintenance, but still need an efficient management model to raise funds for repairs. Also, hydro is confirmed as providing continuous and high-quality supply, while solar and wind options allow more flexible designs. In all cases, a well-planned management model is essential for reducing the default rate, organizing effective maintenance and allowing the sustainable development of the community.

1. Introduction

Nowadays, around 850 million people worldwide have no access to electricity [1], mainly in remote rural areas [2]. Electrification usually expands through the extension of the national grid [3], despite the huge economic cost of extending it to remote, scattered and inaccessible areas [4]. Alternatively, stand-alone electrification systems are commonly implemented in such areas. Individual systems have been used in many projects, since they are a simple solution and electricity access is achieved for usually low upfront costs [5]. Meanwhile, electrification systems based on microgrids are receiving increased attention as they are able to provide a flexible and scalable service [6] and allow cost savings through economies of scale [7].

Stand-alone electrification systems can be based on renewable and non-renewable technologies, such as solar PV, wind, micro-hydro, biogas or diesel generators [8]. Despite the satisfactory performance of biogas technology, especially for cooking purposes [9], this study focusses on the first three as they are the most-used generation sources for off-grid renewable systems worldwide [10] and can supply clean, reliable and affordable energy services [11]. Indeed, solar PV is the most-used solution for extending cheap electricity access through solar home systems, as the price has fallen significantly in the last 10 years [12]. Wind systems have been increasingly studied and promoted for some years now [13], since the investment/production ratio can be significantly reduced in windy areas compared to solar PV [3]. Where potential exists, micro-hydro is an excellent option due to its ability to provide a continuous supply with little impact on the surrounding environment [14]. These technologies all take advantage of local resources, which reduces external dependence and contributes to promoting the long-term sustainability of projects [15]. Moreover, hybrid

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systems combining two or more technologies are increasingly being used, such as solar photovoltaic (PV) and wind [16], since they complement each other and overcome the supply intermittency of electrification systems based on a single technology [17].

In Peru, several electrification projects have been implemented by a group of Non-Governmental Organizations (NGOs) led by Practical Action from Peru (PA), Engineering Without Borders from Spain (EWB) and Green Empowerment from USA (GE). Some of these projects were located in the region of Cajamarca and aimed at promoting universal and sustainable access to energy services as part of an interactive design and implementation procedure to empower the benefiting communities. The system designs of the projects differ in the technologies used for electricity generation (solar PV, wind and micro-hydro) and distribution (individual systems or microgrids).

A few studies have already been carried out to evaluate the socio-economic impact of some of these projects. Ferrer-Martí et al. [3] consider the project design and evaluation phases when assessing the technical and socio-economic sustainability of three wind-based projects. Domenech et al. [18] highlight the need to adapt the system design to micro-scale resource evaluation and socio-economic diagnostics, showing the advantages in a rural community where 4 different technologies were implemented. Lillo et al. [19] use the HDI approach to assess the management model of the electrification systems implemented in four different rural communities and make recommendations to increase the effectiveness of the management model. However, these studies do not assess at the same time all the possible renewable-based electrification designs implemented in the area, which restricts the scope of the obtained conclusions for future projects.

As pointed out in the following literature review (section 2), there is a lack of studies that provide a unified comparison of the three basic renewable energy technologies for stand-alone electrification (solar PV, wind and hydro) and the main distribution options (individual systems and microgrids). The conclusions of such a comparison are necessary both at an institutional level, to guide in implementing policies that foster electrification in rural areas and at an academic level, to provide insights for future methodology development involving rural electrification design. Without this information, important considerations can be missing and the long-term success of the electrification projects may be affected.

In this context, this study performs a two-phase assessment of 9 electrification projects using different technologies for electricity generation and distribution, located in 6 communities in Cajamarca (Peru), to reach global conclusions about the long-term adequacy of such electrification projects for rural areas. For this purpose, a set of objectives for sustainability evaluation are defined, grouped into technical, social, economic and environmental dimensions. In phase 1, the progress of the projects is qualitatively assessed, comparing the information from a first evaluation (2011–2012) detailed in Refs. [3,19], with a second field visit (2016). In phase 2, an in-depth analysis of the technical status of the systems and the community development is performed using 28 quantitative indicators. The evaluation of these indicators is obtained through surveys conducted during the second visit to community technicians and beneficiaries. A total of 139 beneficiaries have been addressed in order to ensure representative answers for all the combinations of electricity generation and distribution options analysed. This long-term two-phase evaluation enables the strengths and weaknesses of the projects to be identified, distinguishing their progression over time and what was (or was not) working previously. The final results prove that the technical sustainability of the projects depends on the community's ability to organize an effective management model, which can be reinforced or discouraged according to the system design adopted. These results can be helpful for generally strengthening the global strategy of extending electrification through renewable-based stand-alone systems and specifically for electrification promoters in developing countries to improve future initiatives.

The remainder of the paper is organized as follows. Section 2 provides a literature review to justify the scientific gap addressed here. Section 3 presents the assessment method and defines the objectives and indicators used. Section 4 details the socio-economic description of the communities, the technical description of the systems and the survey method used to approach them both. In section 5, the results of the assessment in the communities are presented. Section 6 summarizes the recommendations for future projects and the conclusions of the study are highlighted in section 7.

2. Literature review

Significant research has been carried out in recent years to develop methodologies and procedures for the accurate design of rural electrification systems based on renewable energies (particularly solar PV, wind and micro-hydro) [4,6,20–22]. However, these methodologies do not always include the experience gained from previously implemented projects, thereby missing important insights into the strengths and weaknesses of each electrification option [23]. In addition, assessments of current experiences are necessary to validate whether electrification projects are being deployed efficiently or not [24]. Thus, it is essential to update the knowledge about the reasons for the success or failure of renewable-based stand-alone electrification projects.

Several studies have focused on evaluating the impact of only PV-based projects on the development of the beneficiary communities after some years of implementation. The main focus of such studies has been to highlight the behavioural changes at the household level [25]; the limitations in health and education development [26]; the influence on newly developed cultural activities and communication through mobile devices [27]; the main aspects, such as the income level or access to financial credit, promoting [28] and hindering [29] the adoption of technology; and the particular policies to promote for improving the success of electrification through solar PV, including the creation of subsidies and the promotion of local training programs [30]. Most assessments involved field work, with direct contact with the final beneficiaries and other stakeholders through structured and semi-structured interviews made around three years after the project implementation.

The assessments in the literature of rural electrification systems based on wind and micro-hydro are mostly found in combination with each other and with the PV technology. The imbalance between electrification projects based on PV and micro-hydro is natural, due to a disparity in accessing both resources. However, specific studies of the hydro technology in rural areas have highlighted the greater capacity of micro-hydro to provide a continuous supply, which has direct consequences on the communities' welfare [31]. On the other hand, the predominance of PV over wind is due to the competitive prices of solar-based solutions [32], together with a higher variability and maintenance cost of the wind technology [33]. The same author concludes that wind technology can still have a prominent role in complementing other technologies in hybrid systems and leading the energy supply in windy areas, benefiting from the possibility of local manufacture [34].

In this regard, Chmiel and Bhattacharyya [35] analyse an off-grid microgrid-based system using wind, hydro and diesel (the latter as backup) on the Isle of Eigg, in Scotland; Lopez-Gonzalez et al. [36] examine microgrid-based projects using different combinations of wind, PV and micro-hydro technologies in four Andean countries. These studies focus mainly on determining, through later design optimization, if the system was correct; but they do not aim to examine the impact of electrification in the daily life of beneficiaries. A more recent study [24] analyses three independent off-grid microgrid projects involving a micro-hydro plant, a wind turbine system and a hybrid solar-diesel system, respectively. The comparison provides remarkable insights to improve the effectiveness of rural electrification initiatives from a technical, economic and institutional point of view, but still has limitations due to the non-consideration of hybrid-renewable systems. The study ends with a call for additional evaluations to unravel hidden interactions that influence the success of renewable-based rural electrification projects [24].

At a broader level, regional and national plans for rural electrification have been evaluated, among others, in Peru [37], Brazil [38], and India [39]. These global assessments include many technologies and system designs and are valuable for detecting general tendencies of the electrification extension, such as a possible improvement of 2 homework hours for children, regardless of the electrification technology [37], a general correlation between rural electrification and the improvement in the Human Development Index [38]; or the importance of effective public-private cooperation for systems implementation [39]. Also at a national level, studies analysing the development and challenges of the renewable energy industry have shown the need for financial incentives to improve the economic competitiveness of off-grid projects and attract private investment [40], as well as tendering arrangements that encourage competition among companies and technologies [41] or the development of a solid professional base among the population [42]. These studies all provide valuable insights for boosting renewable energy industries, as well as developing efficient national plans for grid extension. However, due to their broad scope, they omit particular details at a community level that condition the long-term sustainability of low-scale projects.

To illustrate the research gap addressed in this study, Table 1 classifies the works that assess the impact of renewable-based local-scale electrification projects in the beneficiary communities through fieldwork (surveys, interviews, semi-structured interviews, etc.). The classification considers the number of technologies for electricity generation (solar PV, wind and hydro; rows) and distribution (microgrids and individual systems; columns), as well as the time elapsed between project implementation and assessment (short-term, less than 4 years; long-term, 4 years or more; superior and inferior triangle of each cell, respectively). As can be seen, different options for electricity generation and distribution have been studied, either alone (only 1 technology or option) or in combination (2 or more of each kind). Also, although the majority of assessments have been performed at short-term, some studies opted for analysing the long-term impact of the systems on the communities. However, the long-term assessment of the contribution of different options for electricity generation and distribution to sustainable development has not been addressed. This study, which involves field work carried out at least 4 years after project implementation and considers several technologies, including solar, wind, hydro and hybrid systems, as well as microgrids, individual systems and combinations, aims to fill this gap. Hence, more solid conclusions about the strengths and weaknesses of each option can be extracted regarding their capability to contribute to the long-term sustainable development of the beneficiary communities.

3. Methodology of the project evaluation

This study evaluates the impact of 9 electrification projects on the development of 6 rural communities in Peru. For this purpose, this section defines a two-phase evaluation method involving qualitative and quantitative assessments and multiple sustainability objectives. First (3.1), an overview of the two-phase method is presented and justified based on similar literature. Then (3.2) describes the sustainability objectives, sub-objectives and indicators defined to evaluate the technical, social, economic and environmental aspects.

3.1. Evaluation process

Different methods have been used until now to assess rural electrification projects in developing countries. Ilskog [43] developed the first standardized a method to assess the promotion of rural development by defining 39 sustainability indicators grouped into five dimensions: technical; economic; social and ethical; environmental; and organizational and institutional. Despite the structure in dimensions, high correlation is observed since they are all connected to community development as a whole. This correlation is treated alternatively by Hong & Abe [44], who explore the social and economic behavioural tendencies among users with similar attributes such as the level of income, education or occupation. Thus, the results of energy consumption and business development can be explained regarding the population background and its initial status.

Recently, other studies have restored the use of sustainability indicators to assess rural electrification within structured methodologies. In particular, López-González et al. [45] develop a conceptual framework to assist in the systematic analysis of rural electrification projects based on renewable energies during the design and implementation phases. The analysis considers 15 criteria pertaining to 4 sustainability dimensions: environmental, technical, socio-economic and institutional; it is validated with an empirical comparison of the performance of the national grid extension and the isolated renewable-based electrification within the Venezuelan program "Sowing Light". Bhandari et al. [46] select multiple suitable indicators to evaluate the sustainability of a micro-hydro power plant in Nepal with the help of semi-structured interviews with different stakeholders. To evaluate the indicators, a simple procedure is suggested, based on scores from 1 to 5, with 5 being the highest possible score. Boliko & Ialnazov [47] develop a similar framework to evaluate 4 projects (considering grid extension, hybrid mini-grids, solar mini-grids and solar home systems) in rural Kenya. Gómez-Hernández et al. [23] develop a three-level methodology to assess rural electrification projects, focusing first on the general definition at a regional level, then on the technical design at local level and finally on the operation and maintenance management. At each level, ad-hoc criteria and indicators are defined to perform the evaluation.

The aforementioned research is taken as a reference for the dimensions usually included in the sustainability evaluation of rural electrification projects. In this paper, however, a two-phase assessment method is proposed (Fig. 1), examining electrification projects at two different moments of operation (2011–12 and 2016). To do so, a set of

Table 1
Illustration of the research gap.

		According to the number of options for electricity distribution (microgrids and individual systems)	
		1 option	2+ options
According to the number of generation technologies (solar PV, wind and hydro)	Single (1 technology)	[26], [27], [28], [30] / [29], [31]	[25], [39] /
	Hybrid (2+ technologies)	[35] / [24]	[3], [18], [19] [36] /

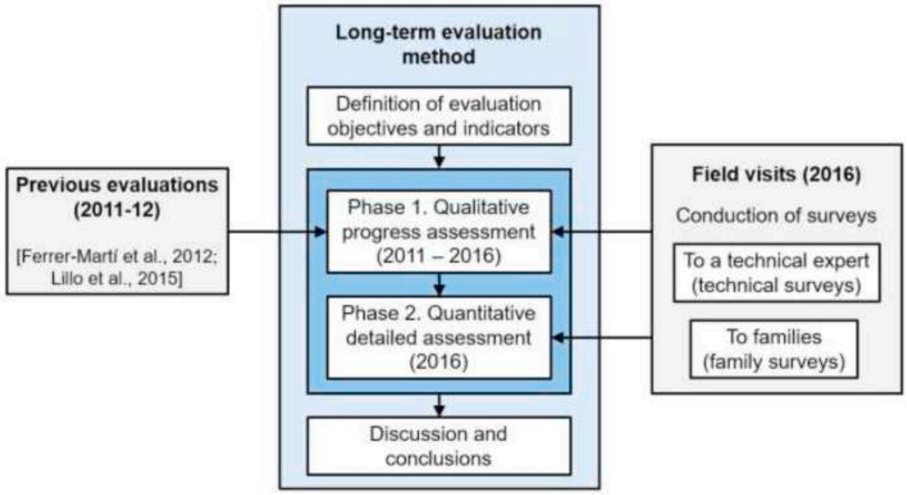

Fig. 1. Two-phase evaluation method for the assessment of rural electrification projects.

sustainability evaluation objectives and indicators are defined to mark the differences in the generation and distribution options analysed. These objectives, grouped into technical, social, economic and environmental dimensions, are assessed in two phases:

- In phase 1, information from previous evaluations in some communities, carried out between 2011 and 2012 [3,26], is qualitatively compared with a second field visit in 2016. Then, changes in the fulfilment of sustainability are evaluated.
- In phase 2, a quantitative analysis of the status of the electrification projects and the development of the population is carried out through 28 indicators assessed from the second visit, in which surveys were conducted with technical experts and beneficiary families.

This method of evaluation involves two separate instances of fieldwork, as well as qualitative and quantitative information, to better encompass the relationships among the own community members and between the community and surrounding actors (i.e. local institutions and external technicians) or the electric equipment itself [48]. More robust conclusions can then be extracted regarding the strengths and weaknesses of the systems that condition the socioeconomic development of the communities over time.

Table 2
Objectives, sub-objectives and indicators defined for the assessment.

Dimensions	Objectives		Sub-objectives	Indicators		+/−	Survey
Technical	OT1	Performance	Ensuring an efficient performance of the system	IT1.1	General operating condition	+	T
				IT1.2	Continuity of supply against failures	+	F
			Diversification of uses	IT1.3	Families who feel the system capacity is sufficient	+	F
	OT2	Maintenance	Increasing technical knowledge among users	IT2.1	Participation of beneficiaries in maintenance tasks	+	T
				IT2.2	Presence of operation manuals in houses	+	T
				IT2.3	Presence of maintenance tools in houses	+	T
			Ensuring effective maintenance within the community	IT2.4	Number of designated operators	+	T
				IT2.5	Type of maintenance realized	+	T
				IT2.6	Perception of the operators work	+	F
			Ensuring effective external maintenance	IT2.7	Perception of the external technicians work	+	F
Social	OS1	Quality of supply	Improving families' lifestyle in households	IS1.1	Satisfaction with the quality of supply	+	F
				IS1.2	Perception of easier household chores	+	F
			Improving education	IS1.3	Perception of the improvement in education	+	F
			Improving health	IS1.4	Perception of the improvement in health	+	F
				IS1.5	Families who no longer use candles	+	F
			Increasing family use of multimedia equipment	IS1.6	Gained access to TV or radio	+	F
				IS1.7	Gained access to internet	+	F
	OS2	Collaboration among users	Strengthen communication within the community	IS2.1	Frequency of neighbours' meetings	+	T
			Ensuring equality in use	IS2.2	Perception of equality in consumption	+	F
	OS3	Institutional support	Ensuring municipality support	IS3.1	Involvement of the municipality with system monitoring and financial support	+	T
Economic	OEC1	Payment rate	Reducing default rate	IEC1.1	Families paying promptly	+	T
			Ensuring accordance with the tariff model	IEC1.2	Families satisfied with the tariff system	+	F
	OEC2	Productivity increase	Strengthening current productive activities	IEC2.1	Families who have increased in productivity	+	F
			Promoting the creation of new productive activities	IEC2.2	Families who have started new productive activities	+	F
Environmental	OEN1	Pollution	Minimizing effects on water, land and air resources	IEN1.1	Detection of pollution in water, land and air resources	–	T
			Minimizing waste generation	IEN1.2	Presence of waste	–	T
			Minimizing effects of noise	IEN1.3	Perception of noise intensification	–	F
	OEN2	Deforestation	Limiting logging	IEN2.1	Need for logging at system setup	–	T

3.2. Definition of sustainability objectives for the assessment

Table 2 summarizes the defined objectives and sub-objectives for evaluating the status of the electrification projects. The accomplishment of each sub-objective is assessed through indicators, for which the source of information is mentioned (T for technical survey and F for family survey). Next, the objectives and indicators are described. Note that all indicators involving technical, social and economic dimensions are positively defined, while environmental indicators are negative.

The technical dimension in rural electrification projects evaluates the system performance, which is key to achieving global access to reliable and modern energy for all [49].

Performance (OT1). The purpose of this objective is to evaluate the working conditions of the system and its suitability regarding the family needs.

- *Ensuring efficient performance of the system.* The associated indicators focus on the general operating conditions of the system (IT1.1) and the continuity of supply reported by the beneficiaries (IT1.2). Failures can be caused by external issues, such as lightning or heavy precipitation, or by technical or mechanical errors due to inappropriate design, the use of low-quality components or poor maintenance [50]. This has different effects depending on the technology used for electricity generation [51], so this objective allows differences between the projects to be highlighted.
- *Diversification of uses.* The corresponding indicator measures the percentage of families who feel the system has sufficient power capacity for their needs (IT1.3). A demand forecast was made during the design phase, based on the current demand of each beneficiary and the expected increases. This forecast could have been insufficient, however, due to the increase in power consumption that the beneficiaries experienced.

Maintenance (OT2). The purpose of this objective is to evaluate the effectiveness of the technical maintenance of the system.

- *Increasing technical knowledge among users.* This specific objective is evaluated taking into account, first, the participation of beneficiaries in maintenance tasks (IT2.1). This progressively empowers the community as more knowledge is gained and mutual collaboration among beneficiaries can arise. The presence of operation manuals (IT2.2) and maintenance tools (IT2.3) in the households is also reported. These elements are considered essential for the whole community's participation in maintenance duties.
- *Ensuring effective maintenance within the community.* A low level of organization is essential in the community, to assign maintenance tasks to the best prepared members. This sub-objective is evaluated through three indicators: the number of operators designated (IT2.4); the type of maintenance carried out (IT2.5), which can be corrective, when a failure occurs, or predictive, if it is performed on a regular basis (or none, if there is no maintenance) and finally, the satisfaction of the families with the operators' work when maintenance tasks are performed (IT2.6).
- *Ensuring effective external maintenance.* Despite excellent internal organization within the community, a lack of high-level technical knowledge and specific replacement components obliges the community to turn to an external company to perform the appropriate maintenance when major failures occur. The corresponding indicator evaluates the satisfaction of the families with the work of these external technicians when this service is performed (IT2.7).

The social dimension in rural electrification projects is closely associated with increasing end-users' empowerment, promoting equity in access to basic services such as education and health, and reducing illiteracy and diseases [49].

Quality of supply (OS1). This objective aims to evaluate the impact of electricity access on the families' daily lives.

- *Improving families' lifestyle in households.* The associated indicators consider the overall satisfaction of the families with the quality of supply (IS1.1) and the percentage of families who report an improvement regarding the performance of household chores (IS1.2). Regardless of the potential acquisition of domestic appliances, electricity access implicitly makes household chores easier, as more time is available due to the increase in light hours.
- *Improving education.* The 4th Sustainable Development Goal of the United Nations (UN) promotes access to inclusive and high-quality education as essential for reducing global inequalities [52]. Children with electricity access at home have been proven to spend more hours doing homework which directly affects their academic performance [53]. Also, an improvement can be achieved in the education service at school. The corresponding indicator evaluates the percentage of families who have noticed an improvement in their children's education (IS1.3).
- *Improving health.* Similar to the above sub-objective, the UN promotes the goal of healthy lives for all in order to increase life expectancy and fight against most communicable diseases [52]. The indicators focus on the families' general perception of health improvement (IS1.4) and the continued use of candles after system implementation (IS1.5), which produces significant breathing difficulties in beneficiaries.
- *Increasing family use of multimedia equipment.* The fulfilment of this specific objective is estimated by considering the percentage of families who have gained access to TV or radio (IS1.6) and Internet (IS1.7). Such items are essential both to ensure broader access to information and to provide entertainment and comfort.

Collaboration among users (OS2). This objective aims to evaluate the community's ability to solve potential problems and detect causes of possible conflicts.

- *Strengthen communication within the community.* The corresponding indicator determines how frequently meetings are held in the community (IS2.1) to distribute management roles, assign maintenance tasks or promote new activities.
- *Ensuring equality in use.* Perception of inappropriate use by other beneficiaries may cause conflicts and consequently affect collaboration among beneficiaries. Therefore, an indicator is used to quantitatively calculate the percentage of families who feel their neighbours use the electricity service appropriately(IS2.2).

Institutional support *(OS3).* This objective aims to evaluate the presence of institutional support for the project at local level.

- *Ensuring municipality support.* Recent studies highlight the close connection between effective institutional support and long-term success of the electrification projects [54]. Therefore, the corresponding indicator evaluates the involvement of the local municipality with the system, monitoring the project and supporting it financially (IS3.1).

The economic dimension in rural electrification projects evaluates the payment rate sustainability by means of the beneficiaries' satisfaction, as well as the economic development of the community through the increase in established, or new, productive activities.

Payment rate (OEC1). The purpose of this objective is to evaluate the satisfaction of the community with the current tariff system.

- *Reducing default rate.* At the system design phase, the community and the NGO PA agreed on an affordable base-line monthly tariff. However, bad system performance or an increase of social conflicts can

affect the sustainability of the tariff model. This assessment looks at whether the families are paying the tariffs regularly (IEC1.1).
- *Ensuring accordance with the tariff model.* Inequality in, and abuse of, the system as perceived by the beneficiaries can lead to social tension and conflicts within the community [55]. Accordingly, the indicator calculates the percentage of families who are satisfied with the agreed fixed tariff system (IEC1.2).

Productivity increase (OEC2). The purpose of this objective is to evaluate the productive opportunities generated as a result of the electrification project.

- *Strengthening current productive activities.* Electricity access provides an opportunity for productive activities developed in the community, whose productivity can be increased through the acquisition of more modern electric tools. The assessment reports the percentage of families whose productive activities have been further developed since the electrification project (IEC2.1).
- *Promoting the creation of new productive activities.* Potentially new productive activities, such as opening a grocery store or cheese-making, can be developed as a result of electricity access. Similar to the previous sub-objective, the corresponding indicator focusses on the percentage of families who have started new economic activities (IEC2.2).

The environmental dimension in rural electrification projects focusses on assessing the project influence on the local environment, taking into account encroachment on natural resources and potential emissions [43].

Pollution (OEN1). This objective aims to evaluate the negative effects of the electrification systems on local resources during operation.

- *Minimizing effects on water, land and air resources.* The different technologies for electricity generation can affect the community's local natural resources. Therefore, the potential negative impacts of the electrification project on the communities' water, land and air resources are reported (IEN1.1).
- *Minimizing waste generation.* Operation, as well as decommissioning of the electric components at the end of their lifetime, can generate waste, especially when using batteries [56]. The corresponding indicator assesses the presence of waste as a result of the project (IEN1.2).
- *Minimizing effects of noise.* Mechanisms in electric components, such as wind turbines, generate noise that has been proven to affect human health due to annoyance and sleep disturbance [57]. The defined indicator evaluates the percentage of families who have noticed increased noise annoyance (IEN1.3).

Deforestation (OEN2). This objective aims to evaluate the particular impact of deforestation at the moment of the system's installation.

- *Limiting logging.* Due to the surrounding conditions of the community, some logging might have been necessary when installing the electrification systems. The indicator focusses on evaluating this impact (IEN2.1).

4. Description of the case studies

Despite the financial and organizational efforts of the Peruvian government and regional authorities in the last decade, 18.2% of the population living in rural areas still do not have electricity access [58]. This exceeds the average rate of the non-electrified rural population throughout Latin America, which is around 7.1% [58], and shows that Peru still lags behind in electricity extension. Since most rural communities are difficult to access, due to remoteness and lack of appropriate infrastructure, national grid extension is usually economically unaffordable and off-grid systems based on solar PV, micro-hydro plants and wind turbines are being promoted [59].

The NGOs PA, EWB and GE promoted these off-grid renewable-based systems in the region of Cajamarca, with emphasis on adapting the electrification solution to the particular features of each community. Thus, standardized solutions were avoided and a conscientious resources evaluation was carried out alongside the regional and local authorities and community group leaders [60]. This contribution allowed accurate technical and social diagnoses of the communities, which turned later to appropriate designs for each case. Due to the previous successful experiences of PA, micro-hydro plants were given priority if the water resource was available and the community was in favour of it. Otherwise, wind and solar PV designs were promoted, selecting the configuration option (individual systems or microgrid) according to economic and social matters, such as the cost of extending microgrids and the level of engagement observed. These concerns could also lead to the use of various technologies for one community, if considered appropriate.

Along with the technical design, the experience of PA has led to the implementation of a management model which aims to ensure the technical and financial long-term sustainability of the off-grid projects [3]. This model has been implemented in each benefiting community and is based on the collaboration of three actors (Fig. 2). First, the systems' users are required to pay a monthly tariff for the equipment maintenance and are allowed to attend the assembly that takes place periodically. This assembly elects a control unit, composed of local people, which is in charge of ensuring fulfilment of obligations and dealing with suggestions or complaints. Second, a microenterprise run by an operator and an administrator, designated by the beneficiaries, is responsible for performing corrective and preventive maintenance and depositing the tariffs into a reserve fund to cover future replacements. Finally, the municipality is the legal owner of the systems and signs a concession contract for the project management in favour of the microenterprise. However, as the legal owner, the municipality has to provide financial and technical support to ensure the sustainability of the project when compromised. A more detailed description of the actors involved in the management model and their interactions can be found in Ferrer-Martí et al. [3] and Lillo et al. [19].

The remainder of the section is divided into two subsections; first, to provide a technical description of the electrification designs assessed in each project (4.1) and, secondly, to illustrate the field research carried out to evaluate their impact on the communities on the basis of the evaluation method defined (4.2).

4.1. Technical description of the systems

This study evaluates 9 electrification systems installed in 6 communities between 2008 and 2012 (Fig. 3). These systems represent all the technologies for electricity generation (solar PV, wind, micro-hydro) and distribution (individual systems and microgrids) installed as part of the rural electrification process that took place in Cajamarca. Table 3 shows the generation and distribution technologies of each project, as well as the number of households, schools, health centres and other buildings electrified. Next, a technical description of the systems implemented in each community is briefly presented.

Alto Peru: This is an extensive community located in a mountainous region with significantly different energy resources throughout the area (see Domenech et al. [18], for a detailed study of the resource potential of the community). This, together with budget limitations, forced the project to be implemented in different stages. This study focusses on the next three electrification steps. First, a small river waterfall was used for a 2 kW micro-hydro power plant to supply 4 houses and the school with a microgrid. This technology provides continuous supply to the school but does not work at nights to allow irrigation; therefore batteries were installed to cover the nocturnal electricity needs. Then, attention was given to the health centre, far from rivers and in the lee of a mountain. In

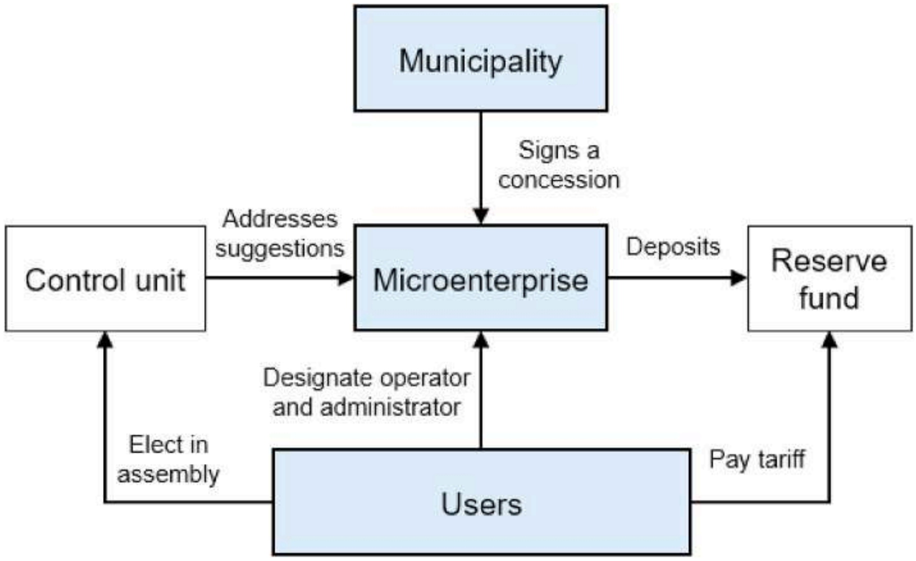

Fig. 2. Graphical representation of the management model implemented by PA.

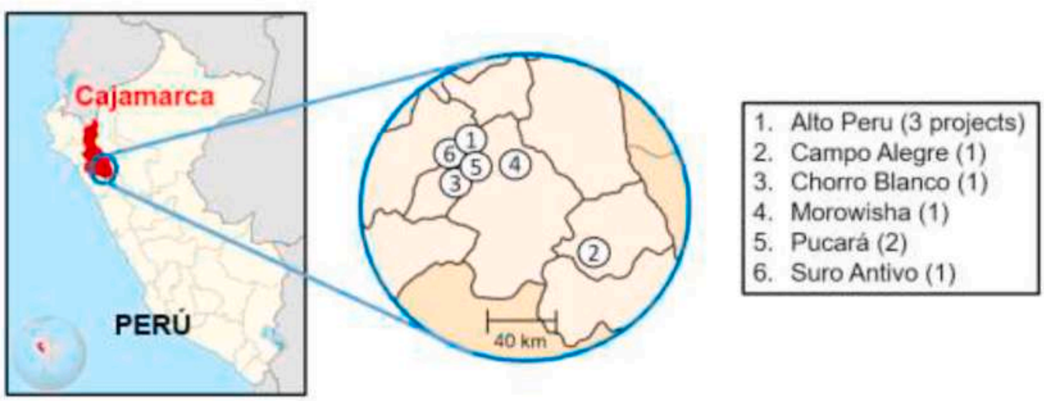

Fig. 3. Location of the communities in which projects are assessed.

Table 3
Main technical features and beneficiary buildings of each project.

		Technical description		Beneficiary buildings			
Community	Projects	Technologies generation option	Distribution option	Households	Schools	Health centre	Other facilities
1) Alto Peru	1)	Micro-hydro (H)	Microgrid (M)	4	1		
	2)	Solar PV (PV)	Microgrid (M)	2		1	2 restaurants
	3)	Solar PV (PV)	Individual systems (I)	39			2 grocery stores
2) Campo Alegre	4)	Solar PV (PV) and Wind (W)	Individual systems (I)	20			
3) Chorro Blanco	5)	Micro-hydro (PV)	Microgrid (M)	37	1		
4) Morowisha	6)	Solar PV (PV) and Wind (W)	Microgrid (M)	4	1		
5) Pucará	7)	Micro-hydro (H)	Microgrid (M)	22	1		2 churches
	8)	Solar PV (PV)	Individual systems (I)	7			
6) Suro Antivo	9)	Micro-hydro (H)	Microgrid (M)	100	1		

order to provide adequate supply quality to this important building, a 760 W PV microgrid was installed, which also provided excess electricity to 2 nearby households and 2 restaurants. Finally, because of the dispersal of the remaining 39 households and 2 grocery stores, as well as the social conflicts among the population that limited the applicability of microgrids, individual 95 W PV systems were chosen.

Campo Alegre: Given the lack of nearby waterfalls and the scattered distribution of the households, an individual supply solution was chosen using, for the first time in Peru, hybrid small wind-PV systems for the 20 households. In particular, a nationally produced 300 W wind turbine was installed at each household, in addition to a 50 W PV panel to reinforce supply quality [12]. Moreover, unlike all the other projects, to save costs inverters were not included and users were supplied with DC straight from the batteries.

Chorro Blanco: The centre of this community is less than 1 km from a river, so a 20 kW micro-hydro power plant was installed to supply electricity to the 37 households and a school (a few years later) with microgrid-based distribution. After an agreement reached by all the community, the power plant works only at the peak demand hours (in the mornings and the evenings) so the inhabitants have adapted their schedules to the availability of electricity.

Morowisha: A 4 kW micro-hydro power plant was initially conceived. However, opposition from some beneficiaries, who use water from the river for irrigation, made this technology inviable. Therefore, a wind-PV microgrid based on a 500 W turbine and eight 50 W PV panels was conceived for the village centre, supplying 4 households and the school.

Pucará: This community has a relatively high population density at the centre, while some households are located far from each other on the outskirts, scattered over a mountainous region. Therefore, two different electrification systems were implemented. Taking advantage of a nearby river waterfall, an 11 kW micro-hydro power plant was installed to supply 22 households, a school and 2 churches with a microgrid. Meanwhile, individual solar systems (95 W) were implemented in the 7 nearby households.

Suro Antivo: This community is located close to an important river, around 500 m from the centre, so a 25 kW micro-hydro power plant and a microgrid were installed to cover the electricity needs of 60 houses (the 45 closest to the centre in the first phase; the remaining 15 in the second phase a few months later). Given the good performance of the system, the assembly has recently decided to expand the grid to 40 houses and a school from two nearby communities: Ingatambo and El Chorro.

Regarding the management model, as mentioned before, a similar scheme was implemented for all communities. All the families are trained in the efficient usage of electricity as well as in carrying out domestic maintenance, including batteries. Electricity is mainly used for in-house purposes such as lighting and telecommunications and, in the case of micro-hydro plants, also for public lighting and community productive activities. Indeed, when the demand increases, the monthly tariff is progressively more expensive for wind and PV systems because of the limited supply while it is progressively cheaper for the hydro.

4.2. Field research

A field visit was made to the 6 studied communities in order to analyse their socio-economic development and the performance of the different electrification systems through sustainability objectives and indicators. In this visit, two different surveys were presented and answered by technicians and families. Table 4 shows, for each combination of electricity generation technology (solar PV, PV; wind, W; and micro-hydro, H) and distribution (individual systems, I; microgrid, M), the amount of technical and family surveys carried out, and the percentage of beneficiaries interviewed. The number of beneficiaries addressed for each electrification system was influenced by the total number of users (and the diversity among them), in order to gather the complete mindset of the beneficiaries. Therefore, more surveys were necessary for H-M systems than for PV-I and PV-M, for example, to achieve the appropriate rates of beneficiaries interviewed [19].

Technical surveys are answered by a representative and the technical operator of the community. First of all, a general overview of the electrification systems was given to report the occurrence of any relevant or unexpected events. Next, the survey was divided into 4 sections:

Table 4
Distribution of technical and family surveys about the electrification systems.

System	Technical surveys (T)	Family surveys (F)		
		Number of surveys	Number of people represented	% of beneficiaries interviewed
PV-I	2	9	34	18.48
PV-M	1	1	3	37.5
PV/W–I	1	8	38	47.5
PV/W-M	1	2	7	43.75
H-M	4	14	57	11.31

1. Operating conditions of the electrical equipment.
2. Implementation of civil work to increase lighting points, allow internet connection or improve access to schools or health centres.
3. Possible effects of logging due to the project implementation and generally negative environmental consequences on the community resources.
4. Maintenance plans developed by the community, reporting specifically their involvement in maintenance tasks and the availability of tools and other equipment in households for such purposes.

In addition, a total of 34 family surveys were made, representing 139 beneficiaries. This survey focusses on understanding the beneficiaries' perception of:

- The quality of the supply received at households.
- The impact of the project on their lives, focusing on health, education and comfort issues.
- The correct or incorrect use by their neighbours, resulting in potentially negative effects on their own supply or on the environment.

Both surveys included open and multi-choice questions to obtain as much information as possible and, at the same time, facilitate the reasoning process of the people interviewed. For further details of the technical and family surveys see Appendices A and B, respectively.

5. Evaluation results

As stated in Fig. 1 the evaluation method is based on an assessment of the evolution of the sustainability objectives by means of project visits at different moments. First (5.1), the fulfilment of the objectives is qualitatively assessed by comparing the conclusions of the two visits in some of the projects. Then (5.2), a more complete analysis is carried out for all the studied communities from the surveys conducted in the second field visit. Indicators are then used to quantitatively evaluate the sustainability objectives. The synergy between both analyses provides a detailed picture of how the electrification projects have influenced beneficiaries' the development, allowing recommendations to be finally extracted in the next section.

5.1. Phase 1. qualitative assessment of the progress experienced by four communities

To start with the presentation of results, a qualitative approach is taken to compare the status of the electrification systems from the first visit in 2011–12 (Table 5, first column of each community) with that obtained in the second one in 2016 (Table 5, second column of each community). Since the aim of this phase is to perform a high-level evaluation of the progress experienced by the communities, only the objectives are qualitatively assessed; the detailed evaluation of the subobjectives through the indicators is carried out in phase 2. Moreover, only the four communities that were visited at both moments are evaluated: Alto Peru, Campo Alegre, Chorro Blanco and Suro Antivo. The electrification projects implemented in these communities can be considered representative of all the options for electricity generation (solar PV, PV; wind, W; micro-hydro, H) and distribution (individual systems, I; microgrid, M). For the evaluation, linguistic scales composed of three (i.e., Good, Medium, Bad) or two options (Yes/No) are used, as in similar projects [4].

In Alto Peru, three electrification systems were installed between 2009 and 2010, based on different options for electricity generation and distribution. After about two years (2011–12), apart from the good technical performance of the systems, most of the objectives were already negatively assessed. As in other communities, a uniform baseline payment tariff was set, regardless of the different systems implemented. This variety of electrification options produced significantly

Table 5
Qualitative comparison of the fulfillment of the objectives in the two evaluation instants.

Dimension	Objective		Assessment scale	Alto Peru (PV–I, PV-M, H-M)		Campo Alegre (PV/W–I)		Chorro Blanco (H-M)		Suro Antivo (H-M)	
				1st visit	2nd visit	1st visit	2nd visit	1st visit	2nd visit	1st visit	2nd visit
Technical	OT1	Performance	Good/Medium/Bad	Good	Bad	Good	Medium	Good	Good	Good	Good
	OT2	Maintenance	High/Medium/Low	Low	Low	Medium	Low	High	High	High	High
Social	OS1	Quality of supply	High/Medium /Low	Low	Low	Medium	Low	High	High	High	High
	OS2	Collaboration among users	High/Medium/Low	Low	Low	Low	Low	High	High	High	High
	OS3	Institutional support	Yes/No	No	No	Yes	No	No	No	No	Yes
Economic	OEC1	Payment rate	High/Medium/Low	Medium	Low	High	Low	High	High	High	High
	OEC2	Productive increase	Yes/No	No	No	No	No	No	Yes	Yes	Yes
Environ-mental	OEN1	Pollution	Yes/No	No	No	No	No	No	No	No	No
	OEN2	Deforestation	Yes/No	Yes	Yes	No	No	Yes	Yes	Yes	Yes

different supply qualities, generating a feeling of unfairness among some users. When after some years the systems started to fail, the payment rate diminished, thereby reducing the ability to maintain the systems and repair failures. As a result, only some of the individual PV systems are still working, while the microgrids based on a micro-hydro plant and solar PV have been abandoned.

In Campo Alegre, individual wind-PV systems had been running successfully for 3 years when the first evaluation was carried out. Although good service quality was reported, some beneficiaries complained about the high frequency of failures that were difficult to repair due to the low collaboration among users. In 2011, the project management was transferred from PA to Hidrandina. Subsequently, conflicts arose in the community caused by the management of money for spare parts, leading to considerable economic difficulties for beneficiaries and a lack of appropriate system maintenance. Finally, the beneficiaries gradually stopped paying the electricity tariffs and focussed only on maintaining their own equipment with their limited technical knowledge. In 2016, 13 out of 20 systems were still running, until a major failure occurs.

In Chorro Blanco, two years after its setup (2011–12), the micro-hydro plant was providing the community with a high-quality electricity service. Since then, regular and effective maintenance and a successful management model, based on community collaboration, have ensured a well-maintained high-quality power supply to cover the needs of beneficiaries. Although the support of the municipality has been requested and denied several times, the community has successfully developed by itself, with new productive activities. It has even extended the microgrid to a nearby municipal school, permitting the use of computers and internet. More initiatives are currently being planned, taking into account the underuse of the plant: only 5 kW out of the 20 kW capacity.

In Suro Antivo, a similar high-quality service situation to Chorro Blanco was reported in the first evaluation, a year after the installation of the micro-hydro plant. Also, an efficient management model enabled productive initiatives from the beginning, such as a sanitation project for the water channel or several small businesses (grocery stores, woodworking, etc.). Since then, the municipality has started providing active support to the project, maintaining the highest technical and social standards. In addition, the microgrid has been extended to 40 additional users and a school (31 students and 2 teachers) belonging to the nearby communities of Ingatambo and El Chorro. Awareness of the project's success has also motivated the community to try new productive activities and some beneficiaries have expressed their desire to attempt more technical irrigation or modern woodworking procedures. This cyclical process is illustrated in Fig. 4.

The comparative evaluations of these four projects show significantly different outcomes. Regarding electricity generation, given their variable nature the PV and wind projects have not offered adequate supply quality from the beginning. This, together with power limitations, has limited the opportunities for productive activities, causing

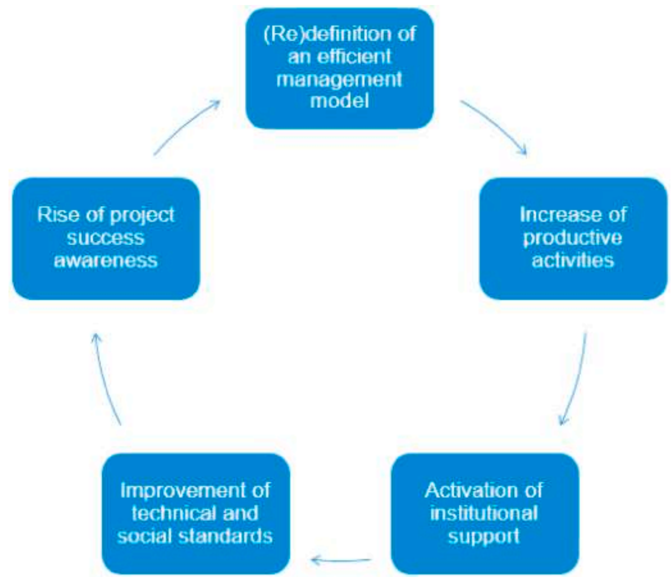

Fig. 4. Successful cyclical process observed in the community of Suro Antivo.

social conflicts and a lack of confidence among users, who have gradually stopped paying the tariff. Indeed, maintenance has not been properly performed, causing greater limitations in performance and, ultimately, abandonment of the system. In contrast, micro-hydro power plants provide a higher supply quality and require a strong community involvement after installation [19]. Hence, new productive activities can be launched once there is an effective management model, making users aware of the need for adequate maintenance and thereby reinforcing performance. Note that for the micro-hydro in Alto Peru, the limited working time (12 h/day) and the subsequent need for batteries has raised the project cost while also limiting supply quality, which is at the root of its lower performance in comparison with Chorro Blanco and Suro Antivo. Concerning the electricity distribution, microgrids require close collaboration among users to reach agreements and solve potential problems, which has failed in Alto Peru but worked in Chorro Blanco and Suro Antivo. Individual systems have worked for longer periods depending on how each particular family undertakes the maintenance tasks. However, families are unable by themselves to cover the replacement of failed equipment, so the lack of a community management model also has a negative effect.

5.2. Phase 2. quantitative assessment of the situation of the communities

A further analysis is now presented, focusing on the status of the electrification systems observed in the second visit and the complete development experienced in the 6 studied communities. As stated in section 3, the fulfilment of the sustainability objectives is now quantitatively evaluated through indicators (Table 6).

The assessment is divided in the next paragraphs, considering the different dimensions assessed:

1. The technical status of the systems. The main efforts in this part concentrate on understanding the causes behind the greater or lesser success of the electrification projects.
2. The social development of the communities, focusing on the beneficiaries' perception of the improvement in their daily lives and the measures taken by the communities to strengthen the organization as a whole.
3. The economic consequences of the projects for the communities, differentiating the changes in new productive activities and the default rate according to the system configuration and the management model used.
4. The environmental impact on the local resources since the project's implementation.

5.2.1. Results of the technical aspects

The projects can be divided into those in good, medium and bad working condition (IT1.1). A correlation exists between the operating condition of the systems (IT1.1) and the quality of the maintenance performed by the operators (IT2.4 - IT2.6), responsible for corrective and preventive tasks, and the external technicians (IT2.7) who are called for major repairs. Despite the training courses held by PA during the project design and implementation, the technical knowledge of the beneficiaries is quite low and their contribution to maintenance, although existing (IT2.1), is often insufficient. In fact, only the beneficiaries in Suro Antivo, Chorro Blanco and Pucará have tools at home for small repairs, and only in Pucará do they have maintenance handbooks (IT2.2, IT2.3). This lack of tools and handbooks makes beneficiaries highly dependent on external technicians and community operators to perform the necessary maintenance. When analysing this correlation in detail, mainly in the systems working in good condition (Chorro Blanco, Pucará and Suro Antivo), the operators are reported as fulfilling their duties (IT2.5), which is positively valued by the beneficiaries (IT2.6). Moreover, these communities report the highest number of designated operators (IT2.4). On the other hand, the beneficiaries' perception of the work from both the operators and external technicians decreases when the operating conditions of the systems are not as good (IT2.6, IT2.7).

Accordingly, the experience of un-successful projects (IT1.1) shows that community involvement is essential for organizing an effective management model capable of overcoming technical difficulties. For example, in Morowisha, the wind-PV microgrid had been working for three years, when lightning caused fatal damage to the inverter. Although the external technician was asked to come to repair it, the community decided to split the emergency fund and no tariffs are paid anymore. Users are now without electricity or with small PV panels and batteries. One year before the incident, however, the school service was stopped since parents did not want to pay the electricity tariff. Beneficiaries from Campo Alegre also stopped paying the tariffs after an incident with the management company, which has left the community incapable of dealing with major failures affecting the individual systems. Despite the deteriorating operating conditions, small damages are still repaired by a local operator, whose work is appreciated by the community (IT2.6). Another example of ineffective maintenance is observed in the two non-working projects evaluated in Alto Peru. The micro-hydro powerhouse is dirty, partly demolished and covered by undergrowth. Meanwhile, electricity lines in the solar-PV microgrid are useless; and only one family, which became independent, still has electricity access.

Effective maintenance is particularly important for more complex systems, which can base their electricity generation on a micro-hydro plant (instead of wind turbines or PV panels); their distribution is via microgrids rather than individual systems, or using both in combination. If such effective maintenance is achieved, those systems can provide a high-quality and abundant supply, widely fulfilling community expectations (IT1.3). Individual systems based on wind or PV, on the other hand, are simpler and can perform for longer without high maintenance. However, they usually have higher limitations (IT1.3) as the amount of electricity provided is not as flexible to changes in demand. Although the continuity of the supply against failures is mostly high, regardless of the technology used for electricity generation (IT1.2), differences appear when analysing the causes of serious damage. Thus, wind systems are more likely to fail due to the wind turbine mast collapsing as a result of heavy wind or lightning, as happened in Campo Alegre. PV systems, on the other hand, are easier to maintain as they are placed closer to the ground. After failures in the wind turbines, batteries are the equipment most prone to failure, which has major effects on the individual systems autonomy.

5.2.2. Results of the social aspects

In all cases, candles were used for lighting before project implementation. Although the use of candles is still significant (around 50% of the families continue to use them regularly, IS1.5) and despite the failures observed in some communities, the beneficiaries are generally highly satisfied with the positive effects of the electrification projects on their lives (IS1.1). The beneficiaries perceive a great improvement in health (IS1.4), basically due to a reduction in the amount of time using candles. Also, the electrical systems ease household chores (IS1.2), such as cooking or cleaning, and benefit children's education (IS1.3). Indeed, the amount of time spent on homework and literacy in Campo Alegre has increased by 1–2 h [3]. As might be expected, the perception of improvement in education is particularly high within communities where the school was electrified (Morowisha, Chorro Blanco). Despite not achieving the highest satisfaction rate, beneficiaries in Suro Antivo report that the electrical supply to the school has allowed the use of videos and other multimedia material to assist the lessons. At the household level, the electrification projects have been crucial in providing access to TV and radio to almost all beneficiaries of Suro Antivo and Chorro Blanco, and to half of the beneficiaries living in Alto Peru and Pucará (IS1.6). However, access to internet depends on additional support funds and community organization, requires extra equipment such as parabolic antennae and therefore is not extended (only reaching 50% of the families in the best case, Morowisha, IS1.7). This limitation certainly reduces the communities' perception of education improvement.

Beneficiaries who celebrate regular meetings (IS2.1) show greater community involvement, which is key to overcoming technical difficulties as well as ensuring the success of new initiatives. In Chorro Blanco, meetings are held every three months and the management board has been renovated twice since the project implementation. In Pucará, monthly meetings have successfully arranged with the designated operators to share maintenance tasks among all beneficiaries. These meetings are a good example of community engagement and allow sharing techniques and methods of performing maintenance tasks between more and less-experienced beneficiaries. As a result, the community gains a communal perception of behavioural control over the technologies used, since they have a better understanding about how the technology works and how to manage maintenance. This perception of control, proven to have a significant impact on the willingness to use renewable technologies [62], is especially relevant in microgrid-based projects due to their higher design complexity and the equipment sharing.

However, the promotion of new initiatives from the community has obvious economic and social limitations that can only be overcome with the involvement of the municipality. The results of the evaluation show that the municipality has only given active support to the project in Suro Antivo (IS3.1), leading to significant outcomes. First, the electrification microgrid has been extended to the communities of Ingatambo and El

Table 6
Results of the evaluation of the 9 electrification projects.

Dimensions	Indicators		Indicators assessment	Alto Peru			Campo Alegre	Chorro Blanco	Morowisha	Pucará		Suro Antivo
				H – M[a]	PV - M	PV - I	PV/W - I	H - M	PV/W - M	H - M	PV - I	H - M
Technical	IT1.1	General operating condition	Good/ Medium/Bad	Bad	Bad	Medium	Medium	Good	Bad	Good	Good	Good
	IT1.2	Continuity of supply against failures	High/ Medium/Low	–	Medium	High	High	High	High	Medium	Medium	Medium
	IT1.3	Families who feel the system capacity is sufficient	Percentage of families (%)	–	0	42.9	26.3	57.1	57.1	84.8	0	62.5
	IT2.1	Participation of the beneficiaries in maintenance tasks	Yes/No	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes
	IT2.2	Presence of operation manuals in houses	Yes/No	No	No	No	No	No	No	Yes	–	No
	IT2.3	Presence of maintenance tools in houses	Yes/No	No	No	No	No	Yes	No	Yes	–	Yes
	IT2.4	Number of designated operators	–	0	1	2	1	7	1	8	0	3
	IT2.5	Type of maintenance realized	Preventive/ Corrective/ None	None	None	None	Corrective	Preventive	None	Preventive	Preventive	Corrective
	IT2.6	Perception of the operators work	Good/ Medium/Bad	–	Medium	Bad	Medium	Good	Medium	Good	Good	Good
	IT2.7	Perception of the external technicians work	Good/ Medium/Bad	–	Good	Medium	Good	Good	Good	Good	Good	Good
Social	IS1.1	Satisfaction with the quality of supply	High/ Medium/Low	–	Medium	High	High	High	High	High	High	High
	IS1.2	Perception of easier household chores	Percentage of families (%)	–	100	67.9	100	100	100	100	100	100
	IS1.3	Perception of the improvement in education	High/ Medium/Low	–	Low	Medium	Medium	High	High	Medium	Medium	Medium
	IS1.4	Perception of the improvement in health	Percentage of families (%)	–	100	100	100	100	100	100	100	100
	IS1.5	Families who no longer use candles	Percentage of families (%)	–	100	60.7	42.1	100	57.3	61.5	0	54.2
	IS1.6	Gained access to TV or radio	Percentage of families (%)	–	0	42.9	21.1	100	0	50.0	0	70.8
	IS1.7	Gained access to internet	Percentage of families (%)	–	0	14.3	0	42.9	57.1	23.1	0	0
	IS2.1	Frequency of neighbours' meetings	–	None	None	None	None	Quarterly	None	Monthly	Monthly	Weekly
	IS2.2	Perception of equality in consumption	Percentage of families (%)	–	100	82.1	92.1	100	57.1	42.3	0	100
	IS3.1	Involvement of the municipality with system monitoring and financial support	Yes/No	No	No	No	No	No	No	No	No	Yes
Economic	IEC1.1	Families paying promptly	Yes/No	No	No	No	No	Yes	No	Yes	Yes	Yes
	IEC1.2	Families satisfied with the tariff system	Percentage of families (%)	–	0	71.4	81.6	100	57.1	76.9	100	54.2
	IEC2.1	Families who have increased in productivity	Percentage of families (%)	–	0	10.7	36.8	0	0	34.6	0	37.5
	IEC2.2	Families who have started new productive activities	Percentage of families (%)	–	0	10.7	55.3	0	0	88.5	14.3	41.7
Environmental	IEN1.1	Detection of pollution in water, land and air resources	Yes/No	Yes	No	No	No	No	No	No	No	No
	IEN1.2	Presence of wastes	Yes/No	Yes	Yes	Yes	Yes	No	Yes	No	Yes	No
	IEN1.3	Perception of noise intensification	Percentage of families (%)	–	100	0	65.8	0	0	0	0	0
	IEN2.1	Need of logging at system setup	Yes/No	Yes	Yes	No	No	Yes	No	Yes	No	Yes

[a] Due to the exceptionally bad condition of the system, only the technical survey was performed.

Chorro, benefiting 40 other users and a school with 31 students and 2 teachers. To control the entry of new users to the system, a regulation was agreed to determine an installation fee to cover the installation materials. In addition, the municipal support has also led to the wooden poles being changed for concrete ones and replacement of the electricity transformer, which would have been unaffordable by the community.

Project expansions are definitely a good sign but demand greater organization and community involvement to avoid, for example, operation inequalities due to supply abuse. In fact, some of the beneficiaries of Suro Antivo complained that the microgrid expansion is affecting their own electricity supply, although no misuse is reported (IS2.2). A stronger complaint is observed in Pucará and Morowisha, where a significant percentage of families do not feel there is appropriate use of the electricity service and report abuse by their neighbours (IS2.2). Particularly, in the community of Pucará, a feeling of unfairness has arisen due to the existence of different electrification systems with their own supply quality. In contrast, for the sake of equity, in Chorro Blanco the management model has been modified; beneficiaries who consume more electricity than the amount agreed must pay a surcharge on the base-line tariff. In the case of Campo Alegre, where only individual systems were implemented, the consumption of all users is limited by the capacity of their own equipment, so there are residual complaints in this regard (IS2.2). Such a difference of interaction among users, according to the distribution design implemented (microgrids or individual systems), deserves additional consideration since it complements the discussion presented in Irfan et al. [63]. There, individual behaviour regarding renewable electrification projects was found to be influenced by the actions of the neighbours (following a majority decision). This depended on the socio-cultural context, in particular when comparing the cases of China and Pakistan. However, significant differences can be observed among communities in Peru with a similar socio-cultural context regarding the interaction among users of microgrid distribution projects, in which more complaints are made about inappropriate energy use by neighbours, and those projects based on individual systems.

5.2.3. Results of the economic aspects

A successful management model increases the families' chances of developing new productive activities or increasing productivity (IEC2.1, IEC2.2). For example, in Suro Antivo the operator wants to install a water pumping system to ease irrigation activities during dry periods. Also, although few productive initiatives have been set up, beneficiaries are encouraged to start more technical irrigation or to buy modern tools for woodworking. Such tools have already been purchased by some beneficiaries in Pucará, where activities like opening new grocery stores, selling ice-cream, clothing and cheese-making have also commenced in both the hydro microgrid and the solar-PV individual electrification systems of the community.

As stated, increases in demand are more difficult to face with individual systems. Therefore, new and more intensive productive activities are observed less in such systems. For example, in Campo Alegre some beneficiaries have tried to use a welding machine, but complain that the system is not capable enough. The productive use of individual systems is mainly focused on increasing the productive light hours for sewing or knitting.

The default rate can be directly associated with the operating conditions of the system. As can be seen, the beneficiaries of all correctly performing electrification systems fulfil their obligation to pay (IEC1.1). On the other hand, if the quality of the supply decreases, families gradually stop paying. In this regard, if individual systems are used, each family can take care of its own equipment, so the unwillingness to pay can arise more easily with the first technical problems, as has happened in Alto Peru and Campo Alegre. Conversely, systems organized around a microgrid share the generation and distribution equipment, which reinforces the sense of common ownership and discourages default. A successful management model is also key to keeping beneficiaries motivated and default rates to a minimum. In addition, in the projects design, most communities agreed to set a uniform payment tariff for all the beneficiaries of the community. However, if different electrification systems are installed in one single community, the quality of supply may well be different from one system to the other. This can produce a sense of inequity that can lead to dissatisfaction with the current tariff system (IEC1.2).

5.2.4. Results of the environmental aspects

The micro-hydro plants required civil work and are very noisy while operating. However, since they are installed close to the water flow and far from the houses, there is very little effect on the beneficiaries' lives. Indeed, almost all the noises reported come from the wind turbine helixes, which are particularly annoying as they are installed in individual systems next to the houses, as in Campo Alegre (IEN1.3). In addition, some users in Alto Peru complain about a warning alarm coming from the inverters, unattended due to the poor maintenance conditions. Water, land or air pollution is generally not observed in any community (IEN1.1). However, minor land pollution has been caused due to the poor conditions of the hydro turbine in Alto Peru, with its abandoned electrical wiring, in addition to the civil work carried out.

Logging was mainly carried out in the hydro-based projects (IEN2.1). Nonetheless, no greater environmental effect is expected, since it was small scale logging located outside the community and only occurred once. Also, limited logging was carried out in the microgrid-based projects to extend the electric lines. Finally, waste is observed in the majority of communities (IEN1.2), although beneficiaries do not express much concern about this matter.

6. Discussion and recommendations for future projects

The experience from the projects evaluated shows that stand-alone electrification systems based on renewable energies are a suitable option for electrifying remote areas, but require dealing with technical and organizational challenges. Indeed, conclusions can be extracted for each electricity generation and distribution option and can be used as recommendations for future electrification plans of this kind. Therefore, conclusions to fulfil the sustainable objectives are first summarized (6.1), leading to final recommendations to promoters of future rural electrification initiatives and policy-makers in the sector (6.2).

6.1. Specific recommendations for the sustainable objectives

The experience of the case studies allows discussing the fulfilment of each sustainable objective considered:

- Performance (OT1). All solutions for electricity generation and distribution are technically viable for providing an electricity service in good condition if the appropriate maintenance is implemented (IT1.1). However, higher limitations are reported in regard to individual systems, as they are not as capable of facing increases in demand (IT1.3).
- Maintenance (OT2). Organizing efficient maintenance has proved essential for the viability of the projects, since the technical knowledge of the beneficiaries is usually insufficient (IT2.1 – IT2.3) and they cannot afford repairs when major failures occur. The microgrid-based projects using hydro require a large number of operators to carry out maintenance due to a more complex structure (IT2.4). On the other hand, individual systems based on PV and wind can perform for longer without such regular technical reviews (IT1.1, IT2.5, IT2.6).
- Quality of supply (OS1). All options for electricity generation and distribution are capable of providing a good-quality supply (IS1.1), since improvements in health, daily life and education have been achieved in every project (IS1.2 – IS1.4). Moreover, a strong community commitment is necessary to achieve additional services, such as internet connection (IS1.6 – IS1.7).

- Collaboration among users (OS2). Regular meetings have been shown to be useful for solving potential inequality problems, organizing effective maintenance and encouraging community involvement (IS2.1). Additionally, microgrid-based systems offer the population the opportunity to strengthen mutual efforts since the generation and distribution equipment is shared.
- Institutional support (OS3). The only community where the local authorities actively support the electrification project has been able to extend the electrification system to nearby households (IS3.1). Looking at the other projects, we can see that effective organization through community involvement can definitely compensate for the lack of institutional support, but this organization faces greater difficulties and ambitious initiatives are usually blocked due to a lack of resources.
- Payment rate (OEC1). The default rate is closely related to the operating condition of the systems (IT1.1, IEC1.1), since users will always be more willing to pay if they are satisfied with the supply. However, the electricity distribution option can either encourage or discourage default rates when technical problems arise: while users of individual systems can take care of their own equipment, beneficiaries of a microgrid-system have a common installation and are therefore dependent on each other.
- Productive increase (OEC2). As stated before, the flexibility in supply offered by projects with a microgrid distribution allows increases in demand caused by the start or intensification of productive activities. Also, such activities may require a continuous and effective supply, which is most likely to be achieved with micro-hydro plants or with a well-dimensioned battery system (IEC2.1, IEC2.2). Regardless of the system design, an effective management model is essential for reaching consensus on changes in the tariff system as a result of increased electricity demand due to productive activities. Thus, complaints about abuse or inappropriate use of the supply can be kept to a minimum.
- Pollution (OEN1). Noise perceived by the beneficiaries comes mainly from the helixes in wind systems (IEN1.3). They are particularly annoying when using individual systems, since they are installed closer to the houses. The effect of micro-hydro plants is not as tangible among the beneficiaries, since they are installed far from the village centre. However, significant civil work is required at installation and can have a greater effect on the local environment if in bad condition.
- Deforestation (OEN2). Logging activities mainly occur during the installation of micro-hydro plants and the extension of electric lines (IEN2.1), although little impact is perceived by the communities.

6.2. Final recommendations to promoters and policy-makers

As can be seen from the last discussion, all aspects are interconnected and the fulfilment of some objectives increases the chances of also fulfilling others. In addition, an efficient management model is shown as essential for organizing effective maintenance and ultimately ensuring the long-term sustainability of the project. General insights obtained from the experience of this work are now provided for all promoters of future electrification systems in rural areas, whether they are inhabitants, local or regional authorities, companies or non-governmental organizations.

- Regarding the choice of the technologies for electricity generation, successful projects have been observed with PV, wind and hydro. Thus, despite the above-mentioned advantages and drawbacks of each technology, they are all capable of providing an appropriate electricity service and their selection must depend mainly on an analysis of potential resources.
- Regarding the choice of the electricity distribution option, microgrid-based projects can be suitable for highly cohesive communities which can organize effective maintenance. On the other hand, individual systems might perform better in lower-density communities without significant engagement. For rural communities with non-homogeneous household distribution, there are tools that calculate the optimal design, combining microgrids and individual systems and taking economic, technical and social issues into account [16].
- Regarding the management model implementation, some final remarks must be made:
  - o The tariff system must be appropriate, to facilitate regular technical reviews and component replacements in case of failures.
  - o A fixed tariff for all users is more common and is more likely to generate a wide consensus in the initial stages of the project. However, experience with successful projects shows agreement regarding increases above the base-line tariff for users who consume more electricity, which reduces feelings of inequity.
  - o Community engagement and institutional support from local and regional authorities must be sought from the design phase, providing detailed information and training to final users. Consequently, more economic resources and technical skills are available at both community and institutional levels, which increases the chances of project growth through the development of productive activities.

In short, policy-makers should actively promote off-grid renewable systems to electrify isolated rural areas. Regulatory frameworks are necessary to enable access to technical equipment for electricity generation and distribution. In this sense, local manufacturers and repair workshops must be promoted in order to provide reliable maintenance to nearby communities. Subsidies must also be maintained as a supplement to the tariff set in the community, in case this is not high enough to ensure equipment replacement. Finally, a clear commitment must be made, from the design phase of the project, by local authorities to provide active support to promoters of electricity access.

7. Conclusions

This work evaluates 9 renewable-based electrification projects implemented in 6 rural communities in the region of Cajamarca (Peru) combining different options for electricity generation (solar PV, wind or micro-hydro) and distribution (individual systems or microgrids). In each community, a field visit has been conducted to determine the technical status of the system, the development experienced and the negative effects on the local environment. During the visits, a technical expert in each community was interviewed and a total of 34 surveys were carried out to families representing 139 beneficiaries, to observe their perception of the overall performance of the projects. These surveys were made 4–8 years after the projects' implementation, which reinforces the long-term evaluation of the 9 sustainability objectives defined through indicators. A two-phase procedure has been used for the assessment. In phase 1, a qualitative fulfillment of the objectives has been determined at two moments (2011–12 and 2016), thereby allowing an evaluation of the progress experienced by four communities. In phase 2, a more complete analysis of all communities is quantitatively performed through 28 indicators.

The results obtained are useful for both rural electrification promoters and policy makers, who should take into account that:

- Regarding the technologies for electricity generation, micro-hydro is confirmed as permitting a continuous high-quality supply when effective organization can be maintained over time. Meanwhile, solar PV and wind systems are also technically viable options for expanding rural access to electricity and can perform successfully with a low frequency of technical revision. The ultimate choice of technology should be based mainly on the resource potential of the region and the investment capacity.

- Regarding the distribution option, microgrid-based projects encourage and require higher community involvement and stronger organization to cover maintenance tasks due to more complex designs. If achieved, they are flexible enough to allow long-term project expansions and start new productive activities. Meanwhile, individual systems are easier to install and do not require as much community organization, although experienced technical operators and funding are necessary to deal with failures and repairs.
- Regardless of the generation or distribution options chosen, an effective management model involving both the community and local authorities is essential for long-term success. Particularly, the model should embrace a consensual tariff system that allows replacement of equipment and ultimately avoids discouragement among community members.

Future research could focus on strengthening the conclusions of this paper by extending the evaluation to other regions in Latin America and the rest of the global South. The method of evaluation should be adapted, if necessary, to the context of each country in order to encompass the factors and technologies contributing in each case to long-term project sustainability.

Author statement

Marc Juanpera: Methodology; Investigation; Writing – original draft. Bruno Domenech: Resources; Conceptualization; Methodology. Laia Ferrer-Martí: Conceptualization; Validation; Project administration. Adriana Garzón: Methodology; Investigation; Writing – original draft. Rafael Pastor: Validation; Supervision; Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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APPENDIX A

The technical surveys were carried out in Spanish with a representative and a technical operator of each visited community, to obtain a general overview of the situation of the electrification equipment and the involvement of the community in maintenance tasks. A compressed translation is here presented for dissemination purposes. They were composed of 4 parts (T1-T4).

T1
Operating conditions of the electrical equipment (combining open with multi-choice questions)

Type of system:	Province	Community:	Coordinates:
Equipment for electricity generation 1 (W):	Brand/Model:	Operation state:	Observations:
Equipment for electricity generation 2 (W):	Brand/Model:	Operation state:	Observations:
Equipment for electricity generation 3 (W):	Brand/Model:	Operation state:	Observations:
Batteries (Ah):	Brand/Model:	Operation state:	Observations:
Inverters (W):	Brand/Model:	Operation state:	Observations:
Controllers (W):	Brand/Model:	Operation state:	Observations:
Additional observations:			
Is there protection against atmospheric discharges?		Yes; No	Observations:
Is the location of the generation equipment illuminated? Is it in good condition?		Yes; No Good; Regular; Bad	Observations:
Is there a perimeter fence to limit the location of the generation equipment? Is it in good condition?		Yes; No Good; Regular; Bad	Observations:
Can debris or undergrowth be observed?		Yes; No	Observations:

T2
Implementation of civil work (combining open with multi-choice questions)

N° of poles: Material: Metallic; Wooden	Conditions: Good; Bad	Distribution voltage:	Observations:
Who performed maintenance of the poles? With which frequency? Is it performed professionally and safely?			
N° of outside lights: Type of lighting poles: Single blade; Double blade	Conditions: Good; Bad	Voltage: Type and power (W):	Observations:
Who performed maintenance of the poles? With which frequency? Is it performed professionally and safely?			
Are the access roads paved?	Yes; No	Before; due to; After the system	Observations:
Does the community have access to internet?	Yes; No	Before; due to; After the system	Observations:
Does the community have access to mobile telephony with good coverage?	Yes; No	Before; due to; After the system	Observations:
Does the community have a school?	Yes; No	Before; due to; After the system	Observations:
Does the community have a health centre?	Yes; No	Before; due to; After the system	Observations:

T3
Environmental impact (multi-choice questions)

The logging is for:		Microgrid lines; Public lighting
Who is in charge of the logging?		Community (which frequency?); Others (which frequency?);
Is there water pollution?		In river; Lake; Pipes; Wells; None
If yes, which water pollutant is observed?		Rubbish; Solid waste; Lubricants; Fuel, Sewage; Others?
Is there soil pollution?		Yes; No
If yes,	where is the soil pollution mostly located?	House surroundings; Community; Community surroundings
	which soil pollutant is observed?	Organic rubbish; Hydrocarbon; Plastic
Is there air pollution?		Yes; No
If yes;	the air pollution affects people from?	House surroundings; Community; Community surroundings
	which air pollutant is observed?	Waste combustion; Wooden/Coal kitchen; Others?
Are there collateral damages due to pollution?		Yes; No
If yes;	do the collateral damages impact ecosystems?	Plants; Animals; Others?
	do the collateral damages impact people?	Adults; Children; Elderly
Observations:		

T4
Maintenance plans (combining open with multi-choice questions)

Are there maintenance plans for the electrification system, the distribution network to houses and public lightning?	Yes; No		Observations:
Which type of maintenance is performed in the community?	Predictive; Preventive; Corrective		Observations:
Is the community involved in maintenance?	Electric system; Distribution network; Public lighting		Observations:
Indicate which equipment is attended by the community operator:			
In general, which type of maintenance is done by the operator?	Predictive; Preventive; Corrective		Observations:
How many operators are there in the community?	Male (<65 years):	Female (<65 years):	Female (<18 years):
	Male (>65 years):	Female (>65 years):	Male (<18 years):
Does the community have tools for maintenance purposes?		Yes; No	
Does the community operator receive economic retribution? Is it enrolled in a social program from the government?		Yes; No	Observations:
Does the community have operation manuals to maintain the technologies located there?		Yes; No	
Are there spare parts in the community for emergency situations?	Yes (which ones?); No;		
Which type of maintenance is performed by external technicians?	Predictive; Preventive; Corrective		Observations:
How frequently are maintenance inspections performed by external technicians?	Weekly; Monthly; Annually		Observations:
Which means of communication are there among community and external technicians?			

APPENDIX B

The family surveys were held in Spanish for the beneficiaries of the system and a compressed translation is presented here for dissemination purposes. They were composed of 3 parts (F1–F3).

F1
Perception of the supplied quality received by households (multi-choice questions)

F1.1 How would you qualify the quality of the electricity service?	Excellent; Very good; Good; Bad; Very bad; Terrible
F1.2 Would you consider that the community operators are qualified and diligent regarding system failures?	Very qualified; Slightly qualified; Not qualified at all Very diligent; Slightly diligent; Not diligent at all
F1.3 Would you consider that maintenance operators are qualified and diligent regarding system failures?	Very qualified; Slightly qualified; Not qualified at all Very diligent; Slightly diligent; Not diligent at all
F1.4 How would you qualify the system failures regarding frequency and duration?	Very frequent; Slightly frequent; Not frequent at all Very extended; Slightly extended; Not extended at all
F1.5 Would you consider that the quality of the service has changed? Since when?	It has improved; It has worsened; It has remained the same First months; First years; Recent years/months
F1.6 In case the household has an additional self-generation system; did you install for surplus demand requirements, bad quality of the service or was it there before the system installation?	Surplus demand requirements (please say which ones); Bad quality of the service; It was there before (active nowadays?) First months; First years; Recent years/months
F1.7 Which are the most common system failures?	Open answer.

F2
Perception of the socioeconomic impact of the project on the beneficiaries' lives (multi-choice questions)

F2.1 How would you qualify your or your family's access to education/information as consequence of the electricity service in the community?	Definite improvement in access to education; Slight improvement in access to education; no impact on education Determine for: Access to internet (Yes; No)? Access to radio/TV (Yes; No)? Others?
F2.2 Would you consider that the household chores (cooking, cleaning, clothes washing) have changed?	Yes; No; Why?
F2.3 Would you consider that your or your family's health conditions have improved since the electricity service?	Yes; No; Why?
F2.4 Would you consider that the system has allowed the development of new productive activities?	Yes; No; Which ones?
F2.5 Would you like to start new productive activities using the electric service?	Yes; No; Which ones?
F2.6 Would you consider that the system connections limit the installation of necessary new devices?	Yes; No; Which ones?

F3
Rational use of energy and environmental impact (multi-choice questions)

F3.1 Does the system produce any annoying noise for you or your family?	Yes; No; Which ones?
F3.2 Have you observed any waste accumulation due to the system?	Yes; No; Which ones?
F3.3 Would you say that some neighbours abuse the energy? Has it produced failures?	Yes; No; Which ones?
F3.4 Would you consider that a different tariff system should be implemented?	Yes; No. If Yes: Fixed tariff; According to consumption
F3.5 Have you observed any water pollution due to the system?	Yes; No; Which ones?

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4. PAPER 2: Multicriteria-based methodology for the design of rural electrification systems. A case study in Nigeria

ABSTRACT

Electrification with micro-grids is receiving increasing attention to electrify rural areas in developing countries. However, determining the best local supply solution is a complex problem that requires considering different generation technologies (i.e. solar PV, wind or diesel) and different system configurations (off-grid or on-grid). Most existing decision aid tools to assess this design only consider economical and technical issues in a single optimization process. However, social and environmental considerations have been proven key issues to ensure long-term sustainability of the projects. In this context, the objective of this work is to develop a multicriteria procedure to allow comparing electrification designs with on-grid or isolated micro-grids and different technologies considering multiple aspects. This multicriteria procedure is integrated in a two-phased methodology to assist the design of the system to electrification promoters in a structured process. First, different electrification alternatives are generated with an open-source techno-economic optimization model; next, these alternatives are evaluated and ranked with the multicriteria procedure, which considers 12 criteria representing economic, technical, socio-institutional and environmental aspects. The whole design methodology is validated with a real case study of 26 population settlements in Plateau State, Nigeria. Experts in rural electrification within the Nigerian context have been consulted to weight the criteria and particularize their evaluation for the specific case study. Results show that solar PV technology based systems are the most suitable electrification designs for communities in Nigeria, while grid connection feasibility depends on the size of the community and the distance to the closest national grid consumption point.

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Multicriteria-based methodology for the design of rural electrification systems. A case study in Nigeria

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Electrification with micro-grids is receiving increasing attention to electrify rural areas in developing countries. However, determining the best local supply solution is a complex problem that requires considering different generation technologies (i.e. solar PV, wind or diesel) and different system configurations (off-grid or on-grid). Most existing decision aid tools to assess this design only consider economical and technical issues in a single optimization process. However, social and environmental considerations have been proven key issues to ensure long-term sustainability of the projects. In this context, the objective of this work is to develop a multicriteria procedure to allow comparing electrification designs with on-grid or isolated micro-grids and different technologies considering multiple aspects. This multicriteria procedure is integrated in a two-phased methodology to assist the design of the system to electrification promoters in a structured process. First, different electrification alternatives are generated with an open-source techno-economic optimization model; next, these alternatives are evaluated and ranked with the multicriteria procedure, which considers 12 criteria representing economic, technical, socio-institutional and environmental aspects. The whole design methodology is validated with a real case study of 26 population settlements in Plateau State, Nigeria. Experts in rural electrification within the Nigerian context have been consulted to weight the criteria and particularize their evaluation for the specific case study. Results show that solar PV technology based systems are the most suitable electrification designs for communities in Nigeria, while grid connection feasibility depends on the size of the community and the distance to the closest national grid consumption point.

1. Introduction

Nowadays, around 850 million people do not have electricity access [1], mainly living in rural and remote areas [2]. The conventional strategy to expand electricity access is extending the national grid [3]. However, significant techno-economic constraints can appear in mountainous or remote areas, due to the hilly terrain, scattered communities and low consumption levels [3]. Moreover, individual systems are a cheap and easy electrification option but may arise inequalities within the community and cannot be adapted to potential increases on demand [4]. Alternatively, electrification systems based on micro-grids (MGs) are receiving increased attention, as they provide a greater equity and flexibility in consumption, and cost savings through economies of scale [5,6].

MGs are capable of operating in both stand-alone (off-grid) and grid-connected (on-grid) modes [7,8]. On the one hand, off-grid MGs aim to improve life's quality of people living in areas for which an extension of the national grid could take too much time and is not economic affordable [9]. Differently, if the aforementioned constraints for national grid extension are overcome, on-grid MGs ensure an improvement on reliability and resilience of supply [9], as well as potential electricity exchanges with the main grid that can lead to reductions in the total costs and, consequently, to a more likely economic viability of the electrification project [10].

Regarding the technologies of electricity generation within the MGs, wind and solar photovoltaic (PV) technologies are increasingly used since they are available worldwide [11,12]. In particular, hybrid wind-PV systems are interesting, as they can complement each other and

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reduce project costs while increasing supply quality [2,13]. Despite the growth in hybrid wind-PV systems worldwide, most rural electrification projects in Africa are still based on diesel generators [14]. In fact, in order to achieve universal access to electricity in 2030 [15], the use of diesel technology within the poorest regions of developing countries is expected to grow [16,17].

Therefore, rural electrification planning should take into account scenarios that combine different electricity distribution options (national grid extension and decentralized off-grid systems) with different technologies of electricity generation: renewable and non-renewable [18]. There are several tools able to consider such scenarios and generate electrification alternatives through techno-economic optimization methods. Among all of them, HOMER [19] and ViPOR [20] are widely used in developing countries. In particular, HOMER considers many technologies and designs the generation system meticulously, while ViPOR focuses on distribution scheme planning [21]. Also, open-source tools have been developed for techno-economic optimization and simulation of energy systems, such as OSeMOSYS [22] and, more recently and with greater focus on mini-grids and Solar Home Systems, Offgridders [23].

However, the aforementioned tools only take into account technical and economic issues to identify the best electrification system design for rural locations, which proved to be insufficient to ensure long-term sustainability of the project [24,25]. Additional factors are being considered relevant, such as: adequate policy prescription [26], wide institutional support to electricity programs through solid regulation and incentives to private investment [27] and inclusion of final electricity users' opinions in the design process [21]. In consequence, recently studies have included other dimensions in the evaluation processes of rural electrification systems. Some examples consider five dimensions (technical, economical, ethic-social, environmental and institutional) to define respective sustainable evaluation methodologies [28–30]; while López-González et al. [31] propose four dimensions for the design and evaluation of rural electrification programs: environmental, technical, socioeconomic and institutional.

Introducing new dimensions next to the economic and technical increases the complexity of the projects' design process [21]. Therefore, a two-phased process constitutes an easy-to-follow structure [32]: in phase 1, electrification alternatives are generated using optimization processes; and in phase 2, the best alternative is selected using multicriteria techniques. Thus, a great accuracy is obtained in the problem optimization and the decision-making process gets easier since the potential solutions and their performance is known before deciding [21, 33].

Already some two-phased tools have been designed to assist decision-making in rural electrification problems. For example, OptElDec [34] sizes several technologies to supply electricity to isolated MGs and selects the best one according to their performance on some criteria. Other similar tools also allow combining different technologies, such as SURE [35], and offer a high detail of the final distribution scheme, such as the methodology proposed in Domenech et al. [21]. However, none of these tools consider the possible extension of the national grid when sizing the equipment and selecting the best alternative.

In this context, this research aims to develop a multicriteria procedure to select the best electrification design from different ones considering both on-grid and isolated MGs and combining different technologies for electricity generation. This multicriteria procedure is integrated in a two-phased methodology capable of designing rural electrification systems in a structured process that takes into account multiple aspects. First, electrification alternatives are generated with a techno-economic optimization model. Then, the best alternative is selected based on their performance in 12 criteria grouped into four dimensions: economic, technical, socio-institutional and environmental. These criteria have been defined specifically to allow comparing electrification designs which might consider national grid extension and different generation technologies, and are particularized for each case study based on experts' opinions. The resulting methodology is expected to assist decision and policy makers in this complex process of determining the best electrification design within an integral approach. Also, its performance is finally validated with a real case study of 26 population settlements in Nigeria.

The rest of the paper is organized as follows. In section 2, a quick overview of the two-phased methodology is realized. Sections 3 and 4 deepen the description of the methodology focusing on how alternatives are generated (section 3) and how are evaluated and ranked (section 4). Section 5 applies the methodology to a case study of 26 communities in Nigeria and selects the best electrification alternative for each one. Finally, in section 6 conclusions of the work are summarized and future lines of research are mentioned.

2. Methodology for the design of rural electrification systems

Rural electrification is a multidimensional problem [36] that involves a great variety of stakeholders [37]: from the target group to local industries and non-governmental organizations. Each stakeholder has its particular needs and expectations [38,39] which should be fulfilled with the planned electrification program to ensure long-term sustainability. Therefore, decisions based exclusively on economic and technical issues lack on the interdisciplinary approach needed in the design of an electrification project [40].

Tools for electrification planning usually focus only on the economic and technical side, forgetting or considering with lower detail social and environmental consequences of the system design. In this context, this study utilizes a two-phased design methodology (Fig. 1) which combines techno-economic optimizations of different electrification scenarios with a multicriteria evaluation within a holistic procedure to enable the selection of the best design considering multiple aspects.

In phase 1, different electrification designs are obtained using a techno-economic optimization model. This phase requires a definition of scenarios that may differ in the technologies considered for electricity generation and in the possible connection of the MGs to the national grid. In detail, on-grid and off-grid scenarios are considered, with PV, diesel and wind as generation technologies within the MGs. Then, an electrification alternative is obtained from each scenario using an optimization process aimed at minimizing the annual cost of the electrification project while ensuring technical viability. This phase, and particularly the optimization model used, is further described in section 3.

In phase 2, a multicriteria analysis is designed to evaluate and rank the alternatives in order to allow a justified selection of the best design for each community. Based on similar analysis in the literature, it follows a four-points structure [41]. First, a set of appropriate criteria is defined. These criteria are then weighted in order to establish their

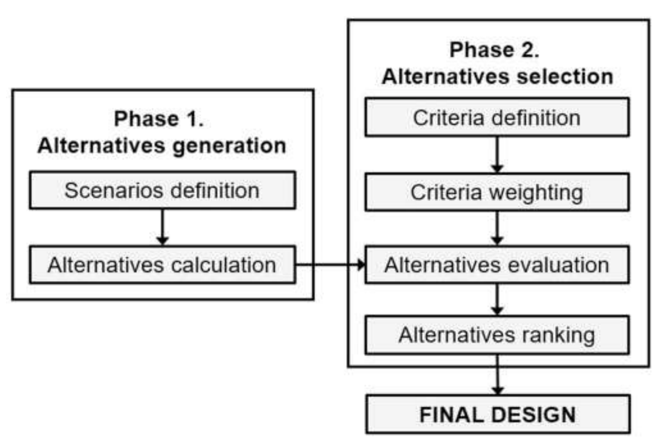

Fig. 1. Methodology followed for the design of electrification systems.

relative importance [42,43]. Next, the electrification alternatives generated in phase 1 are evaluated according to each criterion by assigning a score to each pair criterion-alternative. Finally, a global score for each alternative is calculated by aggregating all evaluation results considering criteria weights. These global scores define the ranking of alternatives and help to identify the best overall alternative. This phase's procedure for the problem addressed is presented and further described in section 4.

3. Generation of electrification alternatives

The electrification alternatives are generated in phase 1 with the optimization model of Offgridders, which considers technical and economic constraints. This is an open-source tool [23] able to first define electrification scenarios by defining the needed assets: i.e. a PV plant, a wind farm or diesel generators. Then, the corresponding alternatives are generated by sizing these assets through a techno-economic optimization process. It is based on the Open Energy Modelling Framework (oemof) [44], which allows modelling any energy system (electrification scenarios in this case), using a graph approach. Thus, the energy graph is the representation of the electricity scenario in graph format.

Following the design methodology represented in Fig. 1, the section is divided into two subsections. These subsections aim to describe how scenarios are defined in graph format (3.1) in order to later calculate the corresponding alternatives with an extended formulation of the optimization model (3.2).

3.1. Scenarios definition

In this study, electrification scenarios that include different system configuration options (off-grid and on-grid) and a variety of technologies of electricity generation (solar PV, wind and diesel) are defined. For each scenario, an energy graph is built. As an example, Fig. 2 shows the energy graph (Fig. 2b) equivalent to an on-grid scenario based on PV, wind and diesel generators (schematically represented in Fig. 2a). As it is shown in Fig. 2a, the electricity distribution network within the community is assumed to be based on a single micro-grid (MG). This MG consists of two electricity buses to supply alternating current (AC) demand and direct current (DC) demand from the respective technologies of electricity generation: PV, wind, diesel and the national grid. While PV and wind generation are determined by weather forecasts, diesel and the national grid are considered unlimited sources for the optimization. Therefore, unlike PV and wind generation, a transformer is considered in the energy graph for the diesel source and the national grid to limit electricity supply in those cases. Both the demand and the weather forecasts are determined by time-series data, detailing the hourly power demand of a community and the solar and wind potential, respectively, during the optimization time.

Additionally, batteries are considered to store energy in DC, while inverters and rectifiers convert energy from one bus to the other. The national grid is modelled with two transformers for electricity consumption and feed-in. Finally, extra symbolic components are also included in the model, such as an excess sink and a shortage source. On the one hand, the excess sink is necessary to vent energy in those time steps when renewable generation is higher than demand. On the other hand, the shortage source works as a fake source to balance out potential shortage on supply. Also, this fake source can be used to intentionally avoid fulfilling demand completely by defining a maximum shortage level allowed. Small shortage levels on annual supply (around 5%) permit not to dimension the energy assets for a particularly bad day, which might significantly reduce investment costs.

3.2. Alternatives calculation

To generate the electrification alternatives, each scenario represented with an energy graph is solved through an optimization model that aims to minimize the total cost of the project for the electrification scenario established. The alternatives obtained are characterized by the cost and size of the electrification equipment. In particular, the multicriteria procedure in phase 2 uses the economic outputs, the optimal power capacities and the optimal dispatch at each hour of the optimization time to evaluate the electrification alternatives.

Offgridders' optimization model has been developed in Hoffmann [45] and used to solve scenarios that include both off-grid and on-grid scenarios with electricity generation based on only solar PV and diesel generators [46,47]. Beyond the essential technical constraints, an additional constraint has been formulated to force battery charge as soon as extra electricity is available [45]. Now, to ease a complete understanding of the alternatives evaluation and ranking described in section 4, an extended formulation of the model (version 3.1) is presented to solve the scenario described in Fig. 1, which also includes wind technology. Moreover, this extended formulation includes additional

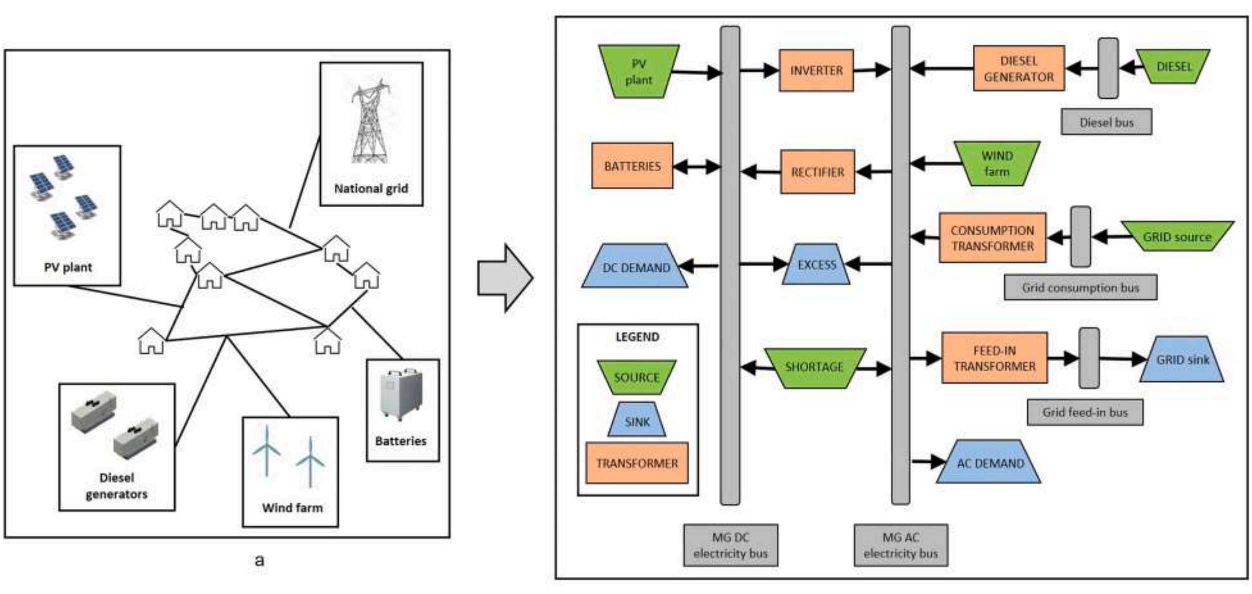

Fig. 2. Scheme of an on-grid electrification scenario based on PV, wind and diesel sources (a) and equivalent energy graph (b).

constraints to allow small shortages on annual demand and to ensure a certain amount of demand can be supplied at any time by weather-independent sources (diesel and the national grid) and the energy stored in the batteries.

3.2.1. Data

- Indices.
  - i assets included in the electrification scenario. This scenario includes: solar PV plant (S), wind farm (W), diesel source (FU), diesel generators (D), batteries (B), inverter (I), rectifier (R), grid source and grid sink (G), consumption transformer (C), feed-in transformer (F), shortage (SH) and excess (E).
  - $t \in \{0, 1, ..T\}$ hourly time step (h). T is the time horizon of the optimization, usually one year (8640 h).
- Economic data.
  - Inv_i investment costs for an installation of asset i ($/kW), $i \in \{W, D, B, I, R, C, F\}$
  - Inv_S investment costs for an installation of the solar PV plant ($/kWpeak)
  - ta_i lifetime of asset i (y), $i \in \{S, W, D, B, I, R, C, F\}$
  - tn lifetime of the project
  - $Opex_i$ specific fixed operational expenditure of asset i ($/kW/y or $/kWpeak/y), $i \in \{S, W, D, B, I, R, C, F\}$
  - $Cvar_i$ variable dispatch costs of asset i ($/kWh), $i \in \{S, W, D, B, I, R, C, F, SH, E\}$
  - p_D diesel price ($/l)
  - p_C grid consumption tariff ($/kWh)
  - p_F grid feed-in tariff ($/kWh)
- Aggregated demand profiles of the community.
  - DAC_t AC power demand in time step t (kW)
  - DDC_t DC power demand in time step t (kW)
- Solar and wind generation forecasts in the community.
  - ES_t solar potential in the community, related to the peak power, in time step t (kW/kWpeak.)
  - EW_t wind potential in the community, related to the maximum generation available, in time step t (kWh/kWhmax.)
- Technical data of the assets.
  - av_t: national grid availability, with 1 indicating availability and 0 indicating a blackout for each time step t.
  - η_i efficiency of asset i (factor), $i \in \{D, I, R, C, F\}$
  - ηin_B inflow conversion factor into the batteries (factor).
  - ηout_B outflow conversion factor from the batteries (factor)
  - ε loss rate in the batteries during a time step (factor)
  - $SOCmin$ minimum state of charge of the batteries (factor)
  - $SOCmax$ maximum state of charge of the batteries (factor)
  - $Cratein$ investment relation between power inflow and batteries' capacity within time step t (factor).
  - $Crateout$ investment relation between batteries' capacity and power outflow within time step t (factor)
- Additional data to add constraints, if desired:
  - U_{SH} maximum allowed shortage of annual energy supplied related to annual demand (factor). 0 if no shortage is allowed.
  - S factor of demand that weather-independent sources can ensure to supply in each time step t (factor). 0 if demand could be completely fulfilled equally by weather-dependent and weather-independent sources.

3.2.2. Decision variables

Non-negative real variables are used to define the power capacities of the assets and the power flows during each time step.

CAP_i power capacity of asset i (kW), $i \in \{W, D, B, I, R, C, F\}$
CAP_S power capacity the solar PV plant (kWpeak)
$FtoAC_{i,t}$ power flow from asset i to electricity AC bus (kW), $i \in \{W, D, I, C, SH\}$
$FACto_{i,t}$ power flow from electricity AC bus to asset i (kW), $i \in \{R, F, E\}$
$FtoDC_{i,t}$ power flow from asset i to electricity DC bus (kW), $i \in \{S, B, R, SH\}$
$FDCto_{i,t}$ power flow from electricity DC bus to asset i (kW), $i \in \{B, I, E\}$
$Ftofu_{FU,t}$ power flow from diesel source to diesel bus (kW)
$Ffuto_{D,t}$ power flow from diesel bus to diesel generator (kW)
$Ftogc_{G,t}$ power flow from national grid to grid consumption bus (kW)
$Fgcto_{C,t}$ power flow from grid consumption bus to grid consumption transformer (kW)
$Ftogf_{F,t}$ power flow from grid feed-in transformer to grid feed-in bus (kW)
$Fgfto_{G,t}$ power flow from grid feed-in bus to national grid (kW).
PB_t state of charge of the batteries (kW)

3.2.3. Objective function

The objective function minimizes the annual costs of the project, considering capital and operational expenditures related to asset's installation and system operation. Annual costs of each asset (a_i) are calculated in a pre-processing step considering capital and operational expenditures ($Capex_i$ and $Opex_i$) (eq. (1)). Capital expenditures take into account necessary replacements for each asset (n_i) and its remaining value at the end of the project lifetime (RV_i) (eqs. (2)–(4)). Finally, the capital recovery factor (CRF_i) is calculated as usual based in the appropriate discount factor (d) (eq. (5)).

$$a_i = Capex_i \cdot CRF_i + Opex_i \tag{1}$$

$$Capex_i = \sum_{m=0}^{n_i} \frac{inv_i}{(1+d)^{m \cdot ta_i}} - RV_i \tag{2}$$

$$RV_i = \frac{\frac{inv_i}{(1+d)^{(n_i-1)\cdot ta_i}}}{ta_i} \cdot ((n_i+1) \cdot ta_i - tn) \tag{3}$$

$$n_i = round\left(\frac{tn}{ta_i} + 0.5\right) - 1 \tag{4}$$

$$CRF_i = \frac{d \cdot (1+d)^{ta_i}}{(1+d)^{ta_i} - 1} \tag{5}$$

The objective function is then defined as following (eq. (6)):

$$[min] z = \sum_{i \in \{S,W,D,B,I,R,C,F\}} a_i \cdot CAP_i + \sum_{\forall t} \left[\sum_{i \in \{S,SH\}} Cvar_i \cdot FtoDC_{i,t} + \sum_{i \in \{W,D,SH\}} Cvar_i \cdot FtoAC_{i,t} + \left[p_D \cdot Ftofu_{FU,t} + p_C \cdot Ftogc_{G,t} - p_F \cdot Fgfto_{G,t} \right] \right] \tag{6}$$

3.2.4. Constraints

Constraints (eq. (7)) force the electricity AC and DC buses, as well as the diesel bus, the grid consumption bus and the grid feed-in bus to be balanced. Constraints (eq. (8)) considers the conversion efficiency of the transformer components. Constraints (eq. (9)) fix the power generation flow of the PV plant and the wind farm according to the generation potential and the optimized capacity of each asset. Constraints (eq. (10)) avoid power flows to exceed the limit set by the capacity of each asset. In particular, the input and output power flow of the battery are limited by the corresponding investment relations. Constraints (eq. (11)) define how the state of charge of the batteries is modified through the optimization time. In detail, a steady state behaviour is stablished and the state of charge is comprised between a minimum and a maximum storage level. Constraint (eq. (12)) uses the fake shortage source to limit the acceptable amount of shortage on annual demand. Finally, constraints (eq. (13)) ensure a certain amount of demand can be supplied by sources that do not depend on weather conditions.

$$\begin{aligned}
&\sum_{i\in\{W,D,I,C,SH\}} FtoAC_{i,t} - \sum_{i\in\{R,F,E\}} FACto_{i,t} = DAC_t \quad \forall t\\
&\sum_{i\in\{S,B,R,SH\}} FtoDC_{i,t} - \sum_{i\in\{B,I,E\}} FDCto_{i,t} = DDC_t \quad \forall t\\
&Ftofu_{FU,t} - Ffuto_{D,t} = 0 \quad \forall t\\
&Ftogc_{G,t} - Fgctoc_{C,t} = 0 \quad \forall t\\
&Ftogf_{F,t} - Fgfto_{G,t} = 0 \quad \forall t
\end{aligned} \tag{7}$$

$$\begin{aligned}
&FtoAC_{D,t} - \eta_D\, Ffuto_{D,t} = 0 \quad \forall t\\
&FtoDC_{R,t} - \eta_R\, FACto_{R,t} = 0 \quad \forall t\\
&FtoAC_{I,t} - \eta_I\, FDCto_{I,t} = 0 \quad \forall t\\
&FtoAC_{C,t} - \eta_C\, Fgctoc_{C,t} = 0 \quad \forall t\\
&Ftogf_{F,t} - \eta_F\;\; FACto_{F,t} = 0 \quad \forall t
\end{aligned} \tag{8}$$

$$\begin{aligned}
&FtoDC_{S,t} - ES_t\, CAP_s = 0 \quad \forall t\\
&FtoAC_{W,t} - EW_t\, CAP_W = 0 \quad \forall t
\end{aligned} \tag{9}$$

$$\begin{aligned}
&FtoAC_{D,t} - CAP_D \le 0 \quad \forall t\\
&\mathrm{FACto}_{R,t} - CAP_R \le 0 \quad \forall t\\
&\mathrm{FDCto}_{I,t} - CAP_I \le 0 \quad \forall t\\
&\mathrm{FtoAC}_{C,t} - CAP_C\cdot av_t \le 0 \quad \forall t\\
&\mathrm{Ftogf}_{F,t} - CAP_F\cdot av_t \le 0 \quad \forall t\\
&\mathrm{FDCto}_{B,t} - Cratein\cdot CAP_B \le 0 \quad \forall t\\
&\mathrm{FtoDC}_{B,t} - Crateout\cdot CAP_B \le 0 \quad \forall t
\end{aligned} \tag{10}$$

$$\begin{aligned}
&PB_t = PB_{t-1}\cdot(1-\varepsilon) + \eta in_B\cdot FDCto_{B,t} - \frac{FtoDC_{B,t}}{\eta in_B} \quad \forall t\\
&PB_0 = PB_T \quad \forall t\\
&SOCmin\cdot CAP_B \le PB_t \le SOCmax\cdot CAP_B \quad \forall t
\end{aligned} \tag{11}$$

$$\sum_{\forall t} FtoDC_{SH,t} + \sum_{\forall t} FtoAC_{SH,t} \le \mathrm{U}_{SH}\cdot\left(\sum_{\forall t} DDC_t + \sum_{\forall t} DAC_t\right) \tag{12}$$

$$\begin{aligned}
&\sum_{i\in\{D,C,SH\}} FtoAC_{i,t} + (PB_t - L_B\cdot CAP_B)\cdot Crateout\cdot \eta out_B\cdot \eta_I \ge DAC_t\cdot S \quad \forall t\\
&\sum_{i\in\{D,C,SH\}} FtoAC_{i,t}\cdot\eta_R + (PB_t - L_B\cdot CAP_B)\cdot Crateout\cdot \eta out_B \ge DDC_t\cdot S \quad \forall t
\end{aligned} \tag{13}$$

4. Selection of electrification alternatives

Multicriteria analysis is a useful technique to select the best electrification alternative, since multiple aspects can be introduced into the decision process. Therefore, it is designed and used in this second phase to evaluate and rank the electrification alternatives obtained in phase 1 after techno-economic optimizations of different scenarios. This multicriteria procedure allows, thus, to include social, institutional and environmental aspects, apart from economic and technical ones, into the electrification systems design. This section is also organized following the design procedure detailed in Fig. 1. First (4.1), some appropriate criteria are defined. Then (4.2), the weighting method for these criteria is presented. Next (4.3), the evaluation procedure of the alternatives is defined for each criterion. Finally (4.4), the compromise ranking method used to rank the alternatives is described.

4.1. Criteria definition

To evaluate alternatives that differ in the technologies used for electricity generation within the MG (PV, wind, diesel) and the system configuration (on-grid or off-grid), 12 criteria have been defined and classified in four dimensions: economic, technical, socio-institutional and environmental. The next paragraphs focus on defining both dimensions and criteria.

The economic dimension evaluates the economic impact of the project throughout its lifetime. Its evaluation in this study is divided into two criteria: the initial costs needed to put the system into operation and the annual balance between required costs for regular operation and maintenance and potential revenues. Next, the two criteria are described.

Initial investment (EC-1): capital costs needed to set up the project. All upfront costs related to the purchase of mechanical equipment, technological installations, construction of facilities and engineering services are included in this criterion.

Operation and maintenance, O&M, balance (EC-2): annual difference between costs paid during the project lifetime to operate and maintain the electrical equipment and revenues for electricity feed-in to national grid. Expenditures such as diesel supply and costs for electricity consumption from the grid are also included.

The technical dimension evaluates the system performance and is related to the accomplishment of global access to reliable energy [15, 31]. Its evaluation in this study is divided into four criteria: the autonomy factor, the existence of annual shortages on demand, the reliability of supply against weather variability or the likelihood of equipment failure. Next, the four criteria are described.

Autonomy factor (T-1): share of electricity supplied from MG sources (solar PV, wind or diesel) compared to total electricity supplied. Local electricity generation instead of grid consuming allows a lower dependence on external factors that can negatively affect electricity supply.

Complete fulfillment of demand (T-2): ratio of the annual energy supplied compared to annual demand, as initial computational experiments have shown that small shortages on annual supply (around 2–5%) induce in significant reductions of investment costs (5–15%). This criterion balances the influence of a reduction in investment costs at the expense of not supplying 100% of demand, and is directly connected to the value for the maximum shortage specified for the optimization.

Reliability of generation sources (T-3): expectation that a power system meets the load requirements at any time [48] according to the forecasted generation profiles. Factors such as weather variability can slightly modify solar and wind forecasts, while deficient infrastructures can provoke delays in diesel supply.

Equipment failure (T-4): likelihood of equipment failure due to technical, mechanical or external issues such as extreme meteorological phenomena (high temperatures, strong wind or high precipitations). Technical and mechanical failures may be caused by inappropriate design, use of unreliable components, improper installation or poor maintenance [49], and usually affect differently each technology of electricity generation [50].

The socio-institutional dimension evaluates the social impact of the project into the communities from a local and a global perspective. In particular, its evaluation in this study is divided into three criteria: the tariff required to be pay by end-users for the electrical service, the users' acceptance of the different technologies of electricity generation and the institutional alignment of the system design with national trend. Next, the three criteria are described.

Tariff for electrical service (S-1): mean amount of money that end-users pay each month for the electrical service. This rate can be free, periodic or according to consumption [51], and determinates the direct economic consequences of the project to end-users. The tariff depends on the regulation market of the country where the project is implemented and must be calculated based on appropriate information of the country.

Users acceptance (S-2): acceptability of the different technologies of electricity generation. If the electrification alternative does not fit into the sociocultural context of the community, it may provoke resistance and difficult the project success [25]. Oppositely, good opinions on one generation source, e.g. due to former experiences, can positively affect its implementation.

Institutional alignment (S-3): alignment of the generation sources with the government's national trend. Subsidies or other eco-political benefits are easier to obtain if the selected technologies fit well with the government strategy for rural electrification.

The environmental dimension evaluates the climate impact of the

Table 1
Dimensions, criteria and indicators for the multicriteria procedure of electrification alternatives.

Dimensions	Criteria		(+/−)	Indicator	Units
Economic	EC-1	Initial investment	–	Sum of all investments costs, including main grid extension and costs within the MG.	m$
	EC-2	O&M balance	–	Sum of all costs related to operation and maintenance of equipment and diesel and grid consumption expenditures. They include also revenues for feed-in to main grid.	m$/y
Technical	T-1	Autonomy factor	+	Percentage of electricity generated locally within the MG (due to renewable sources or diesel generators) vs all electricity generated.	%
	T-2	Complete fulfilment of demand	+	Percentage of annual electricity supplied vs annual demand.	%
	T-3	Reliability of generation sources	+	Weighted average sum of the electricity generated by each technology (weighted by qualitative punctuations given).	factor
	T-4	Equipment failure	+	Weighted average sum of the electricity generated by each technology (weighted by qualitative punctuations given).	factor
Socio-institutional	S-1	Tariff for electrical service	–	Mean amount of money an habitant of a community must pay monthly, based on country regulations regarding electrical tariff for grid service and MGs.	$/kWh
	S-2	Users acceptance	+	Weighted average sum of the electricity generated by each technology (weighted by qualitative punctuations given).	factor
	S-3	Institutional alignment	+	Weighted average sum of the electricity generated by each technology (weighted by qualitative punctuations given).	factor
Environmental	EN-1	CO_2 emissions	–	Tons of CO_2 emitted due to the diesel generators or the electrical national grid.	tons
	EN-2	E-Impact on population	+	Weighted average sum of the optimized power capacity of each technology (weighted by qualitative punctuations given)	factor
	EN-3	Wastes of components	+	Weighted average sum of the optimized power capacity of each electrical component (weighted by qualitative punctuations given)	factor

project and comprehends all project activities influencing the local ecosystems as well as the natural resources of the electrified area [28, 31]. Its evaluation in this study is divided into three criteria: CO_2 emissions due to electricity generation, impact on population due to visual, noise and land-use concerns and wastes of components at the end of their lifetime. Next, the three criteria are described.

CO_2 emissions (EN-1): tones of CO_2 emitted by the electrical system. PV and wind sources are assumed to be completely without emissions, while the emission factor for diesel generators is set to 0.77 $kgCO_2$ per kWh of electricity produced [17]. An emission factor for the main grid must be specifically calculated for the country of application.

E-Impact on population (EN-2): negative effects on local population due to visual impact, noise and land-use as a result of the installation and operation of the electrical equipment.

Wastes of components (EN-3): wastes generation at the end of the components lifetime, considering which percentage of them allow recycle or reuse and how easy each decommission is. This issue is particularly tricky for batteries [52], so it can indirectly affect wind and solar PV technologies.

4.2. Criteria weighting

Once the dimensions and criteria are defined, they are weighted by assigning a value to each dimension and each criterion. This value represents its importance in relation to the others and must be particularized for each project according to the opinion of local experts in the field of rural electrification. Therefore, the results of the weighting for the case study can be found in section 5.2 and are based on the questionnaire sent to local experts attached in Appendix A. In detail, the final weight of each criterion (w_{ij}) and dimension (w_j) is calculated as following (eq. (14)):

$$w_{ij} = \frac{\sum_{k=1}^{n} \frac{r_{ijk}}{\sum_{i'=1}^{m_j} r_{i'jk}}}{n} \qquad w_j = \frac{\sum_{k=1}^{n} \frac{\sum_{i=1}^{m_j} \frac{r_{ijk}}{m_j}}{\sum_{j'=1}^{d} \sum_{i=1}^{m_{j'}} \frac{r_{ij'k}}{m_j}}}{n} \tag{14}$$

where r_{ijk} is the importance rating given by expert k to criterion i belonging to dimension j (obtained with questionnaire in appendix A); m_j is the number of criteria attached to dimension j; n is the number of experts asked and d *is* the number of dimensions.

4.3. Alternatives evaluation

As structured in Fig. 1, once the electrification alternatives are generated (phase 1) and the criteria are defined and weighted (first two steps of phase 2), the evaluation procedure can start. This is based on indicators which evaluate the fulfillment of the corresponding criteria by considering the outputs of the optimization; in particular, the investment costs and operational expenditures required, the assets' optimal capacities and the optimal power flows during the optimization time (Table 1). As a result, a perfect integration of alternatives generation and selection phases can be achieved.

Since both qualitative and quantitative criteria have been defined, the evaluation of the qualitative ones (i.e. robustness of supply, users' acceptance or impact on population) requires a prior assessment. In this assessment, punctuations are given to the performance of the different options of electricity generation (PV, wind, diesel and the national grid) according to each criterion in discussion. These punctuations are used to calculate a weighted average ratio of electricity generation (for T-3, T-4, S-2, S-3) or optimized power capacity (for EN-2, EN-3) from the different technologies. Similar to the criteria weighting, such punctuations must be discussed for each project among a group of experts. Thus, the results of this assessment are presented in section 5.2 and are based on the questionnaire attached in Appendix B.

4.4. Alternatives ranking

The aggregation of the evaluation results can vary according to the multicriteria technique used. This study utilizes the compromise ranking method, due to its proven effectiveness in energy applications in rural areas. In detail, it has been applied to design low-scale electrification systems [21] and biogas digesters for rural areas [43,53]. This method consists of comparing each alternative to an ideal solution, which is an utopian solution that performs optimally for all criteria [54,55]. The closest alternative to the ideal solution is then selected. This closeness concept is calculated through the mathematical distance $L_{s,p}$ from the alternative s to the ideal solution, depending on the metric p (eq. (15)). The lower value an alternative gets, the better it is.

$$L_{s,p} = \left[\sum_{j=1}^{d} W_j^p \left[\sum_{i=1}^{m_j} W_{ij} \cdot \frac{F_i^* - f_{si}}{F_i^* - f_i^*} \right]^p \right]^{1/p} \tag{15}$$

where d is again the number of dimensions; f_{si} is the value of the alternative s for the criterion i; F_i^* is the ideal value for the criterion i (the best among all alternatives); f_i^* is the anti-ideal value for the criterion i (the worst among all alternatives); and as known, W_{ij} is the weight of the criterion i belonging to dimension j; W_j is the weight of dimension j; and m_j is the number of criteria attached to dimension j.

Finally, the metric p represents the importance given to the deviation from the ideal value for each criterion and can vary from 1 to ∞ [56]. When increasing the p value, a higher importance is assigned to the maximum deviation [56]. Thus, while $L_{s,1}$ assignes the same importance to all deviations, $L_{s,\infty}$ considers only the maximum deviation of all criteria. Although different metrics can be applied, a linear combination of metrics 1 and ∞ is recommended in the literature and will therefore be used in this work (eq. (16)) [57], with $\alpha = 0.5$:

$$L_s = \alpha \ L_{s,1} + (1 - \alpha) \ L_{s,\infty} \tag{16}$$

The best electrification design for a community corresponds to the lowest value of L_s.

5. A case study – electrification of rural communties in plateau state, Nigeria

Nigeria is the African country in which more people live without electricity access, at least 90 million [58]. 50% of Nigeria population cannot access electricity, while in rural areas this percentage raises up to 70% [59]. Small incentives for private investment due to electricity tariffs much below investment and operation costs [60] are highlighted as fundamental for such high non-electrification rates. Attempts for tariff regulation have faced strict opposition by consumers, since they are not usually included in the decision-making process [61] nor finally satisfied with the quality of supply provided. Indeed, the excessive unreliability of the national grid, due to lack of maintenance, vandalism and regular thefts [62], have forced to consider decentralized energy options based on MGs for electric supply.

In this context, between 2015 and 2017, a study integrated in the European-aid-funded project Nigerian Energy Support Program (NESP) analyzed the electricity demand of different population settlements of five Nigerian federal states using geospatial information and defined a multi-staged road map to provide electricity to each settlement [58,63]. For small settlements (with an overall peak demand lower than 50 kW), solar home systems were chosen. Meanwhile, for big ones (villages to little towns) two electrification options were evaluated: a MG off-grid scenario based on solar PV, batteries and diesel generators; and the extension of the national grid without any backup. The electrification solution with lowest levelized cost of electricity (LCOE) for each big settlement was selected as final electrification design.

Now, the proposed multicriteria-based methodology is applied to 26 population settlements in order to include social, environmental and institutional aspects into a structured design and evaluation process. This integral process is considered a good opportunity to bridge the gap among institutions, private investors and end-consumers in Nigeria, and pretends to achieve higher consensus that benefit them all. The settlements (belonging to Plateau State, the state of Nigeria with lowest electrification rate of the ones analyzed in the NESP study) are selected so they can be representative of most rural communities in Nigeria. The selection focuses on two parameters: annual peak demand (indicative of the settlement's size) and distance to the closest national grid connection point. Fig. 3 shows that the selected settlements are distributed all over Plateau State and cover peak demand values from 52 to 285 kW. As it can be seen, all settlements present a peak demand higher than 50 kW, which makes them suitable for decentralized energy systems based on MGs. In addition, different distances to the nearest national grid consumption point are taken into account, being the closest settlement 3 km and the furthest 65 km away from it. The two settlements numbered are taken as examples to later show the results obtained.

The application of the design methodology aims to validate the procedure presented to design and select the best electrification alternative for each community taking into account the interests of public institutions, private investors and end-users through the presented multicriteria design process. In particular, for this case of Nigeria, the

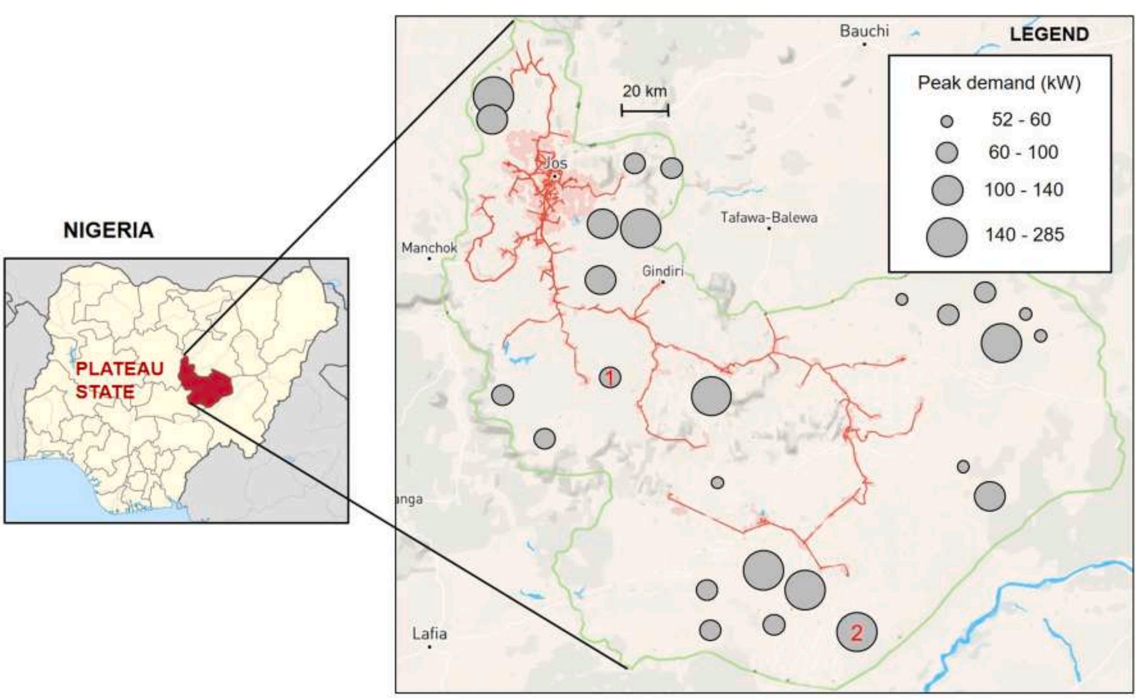

Fig. 3. Selection of 26 settlements in Plateau State for the case study based on peak demand and distance to national grid (background image from http://rrep-nigeria.integration.org/#).

Table 2
Economic and technical data.

Asset	Parameter	Notation	Unit	Value
PV	Investment costs	Inv_S	\$/kWp	1250
	Operational expenditures	$Opex_S$	\$/kWp/y	25
	Lifetime	ta_S	Y	25
Battery	Power investment Capacity investment	Inv_B	\$/kW \$/kWh	500 250
	Variable cost	$Cvar_B$	\$/kWh	6.75
	Maximum state of charge	$SOCmax$	factor	1
	Minimum state of charge	$SOCmin$	factor	0.2
	Inflow conversion factor	η_{Bin}	factor	0.97
	Outflow conversion factor	η_{Bout}	factor	0.97
	C-rate of charge	$Cratein$	factor	1
	C-rate of discharge	$Crateout$	factor	0.5
	Initial storage level	PB_0	factor	0
	Loss rate each timestep	ε	factor	0
	Lifetime	ta_B	y	13.5
Diesel generator	Investment costs	Inv_D	\$/kW	820
	Operational expenditures	$Opex_D$	\$/kW/a	0.05
	Efficiency	η_D	factor	0.33
	Lifetime	ta_D	y	10
	Diesel price	p_D	\$/l	1.04
Central grid	Investment costs	Inv_C , Inv_F	\$/kW	200
	Lifetime	ta_C , ta_F	y	20
	Electricity consumption price	p_C	\$/kWh	0.08
	Electricity feed-in tariff	p_F	\$/kWh	0.05
Others	Discount factor	d	%	16
	Project lifetime	tn	y	20
	Optimization time horizon	T	hours	8760
	Factor of demand supplied by weather-independent sources	S	factor	0.2

methodology is expected to mean a step forward towards a stronger collaboration between communities, private investors and public regulators which can help to reach agreements in the most appropriate design to fulfill quality expectations and allow more attractive returns of investment.

The rest of the section focus on displaying the main results of applying the design methodology shown in Fig. 1. First (5.1), appropriate electrification scenarios for the case study are defined and the corresponding alternatives are obtained. Then (5.2), the results of the weighting of criteria and the technology assessment based on the questionnaires are presented. Next (5.3), results of previous steps are taken to evaluate and rank the alternatives considering all criteria. Finally (5.4), a definite electrification design for each community is recommended and a discussion of the results is realized.

5.1. Scenarios definition and alternatives calculation

For each settlement, different electrification scenarios are considered taking into account different technologies of electricity generation and system distributions. Photovoltaic solar energy has been widely used in Nigeria, due to its enormous solar potential, with fairly distributed solar radiation averaging 5.5 $kWhm^2$/day and average sunshine hours of 6 h/day [64]. Meanwhile, wind energy systems have only had little applications in northern states, such as Sokoto and Katsina [65] and will therefore not be considered here. Moreover, the abovementioned unreliability of the national grid recommends considering always backup sources when the national grid is extended. Consequently, the following four electrification scenarios are analyzed for each community:

1. Off-grid system based on PV and batteries.
2. Off-grid system based on PV, batteries and diesel generators.
3. On-grid system based on PV and batteries.
4. On-grid system based on PV, batteries and diesel generators.

In addition, sub-scenarios are defined to determine the overall effect of considering shortages on the supply of annual demand. Particularly, three levels of shortage are considered for each electrification scenario: 0% (complete fulfillment of demand), 2.5% and 5%. Therefore, 12 electrification alternatives are generated for each settlement (four electrification scenarios with three levels of shortage each).

Such alternatives are obtained using the optimization model detailed in section 3, removing the components not included in each scenario. The data required is taken from the NESP study [63] and is summarized in Table 2. Additionally, two considerations must be given regarding the modelling of the national grid. On the one hand, the unreliability of the national grid can be modelled by a probability distribution of blackouts frequency (32.8 per month) and duration (11.6 h on average), with a standard deviation of 15% [45]. These parameters allow to generate the binary data used in the electrification problem to indicate grid availability. On the other hand, the cost of grid extension was fixed in 20 m \$/km and is added to the total cost of on-grid alternatives as a post-process calculation, considering the distance to the closest national grid connection point. Any other economic or technical value not mentioned nor included in Table 2 is assumed to be non-conditioning: 0,

Table 3
Optimization results of some electrification alternatives for two example settlements and the complete range of values.

Optimization item		Example settlement 1				Example settlement 2				All settlements, scenarios and sub-scenarios (if not zero)
		On-grid PV 0%	On-grid PV & diesel 0%	Off-grid PV 5%	Off-grid PV & diesel 5%	On-grid PV 0%	On-grid PV & diesel 0%	Off-grid PV 5%	Off-grid PV & diesel 5%	
Investment costs	m\$	787.35	355.82	653.03	249.81	2073.55	1194.85	1420.06	628.39	169–7365
O&M balance	m \$/y	44.23	65.96	452.84	82.29	126.49	173.00	131.90	208.54	31–720
Annual PV generation	kWh	214,800	72,231	259,122	90,208	524,177	152,589	511,534	185,751	31,679–3,575,925
Annual diesel generation	kWh	0	47,574	0	114,567	0	91,605	0	237,278	23,189–1,021,049
Annual grid consumption	kWh	14,960	85,471	0	0	10,902	183,757	0	0	940–769,352
Capacity PV	kWp	144.00	48.42	173.72	60.48	331.12	96.39	323.13	117.34	21–2253
Capacity diesel	kW	0	47.61	0	32.70	0	113.54	0	81.30	17–564
Capacity grid transformer	kW	25.56	44.31	0	0	95.53	110.94	0	0	11–492
Capacity battery	kW	519.53	46.40	411.05	26.40	1052.16	143.53	901.51	100.07	11–5558

Table 4
Weights for dimensions and criteria.

Dimensions	Weights	Criteria		Weights
Economic	0.286	EC-1	Initial investment	0.514
		EC-2	O&M costs	0.486
Technical	0.258	T-1	Autonomy factor	0.260
		T-2	Complete fulfilment of demand	0.238
		T-3	Reliability of generation sources	0.247
		T-4	Equipment failure	0.255
Socio-institutional	0.234	S-1	Tariff for electrical service	0.396
		S-2	Users acceptance	0.265
		S-3	Institutional alignment	0.338
Environmental	0.222	EN-1	CO_2 emissions	0.256
		EN-2	E-Impact on population	0.384
		EN-3	Wastes of components	0.360

Table 5
Punctuations to qualitative criteria.

Criteria	Solar PV	Diesel	National grid
Reliability of generation sources	2.75	1.88	1.13
Equipment failure	2.25	1.50	1.13
Users acceptance	2.00	2.67	2.17
Institutional alignment	2.57	1.71	2.14
E-Impact on population	2.63	1.00	1.88
Wastes of components	1.63	1.50	2.63

such as the operational expenditures for the consumption and feed-in transformer ($Opex_C$, $Opex_F$) or 1, such as the efficiencies of the inverter and the rectifier (η_I , η_R).

After the scenarios have been defined, phase 1 concludes with the generation of an electrification alternative for each scenario solving the optimization model detailed. This optimization process determines the optimal value of different items (Table 3), which are used in phase 2 to evaluate the alternatives. Since presenting the results for every settlement (26 in total) and every alternative (12 for each settlement) could be overwhelming, example results are displayed for two specific settlements and for some interesting alternatives: on-grid and off-grid scenarios, with only PV or also with diesel, and considering different shortage levels (0% and 5%). Additionally, the range of values of every item considering all alternatives and settlements is also displayed. This range express a great difference as a result of the different size of the communities, the broad range of distances to the national grid and the different system designs considered.

Concerning the results for the example settlements, the investment costs are significantly reduced if different technologies of electricity generation are available. Also, on-grid scenarios tend to be more expensive than off-grid ones due to the cost of extending the national grid. Finally, optimal capacities and generation flows from the different assets are higher in the second settlement due to its higher size and demand.

5.2. Criteria weights and technology assessment results

Phase 2 of the design methodology requires to particularize the evaluation and ranking procedure according to the Nigerian context. Therefore, questionnaires (Appendixes A and B) were handed out to 10 experts in rural electrification in Nigeria. All experts count on more than 6 years of experience in different areas (public administration, Nigeria government, private companies and non-governmental organizations) and are therefore representative of all stakeholders involved in the electricity market. The survey consists of two sections: section 1 asked for an evaluation of the importance of the 12 criteria on a scale from 1 to 5 (very low importance to very high importance). Then, section 2 asked to punctuate the performance on the qualitative criteria of the three technologies of electricity generation considered in the case study (solar PV, diesel, and national grid extension) on a scale from 1 to 3 (low performance to good performance). These punctuations are included in the indicators to evaluate the qualitative criteria as explained in section 4.3 and detailed in Table 1. The aggregated results of the surveys are displayed in Tables 4 and 5. In the following paragraphs, the main findings are presented as well as their justification through comments from the respondent experts on the surveys.

Table 6
Evaluation results of some electrification alternatives for two example settlements.

Dimensions	Criteria		Example settlement 1				Example settlement 2			
			On-grid PV 0%	On-grid PV & diesel 0%	Off-grid PV 5%	Off-grid PV & diesel 5%	On-grid PV 0%	On-grid PV & diesel 0%	Off-grid PV 5%	Off-grid PV & diesel 5%
Economic	EC-1	m$	787.35	355.82	653.03	249.81	2073.55	1194.85	1420.06	628.39
	EC-2	m$/y	44.23	65.96	452.84	82.29	126.49	173.00	131.90	208.54
Technical	T-1	%	92.65	58.03	100	100	97.43	56.74	100	100
	T-2	%	100	100	95	95	100	100	95	95
	T-3	factor	2.77	2.65	2.75	2.26	2.76	2.67	2.75	2.26
	T-4	factor	2.30	2.39	2.25	1.83	2.26	2.41	2.25	1.83
Socio-institutional	S-1[a]	$/kWh	0.46	0.46	0.67	0.67	0.46	0.46	0.67	0.67
	S-2	factor	2.01	2.21	2.00	2.34	2.00	2.20	2.00	2.33
	S-3	factor	2.54	2.19	2.57	2.09	2.56	2.20	2.57	2.09
Environmental	EN-1[b]	tons	6.58	74.24	0	182.24	4.80	151.39	0	182.70
	EN-2	factor	2.52	1.84	2.63	2.06	2.46	1.79	2.63	1.96
	EN-3	factor	1.67	1.83	1.63	1.60	1.69	1.84	1.63	1.59
		$L_{s,1}$	0.405	0.534	0.398	0.644	0.431	0.574	0.397	0.670
		$L_{s,\infty}$	0.126	0.193	0.155	0.197	0.154	0.192	0.155	0.203
		L_s	**0.266**	0.364	0.277	0.421	0.293	0.383	**0.276**	0.437

[a] The tariff for electrical service in Nigeria is set to 0.67 $/kWh for off-grid scenarios and 0.46 $/kWh for on-grid ones, based on a World Bank report [66] and calculations realized following the Multi-Year Tariff Order (MYTO) methodology (compulsory for tariff calculation of mini-grids in Nigeria and controlled by the Nigerian Electricity Regulatory Comission, NERC).
[b] The emission factor for the Nigerian national grid is set to 0.44 kg CO_2/kWh [67].

The highest weight is assigned to the economic dimension due to the importance of its two criteria: while investment costs (EC-1) are key to raise funding (experts 1, 4 and 5), O&M costs (EC-2) directly affect the long-term sustainability of the project (expert 2). Regarding the technical dimension, all experts agree to highlight the need of a reliable and resistant supply. Consequently, and considering the unreliability of the national grid, a high autonomy factor (T-1) is also prioritized. Oppositely, the lowest weight among the technical criteria is assigned to T-2, as a small shortage on demand supplied is acceptable (experts 1 and 2). Concerning the socio-institutional dimension, an affordable tariff for electrical service (S-1) directly impact the business model sustainability (expert 4), while aligning the electrification solution with institutional goals (S-3) allows higher chances to gain subsidies (expert 5). Finally, the lowest weight of EN-1 within the environmental dimension is explained by a prioritization of supplying electricity, no matter the source (expert 1) and due to the low economic incentives given by the Nigeria government to clean electricity generation (expert 5). Contrarily, although most waste is currently being disposed informally (expert 10), Renewable Energy Recycling Policy is an emerging issue that aims at increasing awareness of the wastes generation (expert 6).

With respect to the technology assessment in section 2, all experts agree on the unreliability of the national grid due to constant failures. Oppositely, solar PV overcomes diesel in reliability of supply due to the number of sun hours in Nigeria (expert 6), the reduced number of moving parts that might cause failure (expert 10), and the better performance if good-quality components are used (expert 4). However, the existing higher diesel diffusion rate compared to solar PV (experts 2 and 6) makes diesel systems more desirable to users, who still show low awareness of solar PV technology (experts 7 and 8). Moreover, solar PV is the government's priority to electrify rural areas (experts 4 and 5), although the national grid is also greatly considered. Finally, low

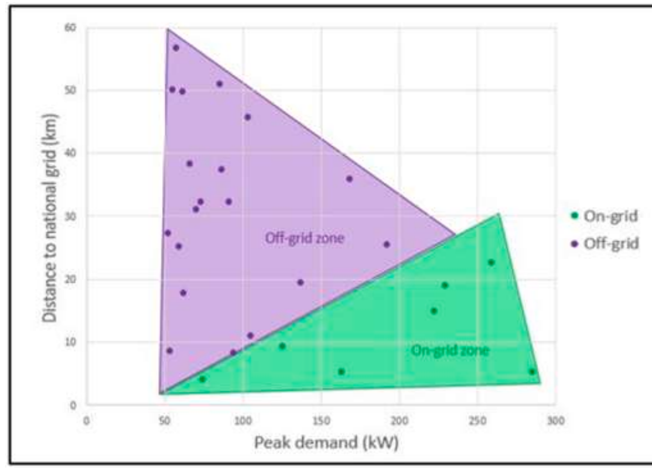

Fig. 5. Division of settlements into zones according to the predominance of each configuration.

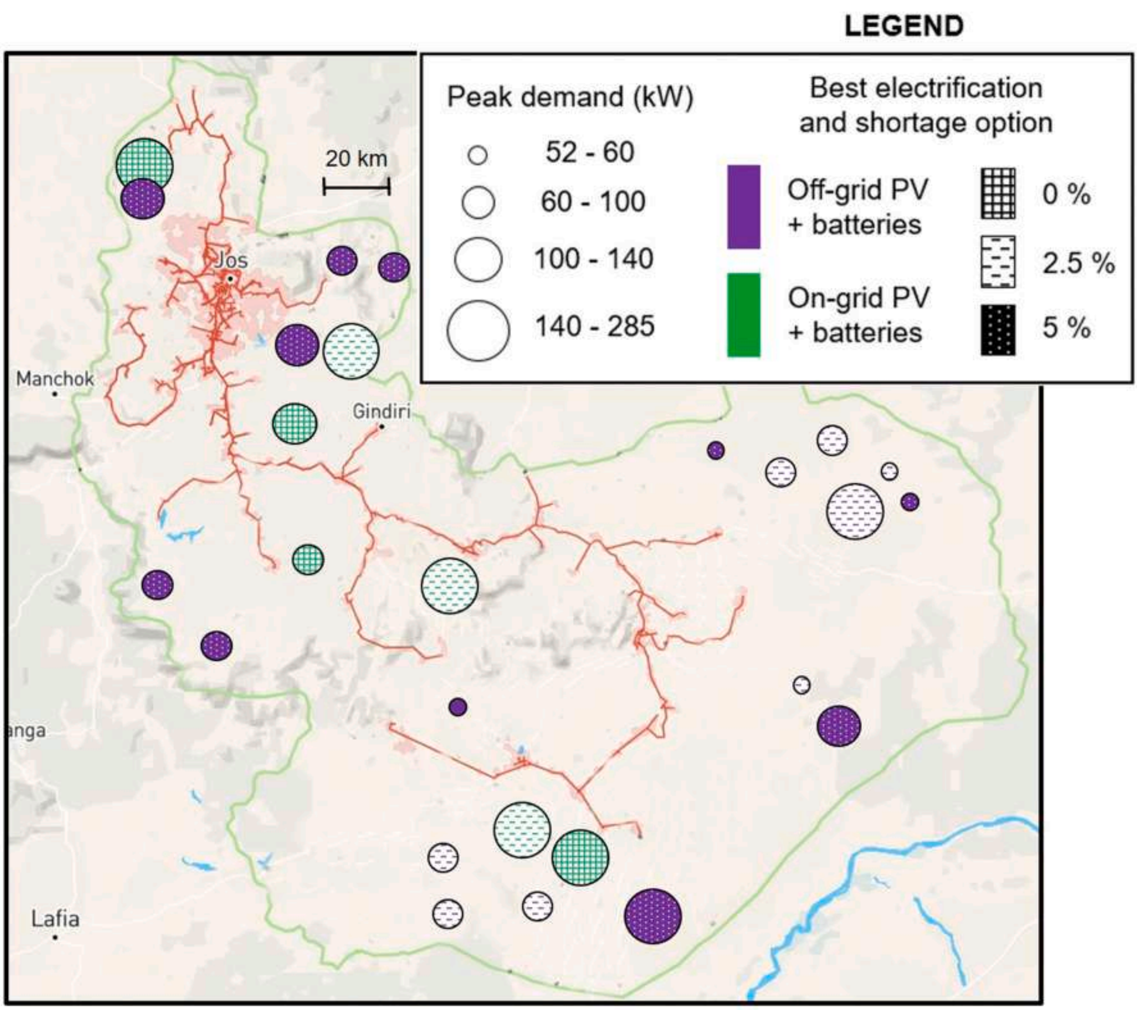

Fig. 4. Final electrification alternative selected for each settlement (background image from http://rrep-nigeria.integration.org/#).

Table 7
Best shortage levels for each system configuration.

Number of settlements in each combination		Shortage levels		
		0%	2.5%	5%
System configuration	On-grid	4	3	0
	Off-grid	0	8	11

punctuations of solar PV and diesel in wastes generation are caused by high wastes at the end of lifetime (majorly due to batteries) and continuous gas emissions, respectively (expert 5).

5.3. Alternatives evaluation and ranking

Once the electrification alternatives are generated and the evaluation procedure is particularized, the different alternatives are evaluated according to each criterion and dimension, and a ranking for each settlement is obtained. Once more, only the results of the evaluation of four alternatives for two example settlements are displayed (Table 6). Relevant information is now given to allow a better understanding of the evaluation procedure and its connection to previous results.

As defined in Table 1, the evaluation for the economic criteria (EC-1 and EC-2) correspond exactly to the investment costs and the O&M balance achieved in Table 3. Also, the autonomy factor (T-1) is only 100% for off-grid configurations, and the shortage level allowed in each sub-scenario determines the fulfillment of demand (T-2). Regarding the qualitative criteria, the results of the assessment of the PV technology directly set the evaluation of the off-grid alternatives which consider only PV, as this is the only technology included. Their evaluation for other alternatives result on a weighted average ratio of electricity generation (for T-3, T-4, S-2, S-3) and power capacity (for EN-2, EN-3) from the different technologies (weighted by the punctuations in Table 5).

Finally, compromise ranking method is used to rank the alternatives for each settlement. As said, the lower the distance to the ideal solution is (L_s), the better the alternative. Therefore, for these settlements the best electrification alternatives are an on-grid and an off-grid configuration, respectively, using only PV technology within the MG.

5.4. Final electrification design for each community

After completing the evaluation and ranking processes for each of the 26 settlements, a final system design can be recommended for each one. Thus, Fig. 4 presents the best electrification alternative for each settlement. Analyzing the results, both on-grid and off-grid configurations stand out as viable and its selection depends on the communities' features. However, a total predominance of solar PV technology in respect to diesel is shown. Although including diesel generators in the electrification scenario can drastically reduce investment costs (52.3% on average with a standard deviation of 10.7%), the influence of all criteria together balance this out in favor of solar PV. Next paragraphs aim to explain the reasons behind the results of the grid configuration and the shortage level, which need further analysis.

Basically, an on-grid or an off-grid configuration for a specific settlement depends on the peak demand of the community and its distance to the national grid (Fig. 5). It is shown that the greater the peak demand is, the more attractive a settlement gets for on-grid alternatives. Thus, off-grid and on-grid alternatives can excel to be the best option for communities with similar distance to the national grid depending on their size. The boundaries between the two zones shown in Fig. 5 determinate the size of a settlement needed to compensate the cost of grid extension for each specific distance.

In the scenarios definition step, sub-scenarios were also defined to calculate electrification alternatives for three levels of shortage on annual demand (0%, for complete fulfillment of demand; 2.5%; and 5%). Table 7 classifies each settlement (26 in total) regarding the best system configuration and the best shortage level obtained. As a first conclusion, as expected, the higher the shortage level, the lower percentage of annual demand supplied, so the lower the investment costs of the electrification system. With that in mind, the results of the analysis (Table 7) show that higher levels of shortage are the best option for off-grid configurations, due to the higher weight given to the investment costs (EC-1) criterion in comparison with the fulfillment of demand (T-2) (Table 3). Contrarily, low levels of shortage are better when on-grid configurations are recommended. Due to the unreliability of the Nigerian national grid, a high fulfillment of demand (0% and 2.5% shortage) must be achieved with a higher share of solar PV compared with national grid consumption; which is beneficial throughout the multicriteria evaluation as the solar PV technology has been better punctuated in most qualitative criteria.

Finally, the whole results shown are compared with the least-cost electricity option recommended in the NESP study [63]. Regarding the systems configuration, there is a significant increase in off-grid recommendations when including a multicriteria approach. In detail, only 40% of on-grid configurations in the NESP study remain unchanged in this study, while an off-grid configuration is now the best option for the other 60%. Oppositely, 100% of off-grid configurations in the NESP study continue to be the best electrification option also in this study. Regarding the technologies of electricity generation, a better or equal performance of solar PV compared to diesel in 10 out of 12 criteria compensates the increase of upfront investment costs and supports the recommendation to promote systems based on PV and batteries for MGs in Nigeria. This comparison should reinforce decision-makers to consider multiple criteria to design more appropriate electrification systems for rural areas.

Overall, these results encourage continuous institutional efforts on improving both public and private capacities to face electrification programs that go beyond traditional grid extension, centralized electricity generation sources and only cost-orientated designs. Indeed, the Nigerian Rural Electrification Agency (REA), in collaboration with the World Bank, has recently started an ambitious electrification project to increase electricity access throughout the country, giving priority to solar-based MGs and considering social and technical aspects in the design [68]. In this line, two final conclusions that should orientate the focus of policy makers in Nigeria in the near future are the following:

- Off-grid electrification of mainly small and medium-sized communities through microgrids stand out as an appropriate solution from a certain distance to the main grid (as seen in Fig. 5). Further regulation should be implemented to provide a safe and attractive environment for private investors to promote systems of this kind.
- The highlighted benefits of solar PV technology compared to diesel, as well as its recent tendency of market cost reduction [69], envisages a most predominance use of solar PV in the near future, which should continue to be promoted from the institutional side.

6. Conclusions

This work develops a multicriteria procedure to evaluate rural electrification systems considering on-grid or off-grid MGs and different technologies of electricity generation (solar PV, wind or diesel). This procedure is integrated in a two-phased methodology to first generate electrification designs and then select the most appropriate one for each community according to the multicriteria procedure. In phase 1, alternatives are generated through techno-economic optimizations. The optimization model used is extended from previous studies with additional assets and constraints to allow the generation of more complete and reliable electrification designs. To evaluate and rank these alternative designs in phase 2, 12 criteria are selected and defined. The criteria evaluation through indicators is based on the outputs of the optimization model. Thus, a perfect integration of alternatives generation and selection phases can be achieved. Consequently, decision-makers dispose of an integrated tool to determine different electrification designs and select the most appropriate guided by a comprehensive final ranking.

The 12 criteria are grouped into four dimensions: economical, technical, socio-institutional and environmental. First, economic criteria include upfront investment costs and operation and maintenance expenditures needed during the projects' lifetime. Second, technical criteria consider the autonomy factor of the system, the existence of small shortages on demand, the reliability of supply against forecasts and the likelihood of equipment failure. Third, the socio-institutional dimension takes into account the tariff for electrical service, the users' acceptance of the different technologies of electricity generation and the alignment of these technologies with the government's tendency. Finally, environmental criteria include CO_2 emissions, environmental impact of the project based on visual, noise impact and land-use, and wastes generation.

The whole design methodology is applied in a case study of 26 different population settlements in Plateau State, Nigeria, which present different values of peak demand and distances to the closest national grid consumption point. Questionnaires to experts in Nigeria electrification context are assessed to determinate the weights of the criteria and to evaluate the performance of the different technologies of electricity generation (solar PV, diesel and the national grid extension) for each qualitative criterion. Four main electrification scenarios are considered for each community combining MG off-grid and on-grid configurations with only solar PV and batteries, or including also diesel generators. Results are provided for the main steps of the methodology: alternatives calculation, criteria weighing and alternatives evaluation and ranking. The design procedure concludes with a final recommendation design for each community: on the one hand, an on-grid alternative based on solar PV and batteries is recommended for 7 settlements, with a distance to the national grid no bigger than 25 km. On the other hand, an off-grid solution based on solar PV and batteries is recommended for 19 settlements, for which an insufficient peak demand does not compensate the cost of extending the national grid. Finally, sub-scenarios defined considering different shortage levels on annual demand supplied show that a small shortage (2.5–5%) is attractive for off-grid scenarios, in order to reduce investment costs. Ultimately, the results obtained remark the adequacy of off-grid microgrids based on solar PV and batteries to electrify rural areas, which should be promoted and carefully regulated by the institutions involved.

Future lines of research must focus on extend the defined static design procedure into a dynamic methodology capable of dividing the electrification of rural communities into progressive steps along time. This is an even more attractive approach for electrification planning as decisions are taken considering all communities at once and feasible objectives can be set for concrete periods of time.

CRediT author contribution statement

M. Juanpera: Term, Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing - original draft. **P. Blechinger:** Term, Conceptualization, Methodology, Validation, Writing - review & editing, Supervision. **L. Ferrer-Martí:** Term, Conceptualization, Methodology, Writing - review & editing, Supervision. **M.M. Hoffmann:** Term, Conceptualization, Methodology, Software, Validation, Formal analysis, Writing - review & editing. **R. Pastor:** Conceptualization, Methodology, Writing - review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

To weight the criteria and dimensions for the presented case study using equation (eq. (14)), first different experts must give an importance rating to the 12 criteria on a scale from 1 (very low importance) to 5 (very high importance). Their results for the case study are presented in Table 4.

Importance ranking scale					
1	2	3	4	5	Z
Very low importance	Low importance	Moderate importance	High importance	Very high importance	Don't know
ECONOMIC DIMENSION					
Criteria	Short description	Indicator			Importance
Initial investment costs	Capital costs needed to be invested in the first moment, to set up the project.	Sum of all investments costs ($).			
Operation, maintenance costs	Costs paid during the project lifetime to operate and maintain the electrical equipment. It also includes other	Sum of all costs related to operation and maintenance of equipment and fuel and grid consumption expenditures ($).			

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	expenditures such as fuel supply and grid consumption costs.		
TECHNICAL DIMENSION			
Criteria	Short description	Indicator	Importance
Autonomy factor	System degree of autonomy stating how much electricity is produced within the mini-grid and how much is consumed from national grid.	Percentage of electricity generated locally within the mini-grid (due to renewable sources or diesel generators) vs all electricity generated (%)	
Complete fulfilment of demand	Importance of completely fulfil demand, as little shortages on annual supply compared to annual demand (around 2–5%) could significantly reduce investment costs (5–15%).	Percentage of annual electricity supplied vs annual demand (%).	
Reliability of generation sources	Robustness of the generation sources, as weather variability could slightly modify solar forecasts, while deficient infrastructures can provoke delays in fuel supply.	Weighted sum of the electricity generated by each generation source, weighted by qualitative punctuations according to their reliability (section 2 of this questionnaire) (factor).	
Equipment failure	Likelihood of equipment failure due to technical or mechanical issues, lack of maintenance or extreme meteorological phenomena (high temperatures, strong wind or high precipitations)	Weighted sum of the electricity generated by each generation source, weighted by qualitative punctuations according to the likelihood of equipment failure for each generation source (section 2 of this questionnaire) (factor).	
SOCIO-INSITUTIONAL DIMENSION			
Criteria	Short description	Indicator	Importance
Tariff for electrical service	Amount of money to be payed by the end-user each month for the electrical service.	Mean amount of money an habitant of a community must pay monthly, based on Jos DisCo electrical tariff and NERC regulation for mini-grids ($/kWh).	
Users acceptance	Acceptability of the different generation sources. The sociocultural context of the community and previous experience can affect their approval by the consumers.	Weighted sum of the electricity generated by each generation source, weighted by qualitative punctuations according to the users acceptance of each of them (section 2 of this questionnaire) (factor).	

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(*continued*)

Institutional alignment	Alignment of the generation sources with the national trend of Nigeria government.	Weighted sum of the electricity generated by each generation source, weighted by qualitative punctuations according to their alignment with Nigeria government's national trend (section 2 of this questionnaire) (factor).	
ENVIRONMENTAL DIMENSION			
Criteria	Short description	Indicator	Importance
CO_2 emissions	Tones of CO_2 emitted by the electrical system.	Tones of CO_2 emitted due to the diesel generators or the electrical national grid (tones CO_2).	
Impact on population	Negative affections on local population due to visual impact, noise and land-use as a result of the installation and operation of the electrical equipment.	Weighted sum of the optimized power capacity of each generation source, weighted by qualitative punctuations according to their impact on population (section 2 of this questionnaire) (factor).	
Wastes of components	Wastes generation at the end of the components lifetime, including which percentage of them allow recycle or reuse and how easy each decommission is. This issue is particularly tricky for batteries.	Weighted sum of the optimized power capacity of each electrical component, weighted by qualitative punctuations according to wastes generation of each component (section 2 of this questionnaire) (factor).	

Appendix B

To evaluate the qualitative criteria according to the indicators definition in Table 1, first different experts must punctuate the performance of each technology for electricity generation included in the case study (PV, diesel and the national grid) regarding each qualitative criterion on a scale from 1 (weak performance) to 3 (good performance). The results of the questionnaire for the case study are presented in Table 5.

Performance evaluation			
1 Weak performance	2 Medium performance	3 Good performance	Z Don't know
QUALITATIVE CRITERIA	PV plant	Diesel generators	National grid
Reliability of generation sources: punctuations on the reliability of each generation source. Weather variability and difficulties in fuel supply must be considered. **1 - unreliable, 3 - reliable**			
Equipment failure: punctuations on the likelihood of failure of the equipment of each generation source. Technical, mechanical issues and resilience to extreme meteorological phenomena must be considered. **1 - likely to fail, 3 - unlikely to fail**			
Users acceptance: punctuations on the estimated opinion of each generation source that the local inhabitants have. Previous experiences and general opinions must be considered. **1 - low acceptation, 3 - high acceptation**			
Institutional alignment: punctuations on the alignment of each generation source with Nigeria government's trend. Past and future national electrification projects, as well as government's will (if possible) must be considered. **1 - low alignment, 3 - high alignment**			
Impact on population: punctuations on the negative impact on population of each generation source are required. Visual and noise impact and land-use must be considered. **1 - great negative impact, 3 - little negative impact**			
Wastes of components: punctuations on the amount of wastes generation of each generation source. Installation, operation and decommission of the necessary equipment must be considered (PV panels require batteries). **1 - high wastes generation, 3 - low wastes generation**			

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5. PAPER 3: Methodology for integrated multicriteria decision-making with uncertainty: extending the compromise ranking method for uncertain evaluation of alternatives

ABSTRACT

Making a decision usually means selecting one from different alternatives to solve a problem according to a set of criteria. Multicriteria analysis usually offers a quantitative approach to ease decision-making by ranking the alternatives. However, uncertainty can arise when rating the importance of criteria and the adequacy of each alternative for each criterion, due to two factors: first, answers are usually expressed in linguistic terms that do not have a unique quantification; and second, there might be a lack of confidence in the response. Most multicriteria procedures combine fuzzy numbers and linguistic scales to deal with the first factor, but underestimate confidence issues. In this context, this work develops a Methodology for Integrated Multicriteria Decision-making with Uncertainty (MIMDU), which considers both factors of uncertainty. MIMDU is structured in three phases: (1) a novel procedure based on fuzzy rating scales to model uncertain opinions; (2) a fuzzy formulation of the compromised ranking method to rank the alternatives; and (3) a systematic procedure for results' interpretation comparing a crisp ranking (without uncertainty) and a fuzzy-based ranking (with uncertainty). The methodology is illustrated with a generic example case, aiming to prove its potential application in any sector. Results show that MIMDU helps decision-makers to choose the most reliable alternative, since significant differences in ranking with and without uncertainty can be addressed. A sensitivity analysis is carried out to bare the effect of confidence in the alternatives evaluation, concluding that worse rankings are obtained for alternatives that are less confidently evaluated. A final comparison with the standard fuzzy VIKOR method shows MIMDU's major preciseness in modelling non-confident opinions and providing more useful and complimentary information to better assist decision-making.

PAPER REFERENCE

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Methodology for integrated multicriteria decision-making with uncertainty: Extending the compromise ranking method for uncertain evaluation of alternatives

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Abstract

Making a decision usually means selecting one from different alternatives to solve a problem according to a set of criteria. Multicriteria analysis usually offers a quantitative approach to ease decision-making by ranking the alternatives. However, uncertainty can arise when rating the importance of criteria and the adequacy of each alternative for each criterion, due to two factors: first, answers are usually expressed in linguistic terms that do not have a unique quantification; and second, there might be a lack of confidence in the response. Most multicriteria procedures combine fuzzy numbers and linguistic scales to deal with the first factor, but underestimate confidence issues. In this context, this work develops a Methodology for Integrated Multicriteria Decision-making with Uncertainty (MIMDU), which considers both factors of uncertainty. MIMDU is structured in three phases: (1) a novel procedure based on fuzzy rating scales to model uncertain opinions; (2) a fuzzy formulation of the compromised ranking method to rank the alternatives; and (3) a systematic procedure for results' interpretation comparing a crisp ranking (without uncertainty) and a fuzzy-based ranking (with uncertainty). The methodology is illustrated with a generic example case, aiming to prove its potential application in any sector. Results show that MIMDU helps decision-makers to choose the most reliable alternative, since significant differences in ranking with and without uncertainty can be addressed. A sensitivity analysis is carried out to bare the effect of confidence in the alternatives evaluation, concluding that worse rankings are obtained for alternatives that are less confidently evaluated. A final comparison with the standard fuzzy VIKOR method shows MIMDU's major preciseness in modelling non-confident opinions and providing more useful and complimentary information to better assist decision-making.

Keywords: Multicriteria decision-making; MIMDU methodology; Fuzzy rating scales; Confidence

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1. Introduction

Managing industrial and service sectors requires making decisions, usually involving the selection of one of several viable alternatives. Choosing the best option is not an easy job, since multiple and often conflicting criteria must be considered [1,2]. In addition, the criteria are unlikely to have the same relevance or importance for the decision to be taken. Determining such a difference can be complex, even for a group of experts, since a lack of confidence can arise. A similar challenge is faced when evaluating each alternative according to each criterion. For example, determining the social implications or the environmental outcomes of one alternative design for rural electrification might not be straightforward.

Multicriteria decision-making (MCDM) is a suitable approach for handling such problems [3]. Specifically, MCDM establishes a framework for structuring decision problems and generating preferences from the available alternatives [4] to ultimately ease the choice of the best one [5]. This framework can be conceptual, such as the Delphi Method, used to reach consensus among experts through an iterative process [6]. However, quantitative-orientated methods, such as ELECTRE, TOPSIS, SURE or VIKOR [7–9], are mostly used in order to reach a comprehensive ranking of alternatives through mathematical formulations. Quantitative MCDM have been applied to many sectors: among others, health technology [10], urban mobility [4], building reuse [11] and evacuation in critical situations [12].

Assisting decision-making through quantitative MCDM usually follows a 4-step structure [13]. First, a set of criteria is defined. Second, the criteria are weighted according to their relative importance [3,14]. Third, the alternatives are evaluated according to each criterion, assigning a score to each alternative-criterion pair. Fourth, a global rank is calculated by aggregating the previous two steps [13]. This global score indicates the relative position of each alternative compared to the others and can be obtained through different multicriteria techniques. Among them [7] the compromised ranking method (CRM), also called VIKOR [15], obtains compromised solutions that can be accepted by all stakeholders involved [3,16]. Therefore, it has been used in diverse sectors [17–19].

Both the criteria weighting and alternatives' evaluation (steps 2 and 3 of the structure of Wang et al. [13]) are difficult tasks that might not have a single answer, so the opinion of different experts is usually sought [17]. However, deciding a quantitative weight for a criterion or rating an alternative regarding a criterion may not be straightforward, and experts might prefer a qualitative assessment (i.e. very important or not important), which is difficult to quantify [7]. Indeed, the same linguistic term might easily not be quantified at the same value by two different experts. Also, in an uncertain environment, experts can hesitate when choosing the linguistic term [20], since they feel there is not enough information [21] or due to limited knowledge [22]. In other words, uncertainty appears because of two factors: difficulty in quantifying human answers and lack of confidence in choosing the right answer.

The first factor of uncertainty has been widely assessed in the literature through fuzzy linguistic scales (FLS). Using FLS, an expert is required to choose from different terms (i.e. *high* or *low*, to rate the importance of a criterion), which are quantified through fuzzy numbers [23]. Such numbers allow a set of numerical values for each single linguistic term to be considered, overcoming quantification difficulties. FLS have been used together with a fuzzy version of VIKOR in various problems: assessing software performance [24,25], determining the best energy mix for a city [26], and evaluating activities within the supply-chain [27].

However, FLS does not appropriately address the second factor of uncertainty, so experts must solve their potentially low confidence by themselves before answering. Also, the reasoning process of experts can be too complex to encompass in one single word, without additional information [28]. In order to overcome such limitations, Rodríguez et al. [28] and Chen & Hong [20] propose advanced linguistic-based methods. Instead of using single terms (such as "high"), the answer is given in a freer and comparative manner (such as "greater than high"), which modifies the fuzzy numbers accordingly. Nevertheless, such methods still require the choice of a sentence that may be difficult due to confidence issues.

Alternatively, the fuzzy rating scale (FRS) [29] is a tool that has proved successful in capturing an accurate reflection of subjectivity, diversity and imprecision in human responses [30]. Using FRS, the responder can continuously adjust the shape of the fuzzy number associated to his/her answer [31,32]. Therefore, both factors of uncertainty can be addressed: the difficulty of quantifying answers through the utilization of fuzzy numbers and the lack of confidence with a flexible responding process. The use of FRS is still not extended, since a relatively complex framework is needed to perform the surveys and some training of responders is required [31]. Despite its use in questionnaires [31,32], as far as the authors know, there is only one application in MCDM [33].

In this context, this work develops a Methodology for Integrated Multicriteria Decision-making with Uncertainty (MIMDU) that considers both the difficulty in quantifying responses and the confidence. The methodology is structured in three phases. In phase 1, a novel answering process using FRS is defined to ease the experts' decision-making while maintaining the potential to model uncertainty. In phase 2, CRM is used due to its successful results in uncertain contexts [24,25,27], presenting a standardized fuzzy formulation (F-CRM) to handle the quantified fuzzy numbers from the previous phase and obtain a fuzzy ranking of alternatives. In phase 3 a systematic procedure is proposed to interpret the fuzzy ranking and provide useful information to the decision-makers. The methodology is illustrated with an example case aiming to show its potential to model uncertainty and assist decision-makers in any sector. In particular, the illustration is provided with, first: a sensitivity analysis to assess how the confidence level in the evaluation of an alternative in phase 1 can affect its final ranking, leading to more confident alternatives to be selected; and second: a comparison with F-VIKOR, due to its similar ambition for finding the most compromised solution, to see the major potential of MIMDU to capture non-confident evaluations and provide more valuable information for decision-making.

The remainder of the paper is organized as follows. Section 2 details the state of art on the three MIMDU phases in order to identify the techniques available. Afterwards, section 3 defines the MIMDU methodology, whose potential is illustrated in section 4. Finally, section 5 presents the conclusions of the work.

2. State of the art on fuzzy MCDM

This section reviews the procedures used in the literature to address the three phases of the MIMDU methodology. First (2.1), the methods to model uncertain opinions; then (2.2), the techniques to calculate a fuzzy ranking of alternatives; finally (2.3), the methods to interpret the ranking results.

2.1. Modelling uncertain opinions

As previously stated, rating the importance of a criterion or the adequacy of an alternative according to a criterion are uncertain tasks due to two factors: first, opinions are not commonly expressed with numbers, but with linguistic terms that do not have a unique quantification [34]; secondly, experts might hesitate about the answers [20]. Fuzzy linguistic scales are commonly used in fuzzy MCDM to deal with the first factor of uncertainty. Thus, for instance, instead of quantifying a "high" rate of importance with a 4 or 4.5 on a 0-5 scale of real values, a fuzzy number that includes different numerical values is assigned. Mathematically, each fuzzy number $\tilde{A} = (X, \mu)$ assigned to a linguistic term (i.e. "low", "medium", "high") establishes the membership degree $\alpha \in [0, 1]$ of each value x from the universe of discourse X (in this case the 0-5 scale), according to their membership function $\mu_{\tilde{A}} : X \to \alpha$, as introduced by Zadeh [23,35]. In order to perform quantitative possibilistic reasoning, in this paper the membership degrees and membership functions are understood as possibility measures and possibility distributions, respectively, by means of postulating, for instance, the proposition: "the importance of a criterion is high", as proposed by Zadeh [36]. That way, numerical values falling either under the lowest bottom-end or over the highest upper-end of the support of the fuzzy numbers are considered impossible to describe the fuzzy variable ("importance of the criterion") under the corresponding proposition; while the numerical values having a membership degree of 1 are totally plausible [37].

The shape of the fuzzy numbers depends on their membership functions $\mu_{\tilde{A}}$. The most common shapes are triangular and trapezoidal [38–41]. Regardless of the shape selected, the use of fuzzy linguistic scales (FLS) requires positioning the fuzzy numbers equidistantly along the universe of discourse. Therefore, all values are equally represented within the linguistic answers available. Fig. 1 shows two examples of FLS to rate the importance of a criterion. As observed, a FLS can differ in the number of answers available (5, left; 9, right) and the shape of the fuzzy numbers (triangular, left; trapezoidal, right).

Rating the importance of the criteria and the evaluation of alternatives on fuzzy linguistic scales does not take into account the lack of confidence experts might have when answering, since the membership functions are crisp [42]. Indeed, one expert could have been completely sure while another could answer the same after deep consideration, but the same fuzzy number is assigned to both answers. Consequently, the shape of the fuzzy numbers must be adapted to the expert's confidence in order to model the answer precisely. Extensions to the initial fuzzy sets have been developed to include the responders' confidence (or hesitance, as its reverse). Atanassov [43] proposed the intuitionistic fuzzy sets (IFS), where the sum of the membership degree and the non-membership degree of any value no longer needs to

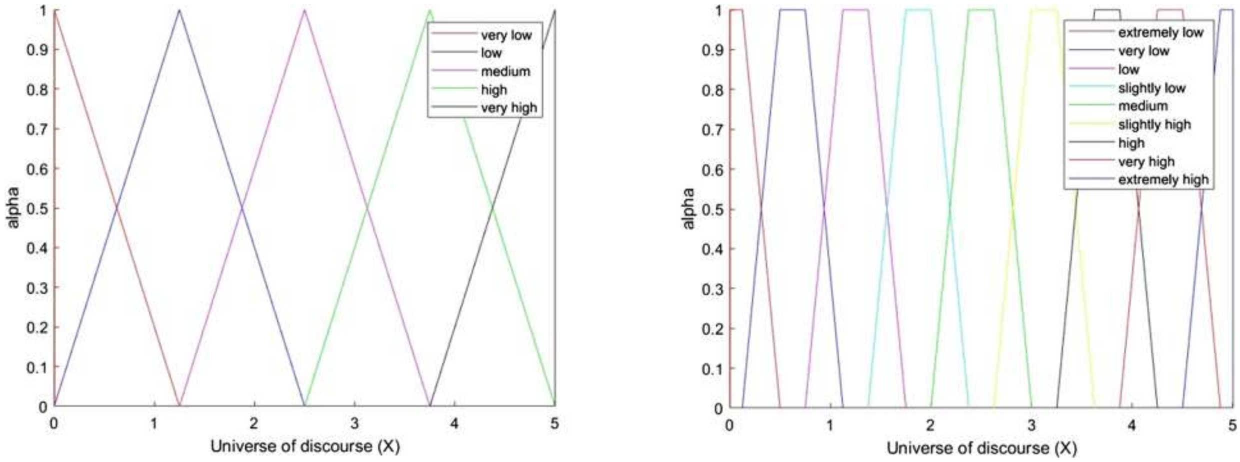

Fig. 1. Fuzzy linguistic scales for rating the importance of a criterion. Five answers and triangular shape (left) and nine answers and trapezoidal shape (right). (For interpretation of the colours in the figure(s), the reader is referred to the web version of this article.)

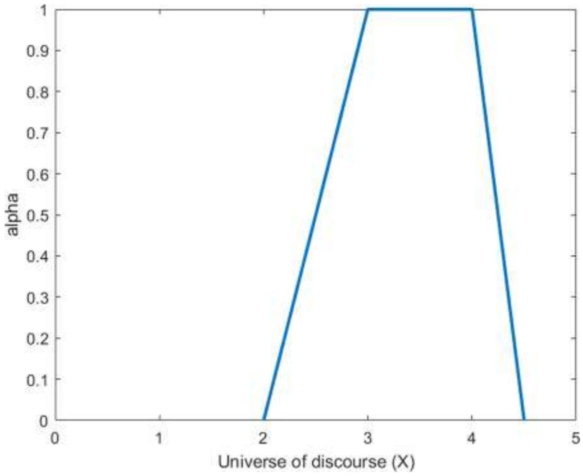

Fig. 2. Example of a trapezoidal fuzzy number build through a FRS.

equal 1, thus defining hesitance as the difference to 1. Several MCDM methods have been recently developed based on IFS, among others [44–46]. Torra [47] presented the hesitant fuzzy sets (HFS), in which the membership degree is determined by a value function. HFS have allowed the development of more complex fuzzy linguistic approaches, such as those presented in Rodríguez et al. [28] and Chen & Hong [20]. Despite the improvement in considering a lack of confidence, these methods still use pre-defined fuzzy numbers to encode opinions.

Alternatively, fuzzy rating scales (FRS) allow the responder to adjust the shape of the fuzzy number continuously. Thus, both factors of uncertainty can be addressed simultaneously. The guidelines for defining a trapezoidal fuzzy number for each answer of an expert using FRS follow 4 steps [31]. First, a bounded numerical scale, such as the interval [0,5], is considered as the universe of discourse. Second, the expert is asked to define the interval of values considered "fully compatible" with the response, for example, the interval [3,4]. This interval constitutes the *core* of the trapezoidal fuzzy number and the values contained have a membership degree of 1 ($\alpha = 1$). Third, the expert is asked to establish the interval of values considered "compatible to some extent" with the response, for example the interval [2,4.5]. This interval constitutes the *support* of the trapezoidal fuzzy number and the values contained have a membership degree above 0 ($\alpha \geq 0$). Finally, both intervals are linearly interpolated to obtain the trapezoidal fuzzy number (Fig. 2).

Either FLS or FRS, as just described, lead to quantitative possibilistic reasoning, since the responses of the experts are modelled with a fuzzy number under a numeric and arbitrary scale defining the universe of discourse. On the other hand, qualitative reasoning is also feasible and more accurate to fuzzy decision-making in such arbitrary scales [57]. This qualitative approach solves the commensurateness problem which claims that the same answer provided by two different respondents (for example: high importance for one criterion) hardy bare the same meaning. Consequently, it avoids performing aggregation operations of the answers apart from maximum and minimum operations and variations of them (i.e. discrimin and leximin operations) [58]. This limits the assistance in decision-making and recommendations are then based on pair-wise comparisons of alternatives that respect three principles: the focus effect, the compatibility with strict pareto-dominance, and the restricted compensation [57]; that generally account for a wider satisfaction of one alternative, compared to another, in the most important criteria. Quantitative-based reasoning procedures, alternatively, account for very refined aggregation methods [57] and their use, particularly with FLS, is very extended in fuzzy multicriteria decision-making in the literature, with multiple applications in fuzzy versions of crisp-existing techniques: among others, F-VIKOR [18,19,48,49], F-TOPSIS [46,50,51], F-ELECTRE [40,52,53], and F-PROMETHEE [54–56].

2.2. Alternatives ranking

Once the weights of criteria and the alternative-criterion ratings are defined through fuzzy numbers, a multicriteria technique is required to rank the alternatives [13]. As stated before, the compromise ranking method (CRM), very similar to the well-known VIKOR, is chosen in this study due to its success in different uncertainty contexts [34,39]. Now the crisp formulation of the CRM is presented, followed by a revision of the possible approaches for arithmetic operations with fuzzy numbers.

Crisp formulation of the compromised ranking method (CRM) The CRM consists in comparing each alternative to an ideal solution, which is a utopian solution performing optimally for all criteria [59,60]. The closer the alternative is to the ideal solution, the better it is. The closeness concept is calculated through the mathematical distance $L_{i,p}$ for alternative i, depending on the metric p. (eq. (1)).

$$L_{i,p} = \left[\sum_{j=1}^{n} W_j^p \cdot \left(\frac{F_j^* - f_{ij}}{F_j^* - f_j^*} \right)^p \right]^{1/p} \tag{1}$$

where n is the number of criteria; W_j is the weight of the criterion j; f_{ij} is the value of alternative i for criterion j; F_j^* is the ideal value for criterion j (the best among all alternatives); and f_j^* is the anti-ideal value for criterion j (the worst among all alternatives). Finally, the metric p indicates the importance assigned to the deviation from the ideal value for each criterion and can vary from 1 to ∞ [61]. A higher importance is assigned to the maximum deviation if p is increased [61]. Thus, while $L_{i,1}$ assigns the same importance to all deviations (obtaining the maximum global utility), $L_{i,\infty}$ considers only the maximum deviation of a criterion (achieving the minimum individual regret) [62] (eq. (2)).

$$\begin{aligned} L_{i,1} &= \sum_{j=1}^{n} W_j \cdot \left(\frac{F_j^* - f_{ij}}{F_j^* - f_j^*} \right) \\ L_{i,\infty} &= \max_{j=1..n} \left[W_j \cdot \left(\frac{F_j^* - f_{ij}}{F_j^* - f_j^*} \right) \right] \end{aligned} \tag{2}$$

Although other metrics apart from $p = 1$ and $p = \infty$ can be applied, a linear combination of these two is recommended in the literature [63] and will be used in this work (eq. (3)), with γ being a parameter for weighting the importance given to the maximum global utility versus the minimum individual regret, and usually taken equal to 0.5 [15]:

$$L_i = \gamma\ L_{i,1} + (1 - \gamma)\ L_{i,\infty} \tag{3}$$

Arithmetic operations with fuzzy numbers In an uncertain framework, the weights of criteria and the evaluation of alternatives are no longer crisp values, but fuzzy numbers. Consequently, a fuzzy arithmetic must be used for the mathematical operations required in (eq. (1)-(3)). Two options have been developed [64]: the extension principle and the α-cut approach. The extension principle achieves better results, as it avoids overestimating uncertainty [64]. However, its implementation is equivalent to the solution of a non-linear problem [65]. Alternatively, numerous algorithms are based on the α-cut approach [66]. An α-cut of a fuzzy number $\tilde{A} = (X, \mu)$, named ${}^{\alpha}A$, is an interval composed of all the elements of the universe of discourse (X) whose membership degrees are equal to or exceed α, where $\alpha \in [0, 1]$, obtained with the membership function $\mu_{\tilde{A}} : X \to \alpha$ (eq. (4)).

$$ {}^{\alpha}A = \left\{ x \in X \mid \mu_{\tilde{A}}(x) \geq \alpha \right\} \tag{4} $$

With this approach, the fuzzy numbers are first discretized into a number of α-cut intervals (from now on, α-cuts) for different values of the membership degree (α). Then, interval calculations [67] are performed on the α-cuts of the primary fuzzy numbers to obtain the α-cuts of the calculated fuzzy number [64].

2.3. Interpreting results

Decisions based on fuzzy ranking of alternatives can be counterintuitive. Therefore, different techniques have been developed to remove fuzziness and express a crisp preference of alternatives. Brunelli & Mezei, [68] propose to divide these techniques into two groups: those transforming fuzzy numbers into crisp values through their best non-fuzzy performance (BNP); and those performing pair-wise comparisons of the fuzzy numbers to determine the degree at which one fuzzy number is greater than another.

Most techniques of the former group are based on the calculation of the Area, the Center of Area (COA), or the Median [69]. Indeed, the COA, meaning the point of the support of the fuzzy number that equally divides the area under the membership function, is the most common method [69] due to its simplicity in obtaining a good estimation of the fuzzy number without needing additional parameters [34]. However, inconsistencies might be generated with these techniques since the membership function is treated as a probability function and divided by its surface, as proved in Dubois & Prade [70]. Indeed, in the framework of quantitative possibilitic reasoning, Dubois [71] concludes the most natural defuzzification option is the Middle Point of the Mean Interval (MPMI) [72]:

$$ MPMI(\tilde{A}) = \int_{0}^{1} \frac{min\ {}^{\alpha}A + max\ {}^{\alpha}A}{2} d\alpha \tag{5} $$

The methods of the latter group use functions to perform pair-wise comparisons of the fuzzy numbers and report a value between 0 and 1, which shows how much greater or smaller the first number is compared to the second. If they are identical, the result is 0.5. The Baas & Kwakernaak method [73] and the Nakamura method [74] are based on the min t-norm determination and the calculation of the weighted distance between each pair of fuzzy numbers [68], respectively. Alternatively, Dubois [75] proposes four indices based on possibility and necessity measures that are necessary and sufficient to characterize the respective configurations of two fuzzy numbers ($\tilde{A}$ and $\tilde{B}$) in a universe of discourse. A possibility measure can be thought as an indicator for an optimistic decision-maker; whereas a necessity measure can correspond to an indicator for a pessimistic decision-maker [76], which needs to know the certainty of one fuzzy number being greater or smaller than another. These four indices are divided in two indices returning possibility measures (eq. (6)-(7)) and necessity measures (eq. (8)-(9)):

$$ \text{Index 1:} \quad \Pi_{\tilde{A}}\left([\tilde{B}, +\infty)\right) = \sup_{\substack{x,y \\ x \geq y}} min\left(\mu_{\tilde{A}}(x), \mu_{\tilde{B}}(y)\right) \tag{6} $$

$$ \text{Index 2:} \quad \Pi_{\tilde{A}}\left(]\tilde{B}, +\infty)\right) = \sup_{x} \inf_{\substack{y \\ y \geq x}} min\left(\mu_{\tilde{A}}(x), 1 - \mu_{\tilde{B}}(y)\right) \tag{7} $$

$$ \text{Index 3:} \quad N_{\tilde{A}}\left([\tilde{B}, +\infty)\right) = \inf_{x} \sup_{\substack{y \\ y \leq x}} min\left(1 - \mu_{\tilde{A}}(x), \mu_{\tilde{B}}(y)\right) \tag{8} $$

$$ \text{Index 4:} \quad N_{\tilde{A}}\left(]\tilde{B}, +\infty)\right) = 1 - \sup_{\substack{x,y \\ x \leq y}} min\left(\mu_{\tilde{A}}(x), \mu_{\tilde{B}}(y)\right) \tag{9} $$

Where eq. (6) (respectively, eq. (7)) yields the grade of possibility of $\tilde{A}$ being greater than or equal to (respectively, strictly greater than) $\tilde{B}$ by referring to the partial matching of the fuzzy set $\tilde{A} \cap [\tilde{B}, +\infty)$ (respectively, $\tilde{A} \cap]\tilde{B}, +\infty)$) of the real numbers greater than or equal to (respectively, strictly greater than) $\tilde{B}$ that are constrained by $\tilde{A}$. Similarly,

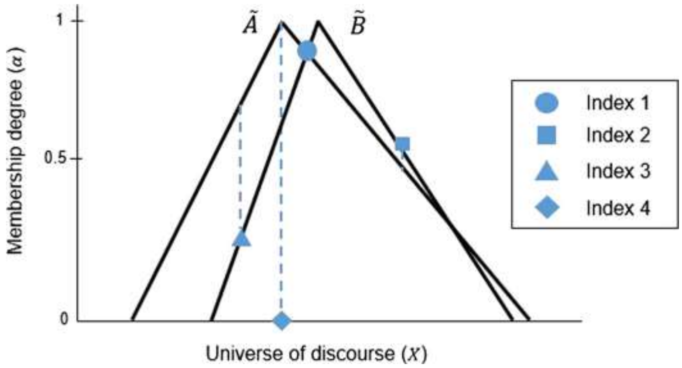

Fig. 3. Example of indices calculation to compare two fuzzy numbers.

eq. (8) (respectively, eq. (9)) yields the grade of necessity of $\tilde{A}$ being greater than or equal to (respectively, strictly greater than) $\tilde{B}$ by referring to the degree of inclusion of $\tilde{A}$ in $[\tilde{B}, +\infty)$ (respectively, in $]\tilde{B}, +\infty)$).

Despite a relative complex formulation, their application in the ranking of two fuzzy numbers with linear or parabolic membership functions is obvious, since it is only a matter of finding intersections among the spreads (left and right) of both numbers. Fig. 3 shows an example of how to calculate these indices for the comparison between any two fuzzy numbers $\tilde{A}$ and $\tilde{B}$; thus, for the statement: "$\tilde{A}$ is greater than $\tilde{B}$". Index 1 is determined by the intersection between the right spread of $\tilde{A}$ and the left spread of $\tilde{B}$; index 2 (respectively, index 3), corresponds to the degree of membership α of the right spread of $\tilde{A}$ (respectively, left spread of $\tilde{B}$) that is the complementary α value of the right spread of $\tilde{B}$ (respectively, left spread of $\tilde{A}$) for a single element of the universe of discourse; and index 4 corresponds to the intersection between the left spread of $\tilde{A}$ and the right spread of $\tilde{B}$. All indices are necessary to compare two fuzzy numbers, since as it can be seen in Fig. 3, the information of the indices might differ from one another; while index 1 determines it is very likely that A1 is greater than A3, index 4 states that it is impossible (the spreads never intersect) and indices 2 and 3 report intermediate answers (being index 3 slightly against the statement and being index 2 almost completely neutral).

For a more in-depth theoretical background of the formation of the four indices, the reader is referred to Dubois [75].

3. MIMDU methodology for integrated multicriteria decision-making with uncertainty

This study presents the Methodology for Integrated Multicriteria Decision-making with Uncertainty (MIMDU), which extends compromise ranking techniques, such as F-VIKOR, by modelling uncertain opinions considering the difficulty in quantifying human responses and their confidence. The methodology is divided into three phases: phase 1 (P1), phase 2 (P2) and phase 3 (P3); as shown in Fig. 4. Prior to phase 1 (input), experts are consulted to rate the importance of each criterion and the adequacy of each alternative-criterion pair. After its application (output), MIMDU provides two alternative rankings (without and with uncertainty) and pair-wise comparisons based on possibility and necessity measures of the alternatives to ease decision-making. Both the ranking and the pair-wise comparisons provide complementary information to assess the effect of the confidence with which alternatives have been evaluated in the final ranking of results. In between, the three phases have the following purposes.

In phase 1, the experts' opinions are modelled through FRS. Specifically, a novel procedure based on Rosa de Sáa et al. [30] and Lubiano et al. [31] is presented to ease the answering process, avoid the need for experts' training and still successfully address the two factors of uncertainty: the difficulty of quantifying responses and the lack of confidence (section 3.1).

In phase 2, a ranking of alternatives is obtained. To do so, a fuzzy formulation of the compromise ranking method (CRM) is standardized using the α-cut approach to calculate the distance to the ideal solution of each alternative (section 3.2).

In phase 3, a systematic procedure for interpreting the results of phase 2 is described. Such interpretation provides a crisp and a fuzzy-based ranking of alternatives (not considering and considering uncertainty, respectively), as well

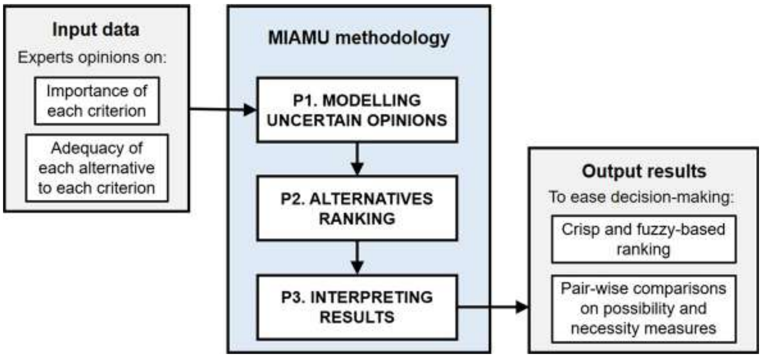

Fig. 4. Structure of the MIMDU methodology.

Table 1
Options to express the level of confidence and quantification of the support related to the range of the universe of discourse.

Confidence in the response	Relative support
Completely sure (CS)	0%
Sure (S)	15%
Indecisive (I)	30%
Unsure (U)	45%
Very unsure (VU)	60%

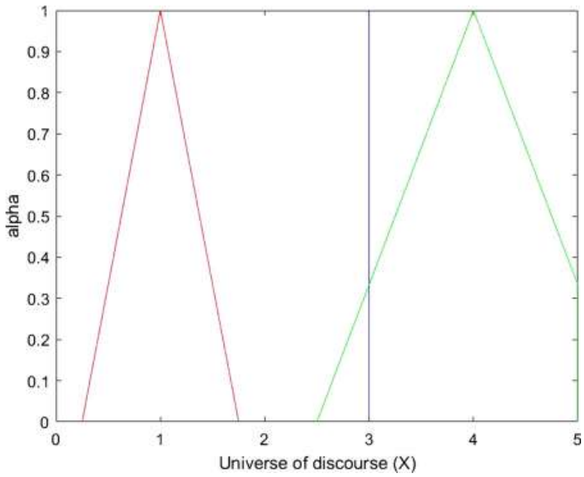

Fig. 5. Examples of answers.

as pair-wise comparisons of alternatives in order to offer as much useful information as possible to decision-makers (section 3.3).

3.1. Modelling uncertain opinions (P1)

This study presents a novel procedure based on FRS to model uncertain opinions. This new procedure eases the response, since few and more intuitive answering options are allowed, but still allows experts to adjust the shape of the fuzzy number according to their thinking process. The approach is structured in two steps:

1. The expert must choose a value on a 0-5 scale to rate the importance of a criterion (a high value means high importance) or to evaluate an alternative according to a criterion (a high value means high adequacy of the alternative to the criterion). The number of scale options available is manageable for experts [77] and equal to the work of Afful-Dadzie et al. [25]. The value chosen becomes the reference value of the answer and constitutes the *core* of the triangular fuzzy number (TFN). Triangular shapes are chosen instead of trapezoidal to allow a crisp analysis of results without considering any uncertainty, which is further explained in section 3.3.
2. The expert must express his/her confidence with the above reference value, from five options: *completely sure*, *sure*, *indecisive*, *unsure* and *very unsure*. Each option has an associated numerical percentage which defines the support of the TFN (relative to the range of the universe of discourse, Table 1). Such percentages are defined so the intermediate answer (*indecisive*) has a support of 1.5 on a 0-5 scale, as in the literature [26,34].

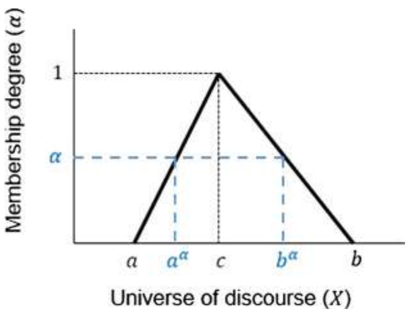

Fig. 6. Representation of an α-cut interval of a triangular fuzzy number.

Fig. 5 shows three examples of expert answers after completing steps 1 and 2 to assess the importance of a criterion. The expert in blue is *completely sure* the importance is 3; the expert in red considers the importance is 1, but feels *indecisive* (support bounded between 0.25 and 1.75); while the expert in green sets the importance to 4 but is *very unsure* (support should be bounded between 2.5 and 5.5). As observed, if the responder is completely sure about the answer (blue), a crisp value is considered. Otherwise, the lower the confidence, the wider the support of the fuzzy number. Note that all fuzzy numbers are truncated at the limit of the universe of discourse, achieving the final support for the expert in *green* (between 2.5 and 5).

As shown before, the described approach has two advantages compared to other fuzzy linguistic processes. First, it allows a more precise modelling of the answers by considering different levels of confidence. In detail, a narrower support is assigned to more confident answers; while progressively more values from the universe of discourse are included when confidence decreases. Secondly, the pressure that experts undergo when addressing answers is reduced, thanks to confidence inclusion. In addition, a better understanding of the modelling is achieved as the whole answer provided fully defines the TFN, instead of defining it beforehand. This is particularly interesting when experts are not used to multicriteria analysis, so traceability across the operations can be more easily achieved.

3.2. Alternatives ranking (P2)

This study presents a fuzzy formulation of the compromised ranking method (F-CRM) using the α-cut approach to obtain a fuzzy ranking of alternatives (eq. (10)). As shown, the formulation is similar to the crisp one (eq. (1)-(3)), but now the weights of criteria (${}^{\alpha}W_j$), the evaluation of alternatives (${}^{\alpha}f_{ij}$) and the distances to the ideal solution (${}^{\alpha}L_{i,p}$ and ${}^{\alpha}L_i$) are fuzzy numbers discretized using the α-cut approach. In particular, the criteria weights and alternatives' evaluations are defined through the α-cuts of the TFN obtained in phase 1. The F-CRM is divided into four steps. Initially (step 0), the α-cuts of the TFN in phase 1 are determined. Then (step 1), the criteria weights are calculated. Next (step 2), the evaluations of alternatives are calculated and the ideal and anti-ideal values (${}^{\alpha}F_j^*$ and ${}^{\alpha}f_j^*$) are identified. Finally (step 3), the distance from each alternative to the ideal solution is calculated, classifying alternatives accordingly.

$$
\begin{aligned}
{}^{\alpha}L_{i,p} &= \left[\sum_{j=1}^{n}({}^{\alpha}W_j)^p \cdot \left(\frac{{}^{\alpha}F_j^* - {}^{\alpha}f_{ij}}{{}^{\alpha}F_j^* - {}^{\alpha}f_j^*}\right)^p\right]^{1/p} \\
{}^{\alpha}L_i &= 0.5 \cdot {}^{\alpha}L_{i,1} + 0.5 \cdot {}^{\alpha}L_{i,\infty}
\end{aligned} \tag{10}
$$

Step 0. Determination of the α-cuts from each TFN This step provides a nexus between phases 1 and 2 of the methodology. In phase 1, a TFN is obtained to express the opinion of each expert concerning the importance of criteria and alternative-criterion evaluations. Now, these results are taken as inputs to determine their α-cuts (Fig. 6, eq. (11)) in order to later apply the F-CRM. Eleven values of α are taken: from 0 to 1 with increments of 0.1 [78], balancing a good approximation of the fuzzy numbers and a relatively quick calculation process.

$$
{}^{\alpha}TFN = \left[a^{\alpha}, b^{\alpha}\right] = [a + (c-a)\cdot\alpha, b - (b-c)\cdot\alpha] \tag{11}
$$

Step 1. Calculation of the criteria weights ${}^{\alpha}W_j$ This step aggregates the experts' opinions regarding the importance of the criteria into a specific weight for each one (also expressed as fuzzy numbers through their α-cuts). Since two experts might have assigned higher or lower rates to all criteria, first of all the α-cuts are standardized by employing a fast procedure presented by Dubois & Prade [79], and discussed by Pavlacka [80] and Dubois [81] (with eq. (12)).

$$ {}^{\alpha}w_{jk} = \left[\frac{a^{\alpha}_{jk}}{a^{\alpha}_{jk} + \sum_{\forall i \neq j} b^{\alpha}_{ik}}, \frac{b^{\alpha}_{jk}}{b^{\alpha}_{jk} + \sum_{\forall i \neq j} a^{\alpha}_{ik}} \right] \tag{12} $$

where $[a^{\alpha}_{jk}, b^{\alpha}_{jk}]$ is the α-cut interval to initially express the importance given by expert $k = 1, ..., r$ to the criterion $j = 1, ..., n$; r is the number of experts consulted; n is the number of criteria considered; and ${}^{\alpha}w_{jk}$ is the standardized α-cut interval. This formulation satisfies the non-emptiness and attainability conditions established by De Campos [82] as necessary for interval normalizations.

Then, the α-cut interval for the weight of criterion j (${}^{\alpha}W_j$) is calculated following (eq. (13)):

$$ {}^{\alpha}W_j = \frac{\sum_{k=1}^{r} {}^{\alpha}w_{jk}}{r} \tag{13} $$

Under a crisp analysis, the sum of all weights equals 1. However, in fuzzy analysis, since α-cuts are used, the sum of all weights for each α-cut equals an interval containing the value 1. The higher the membership degree α, the closer the analysis to a crisp one as the range is reduced. Finally, for $\alpha = 1$, the sum of the weights is exactly the interval [1,1].

Step 2. Calculation of the alternatives evaluations ${}^{\alpha}f_{ij}$ *and identification of the ideal and anti-ideal value of each criterion* ${}^{\alpha}F^*_j$ *and* ${}^{\alpha}f^*_j$ The evaluations of alternatives are also calculated by aggregating experts' opinions (eq. (14)).

$$ {}^{\alpha}f_{ij} = \frac{\sum_{k=1}^{r} {}^{\alpha}f_{ijk}}{r} \tag{14} $$

where ${}^{\alpha}f_{ijk}$ is the α-cut interval to express the evaluation of alternative $i = 1, ..., m$ according to criterion $j = 1, ..., n$ given by expert $k = 1, ..., r$; being m the number of alternatives; while ${}^{\alpha}f_{ij}$ is the α-cut interval of the average evaluation of alternative i according to criterion j.

Next, the ideal and anti-ideal values of each criterion are determined. For each α-cut, the ideal value of a criterion ${}^{\alpha}F^*_j$ corresponds to the maximum or minimum among the evaluations, depending on whether the criterion is beneficial or harmful for the decision. The maximum and minimum values for each α correspond to the highest upper-end and the lowest bottom-end, respectively, among all the α-cuts of the alternatives' evaluations for that α. Conversely, the anti-ideal value is determined by the worst values. Consequently, both the ideal and anti-ideal values are crisp values which only depend on the α-cut considered. Assuming criterion j is beneficial, its ideal and anti-ideal value can be obtained with (eq. (15)):

$$ {}^{\alpha}F^*_j = \max\left(\bigcup_{\forall i} {}^{\alpha}f_{ij} \right) \qquad {}^{\alpha}f^*_j = \min\left(\bigcup_{\forall i} {}^{\alpha}f_{ij} \right) \tag{15} $$

Step 3. Calculation of the distance from each alternative to the ideal solution ${}^{\alpha}L_i$ *and alternatives ranking* Now the distance from each alternative to the ideal solution can be calculated using the F-CRM formulation (eq. (8)). The explanation requires emphasizing the reasoning behind the calculation of the α-cuts for the distance of alternative i to the ideal value of criterion j (${}^{\alpha}dn_{ij}$), with (eq. (16)). This reasoning is important for observing the effects of the uncertainty modelling presented in phase 1 of the methodology and to correctly interpret the results in phase 3. In order to apply (eq. (16)), since crisp and interval values are included, the crisp values are assumed as intervals containing only their own values (i.e. [5,5]).

$$ {}^{\alpha}dn_{ij} = \frac{{}^{\alpha}F^*_j - {}^{\alpha}f_{ij}}{{}^{\alpha}F^*_j - {}^{\alpha}f^*_j} \tag{16} $$

That distance means that for each criterion and each α-cut:

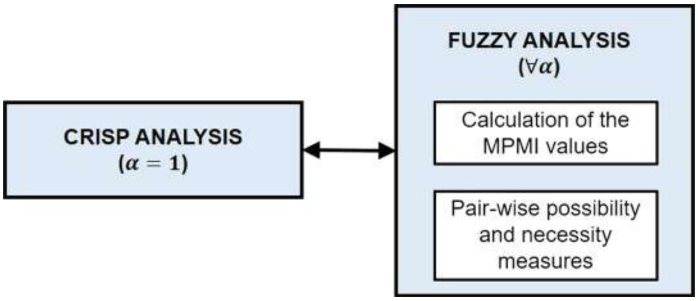

Fig. 7. Procedure for interpreting results based on a comparison of a crisp and fuzzy analysis.

- The bottom-end of the α-cut interval of the alternative which determines the ideal value is 0. In the best case, this alternative is ideal for the criterion. However, since the evaluation ${}^{\alpha}f_{ij}$ is still fuzzy, the α-cut interval of the distance ranges from 0 to a value between 0 and 1.
- The upper-end of the α-cut interval of the alternative which determines the anti-ideal value is 1. In the worst case, this alternative is anti-ideal for the criterion. However, since the evaluation ${}^{\alpha}f_{ij}$ is still fuzzy, the α-cut interval of the distance ranges from a value between 0 and 1.

These two fulfilments connect the modelling of experts' opinions from phase 1 and the ranking of alternatives from phase 2: the lower the confidence when rating the adequacy of an alternative according to a criterion, the fuzzier the evaluation results and the larger the range of the α-cut interval of the alternative's distance to the criterion. Therefore, an increase in the range of the α-cut interval causes higher or lower values of distance to be achieved, depending on how well or badly the alternative has been evaluated on the criterion, which finally affects the ranking of the alternative. This effect is shown and discussed in great detail in the illustration of the methodology in section 4.

Finally (eq. (10)) is applied for each alternative and α, obtaining the α-cuts of the distance to the ideal solution (${}^{\alpha}L_i$). Those fuzzy numbers have to be ranked in increasing order to determine which alternative is closer to the ideal solution. However, interpreting a ranking of those fuzzy numbers is not an easy task, so a systematized procedure is presented in phase 3 (section 3.3).

$$
\begin{aligned}
{}^{\alpha}L_{i,p} &= \left[\sum_{j=1}^{n} ({}^{\alpha}W_j)^p \cdot \left(\frac{{}^{\alpha}F_j^* - {}^{\alpha}f_{ij}}{{}^{\alpha}F_j^* - {}^{\alpha}f_j^*}\right)^p\right]^{1/p} = \left[\sum_{j=1}^{n} ({}^{\alpha}W_j)^p \cdot ({}^{\alpha}dn_{ij})^p\right]^{1/p} \\
{}^{\alpha}L_i &= 0.5 \cdot {}^{\alpha}L_{i,1} + 0.5 \cdot {}^{\alpha}L_{i,\infty}
\end{aligned}
\tag{10}
$$

3.3. Interpreting results (P3)

Phases 1 and 2 of the methodology conclude with a fuzzy number for each alternative ($\tilde{L}_i$) representing the distance to the ideal solution. This phase aims to provide useful information for decision-making by performing a crisp and a fuzzy analysis of the fuzzy numbers, the latter including a calculation of the best non-fuzzy performance value (BNP) for each alternative using the MPMI and pair-wise comparisons between alternatives based on possibility and necessity measures (Fig. 7).

The crisp analysis only takes into account the distance of each alternative to the ideal solution obtained for the 1-cut interval ($\alpha = 1$); in other words, the ${}^{1}L_i$ values, which only consider the values provided by experts in step 1 of phase 1, without uncertainty. This analysis is intrinsically significant, since it is the major source of information in many multicriteria applications [12,15].

The fuzzy analysis uses a method from each group of defuzzyfication techniques to provide additional information considering the lack of confidence. First, the MPMI of each $\tilde{L}_i$ is calculated to estimate the best non-fuzzy performance value for the distance from each alternative to the ideal solution (eq. (5)). Second, the four indices proposed by Dubois [75] (eq. (6)-(9)) are used to determine the possibility and necessity measures of an alternative standing out from the others. Thus, the decision-maker not only knows which alternative is better (with the MPMI calculation), but can also select alternatives based on a possibility and/or necessity thresholds, which can be useful in decisions where

Table 2
Experts' rating of the importance of criteria.

Criteria	Expert	Importance	Confidence
C1	E1	4	I
	E2	3	S
	E3	1	VU
C2	E1	2	U
	E2	4	S
	E3	4	I
C3	E1	3	S
	E2	3	VU
	E3	5	U

Table 3
Experts' rating of the adequacy of alternatives according to criteria.

Criteria	Expert	A1		A2		A3	
		Evaluation	Confidence	Evaluation	Confidence	Evaluation	Confidence
C1	E1	3	S	2	U	1	U
	E2	3	U	2	VU	3	VU
	E3	4	U	4	CS	5	S
C2	E1	1	VU	1	S	5	U
	E2	2	CS	2	I	4	S
	E3	4	S	2	S	3	S
C3	E1	2	I	1	I	3	CS
	E2	3	VU	2	U	3	S
	E3	5	U	3	S	2	I

many alternatives are possible. In such decisions, alternatives falling under a certain threshold of being better than another could be dismissed. The comparison of the crisp and the fuzzy analyses provides a complete set of information to help with the final selection of the best alternative.

4. Illustration of the methodology in an example case

This section illustrates the applicability of the methodology to a generic example case with a low number of alternatives and criteria. Thus, the potential of MIMDU to assist decision-making can be tested, since criteria and alternatives can be particularized for any decision. Specifically, three alternatives (A1, A2, A3) are supposed, one of which has to be chosen according to three criteria (C1, C2, C3). To do so, three experts are consulted (E1, E2, E3) about the importance of each criterion and the adequacy of each alternative according to each criterion.

The section is divided in line with the MIMDU structure: first (4.1), phase 1 is illustrated by modelling the responses of experts considering their confidence; second (4.2), phase 2 is exemplified by applying the F-CRM to obtain a fuzzy ranking of alternatives; third (4.3), phase 3 is shown by following the interpretation process. Finally (4.4), a sensitivity analysis is performed to assess the influence of confidence on the results.

4.1. Phase 1. Modelling uncertain opinions

Each expert is asked to evaluate the importance of each criterion (Table 2) and the adequacy of alternatives according to criteria (Table 3). In both processes, experts first provide a reference value on a 0-5 scale and then the confidence level, from the options in Table 2. Fig. 8 shows some of the TFN determined: Fig. 8a represents fuzzy numbers for each expert's answers about the importance of C1; while Fig. 8b expresses their opinions regarding the adequacy of A1 according to C3.

4.2. Phase 2. Alternatives ranking

Once the opinions of the experts are collected through fuzzy numbers, F-CRM is applied to obtain a final fuzzy ranking of alternatives. Next, the steps from phase 2 are illustrated.

Step 0. Calculation of the α-cuts from each TFN Tables 4 and 5 show the α-cuts of the TFNs represented in Fig. 7, obtained with (eq. (11)). Note that the 1-cut intervals are composed of only the reference values (Tables 2 and 3). Thus, the application of F-CRM (eq. (10)) for these values results in a crisp analysis included in the interpretation of results in phase 3.

Step 1. Calculation of the criteria weights $^{\alpha}W_j$ Once the α-cuts are obtained, the F-CRM starts by calculating the weights of criteria. For each α, the experts' answers regarding the importance of criteria are standardized (eq. (12)) and aggregated (eq. (13)). Table 6 shows the resulting α-cuts of the criteria weights, while Fig. 9 represents the fuzzy numbers of the weights by means of their α-cuts. As observed, the experts have assigned a higher importance to the third criterion. Also, note that the sum of the average values of all α-cuts equals 1. This can be easily identified in the 1-cuts, since they are actually crisp values.

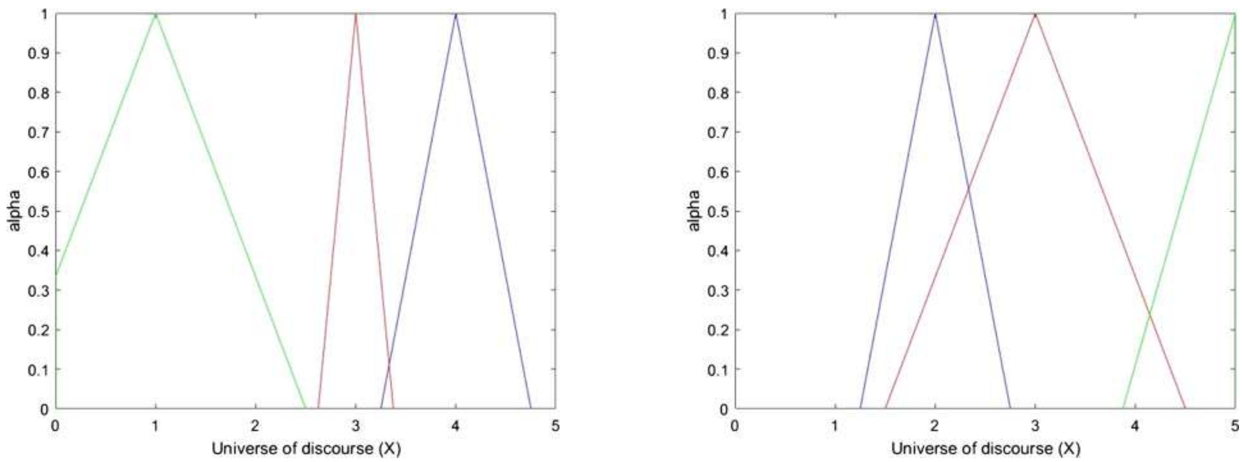

Fig. 8. Fuzzy numbers representing the rating of experts E1 (blue), E2 (red) and E3 (green) for the importance of C1 (left, Fig. 8a) and the adequacy of A1 according to C3 (right, Fig. 8b).

Table 4
α-cuts of the experts' rating of the importance of C1.

α	Importance of C1					
	E1		E2		E3	
0	3.250	4.75	2.625	3.375	0.000	2.500
0.1	3.325	4.675	2.663	3.338	0.000	2.350
0.2	3.400	4.600	2.700	3.300	0.000	2.200
0.3	3.475	4.525	2.738	3.263	0.000	2.050
0.4	3.550	4.450	2.775	3.225	0.100	1.900
0.5	3.625	4.375	2.813	3.188	0.250	1.750
0.6	3.700	4.300	2.850	3.150	0.400	1.600
0.7	3.775	4.225	2.888	3.113	0.550	1.450
0.8	3.850	4.150	2.925	3.075	0.700	1.300
0.9	3.925	4.075	2.963	3.038	0.850	1.150
1	4.000	4.000	3.000	3.000	1.000	1.000

Table 5
α-cuts of the experts' rating of the adequacy of A1 according to C3.

α	Adequacy of A1 to C3					
	E1		E2		E3	
0	1.250	2.750	1.500	4.500	3.875	5.000
0.1	1.325	2.675	1.650	4.350	3.988	5.000
0.2	1.400	2.600	1.800	4.200	4.100	5.000
0.3	1.475	2.525	1.950	4.050	4.213	5.000
0.4	1.550	2.450	2.100	3.900	4.325	5.000
0.5	1.625	2.375	2.250	3.750	4.438	5.000
0.6	1.700	2.300	2.400	3.600	4.550	5.000
0.7	1.775	2.225	2.550	3.450	4.663	5.000
0.8	1.850	2.150	2.700	3.300	4.775	5.000
0.9	1.925	2.075	2.850	3.150	4.888	5.000
1	2.000	2.000	3.000	3.000	5.000	5.000

Step 2. Calculation of the alternatives' evaluations ${}^{\alpha}f_{ij}$ and identification of the ideal and anti-ideal value of each criterion ${}^{\alpha}F_j^*$ and ${}^{\alpha}f_j^*$ The experts' opinions regarding the adequacy of each alternative according to each criterion are aggregated for each α (eq. (14)). Table 7 shows the α-cuts of the evaluations of the three alternatives regarding C3, which are schematically represented in Fig. 10. Then, the ideal and anti-ideal value for each criterion and each α are determined (eq. (15)). As the experts must assess the adequacy of one alternative regarding one criterion, the ideal-value is always the maximum of the upper-end of the α-cuts. In this example case, the ideal and anti-ideal values for C3 are always determined by A1 and A2, respectively (as observed in Table 7), while A3 is always evaluated with values in between.

It must be noted that being the ideal value of a criterion for each α determined by the same alternative is likely to happen but not obligatory, as it relies on the level of confidence. Indeed, Table 7 shows that, although A3 does not achieve such good (low) values as A1, neither does it achieve such bad (high) values as A1. This means that the evaluation of A3 according to C3 has been more confident for the experts, which can affect the final ranking of the alternatives, as is shown later in the section.

Step 3. Calculation of the distance from each alternative to the ideal solution ${}^{\alpha}L_i$ The results of the last step allow, first, calculating the α-cuts of the distances from each alternative to the ideal values of the criteria (eq. (16)). Table 8 and Fig. 11 represent the distances for all alternatives concerning C3. As previously mentioned, since A1 determines the ideal values of C3 for each α, the bottom-end of the α-cuts of A1 is always 0. Conversely, since A2 determines the anti-ideal values of C3, the upper-end of the α-cuts of A2 is always 1. The other values are conditioned by the

Table 6
α-cuts of the criteria weights.

α	$^{\alpha}W_j$					
	C1		C2		C3	
0	0.187	0.411	0.238	0.471	0.253	0.492
0.1	0.193	0.397	0.248	0.459	0.265	0.481
0.2	0.198	0.383	0.258	0.447	0.277	0.472
0.3	0.204	0.370	0.268	0.435	0.290	0.462
0.4	0.214	0.356	0.278	0.421	0.302	0.450
0.5	0.225	0.343	0.288	0.407	0.314	0.437
0.6	0.236	0.331	0.298	0.393	0.327	0.425
0.7	0.247	0.318	0.309	0.379	0.339	0.413
0.8	0.259	0.306	0.319	0.366	0.352	0.401
0.9	0.270	0.293	0.330	0.353	0.365	0.389
1	0.281	0.281	0.341	0.341	0.378	0.378

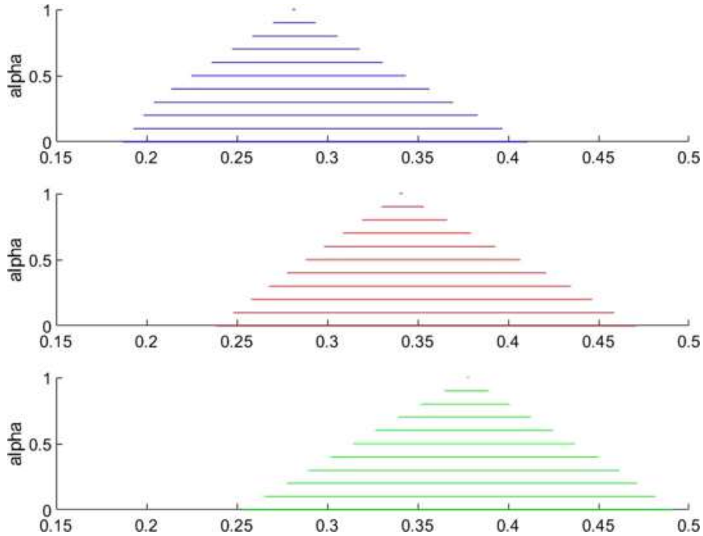

Fig. 9. Weights of criteria C1 (blue), C2 (red) and C3 (green).

Table 7
α-cuts of the alternatives evaluation according to C3, and ideal and anti-ideal value of C3.

α	$^{\alpha}f_{i3}$						$^{\alpha}F_3^*$	$^{\alpha}f_3^*$
	A1		A2		A3			
0	2.208	4.083	1.250	2.750	2.292	3.042	4.083	1.250
0.1	2.321	4.008	1.325	2.675	2.329	3.004	4.008	1.325
0.2	2.433	3.933	1.400	2.600	2.367	2.967	3.933	1.400
0.3	2.546	3.858	1.475	2.525	2.404	2.929	3.858	1.475
0.4	2.658	3.783	1.550	2.450	2.442	2.892	3.783	1.550
0.5	2.771	3.708	1.625	2.375	2.479	2.854	3.708	1.625
0.6	2.883	3.633	1.700	2.300	2.517	2.817	3.633	1.700
0.7	2.996	3.558	1.775	2.225	2.554	2.779	3.558	1.775
0.8	3.108	3.483	1.850	2.150	2.592	2.742	3.483	1.850
0.9	3.221	3.408	1.925	2.075	2.629	2.704	3.408	1.925
1	3.333	3.333	2.000	2.000	2.667	2.667	3.333	2.000

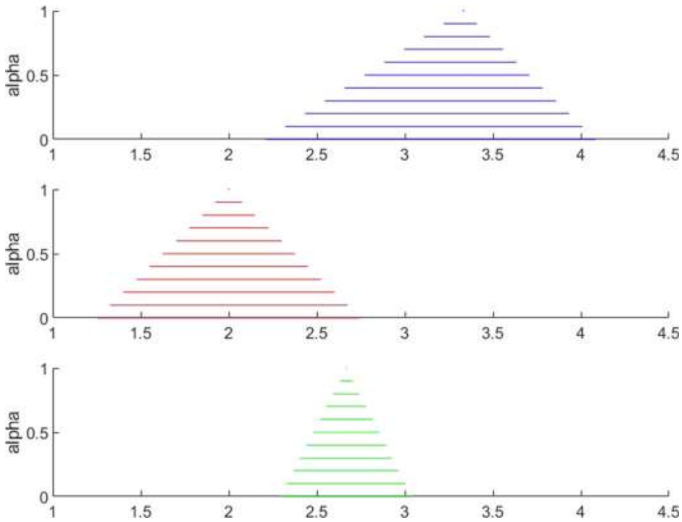

Fig. 10. Evaluation of alternatives A1 (blue), A2 (red) and A3 (green) according to C3.

experts' confidence. In line with the discussion from step 2, since A1 has been less confidently evaluated than A3, despite determining A1 the ideal value of C3, it achieves higher ranges and, consequently, higher upper-end values than A3 of the distance for low membership degrees α (i.e. 0.662 vs. 0.632 for $\alpha = 0$). The range of such intervals is progressively reduced as α increases, until the crisp distance for $\alpha = 1$, which does not consider any confidence.

Finally, the distance to the ideal solution for each alternative is calculated (eq. (10)). Table 9 shows the results of the α-cuts for metrics $p = 1$ ($^{\alpha}L_{i,1}$) and $p = \infty$ ($^{\alpha}L_{i,\infty}$), as well as the average value ($^{\alpha}L_i$) used in the next phase (eq. (10)) to rank the alternatives. The resulting fuzzy numbers ($\tilde{L}_i$) for alternatives A1 (blue), A2 (red) and A3 (green) are shown in Fig. 12.

Table 8
α-cuts of the distance from the alternatives to the ideal value of C3.

α	$^{\alpha}dn_{i3}$					
	A1		A2		A3	
0	0.000	0.662	0.471	1.000	0.367	0.632
0.1	0.000	0.629	0.497	1.000	0.374	0.626
0.2	0.000	0.592	0.526	1.000	0.381	0.618
0.3	0.000	0.551	0.559	1.000	0.390	0.610
0.4	0.000	0.504	0.597	1.000	0.399	0.601
0.5	0.000	0.450	0.640	1.000	0.410	0.590
0.6	0.000	0.388	0.690	1.000	0.422	0.577
0.7	0.000	0.315	0.748	1.000	0.437	0.563
0.8	0.000	0.230	0.816	1.000	0.454	0.546
0.9	0.000	0.126	0.899	1.000	0.475	0.525
1	0.000	0.000	1.000	1.000	0.500	0.500

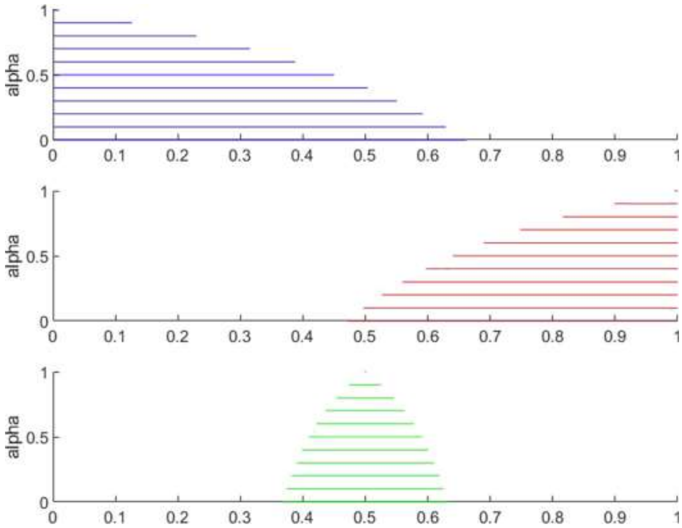

Fig. 11. Distances from alternatives A1 (blue), A2 (red) and A3 (green) to the ideal value of C3.

Table 9
Distances to the ideal solution using metric 1 and ∞, and the average value.

α	$^{\alpha}L_{i,1}$						$^{\alpha}L_{i,\infty}$						$^{\alpha}L_i$					
	A1		A2		A3		A1		A2		A3		A1		A2		A3	
0	0.100	0.984	0.330	1.373	0.116	0.812	0.100	0.363	0.119	0.492	0.093	0.311	0.100	0.673	0.224	0.932	0.105	0.561
0.1	0.110	0.938	0.363	1.337	0.128	0.778	0.110	0.356	0.132	0.481	0.099	0.301	0.110	0.647	0.247	0.909	0.114	0.540
0.2	0.120	0.889	0.398	1.301	0.138	0.738	0.120	0.350	0.146	0.472	0.106	0.292	0.120	0.619	0.272	0.886	0.122	0.515
0.3	0.132	0.838	0.436	1.266	0.149	0.696	0.132	0.344	0.162	0.462	0.113	0.282	0.132	0.591	0.299	0.864	0.131	0.489
0.4	0.144	0.776	0.481	1.227	0.162	0.652	0.144	0.331	0.180	0.450	0.120	0.270	0.144	0.554	0.331	0.838	0.141	0.461
0.5	0.157	0.708	0.533	1.187	0.177	0.607	0.157	0.316	0.201	0.437	0.129	0.258	0.157	0.512	0.367	0.812	0.153	0.432
0.6	0.172	0.635	0.593	1.148	0.196	0.560	0.172	0.301	0.225	0.425	0.138	0.245	0.172	0.468	0.409	0.786	0.167	0.402
0.7	0.187	0.556	0.664	1.110	0.217	0.510	0.187	0.286	0.254	0.413	0.148	0.232	0.187	0.421	0.459	0.761	0.183	0.371
0.8	0.205	0.469	0.750	1.073	0.245	0.458	0.205	0.272	0.287	0.401	0.160	0.219	0.205	0.370	0.519	0.737	0.202	0.338
0.9	0.223	0.368	0.858	1.036	0.280	0.399	0.223	0.257	0.328	0.389	0.173	0.204	0.223	0.312	0.593	0.713	0.227	0.302
1	0.243	0.243	1	1	0.330	0.330	0.243	0.243	0.378	0.378	0.189	0.189	0.243	0.243	0.689	0.689	0.259	0.259

4.3. Phase 3. Interpreting results

The interpretation of results focuses on comparing the crisp ranking, obtained with $\alpha = 1$, and the fuzzy-based ranking, which considers uncertainty collected in all membership degrees (Table 10). The results of the crisp analysis correspond to the crisp distance from each alternative to the ideal solution ($^{1}L_i$). In contrast, the fuzzy analysis is composed of the MPMI of each $\tilde{L}_i$ for the distance from each alternative to the ideal solution (eq. (5)) and the pair-wise comparisons based on four indices stating possibility and necessity measures (eq. (6)-(9)), in order to quantitatively describe the chance that one alternative achieves a lower distance (and consequently performs better) than another.

When looking at the crisp results and the MPMI values, A2 is by far the worst alternative, but different recommendations arise for A1 and A3. The crisp results consider A1 to be 6.58% better than A3, while the MPMI interpretation declares A3 to be 10.64% better than A1. Then, for each cell, the four indices report the possibility and necessity measures of the statement that "the fuzzy number of the alternative in the row is lower than the other in the column"; and consequently reflects the chances of the row-alternative to performing better than the column-alternative (Table 10). All indices agree that both A1 and A3 overcome A2. In fact, index 1 and 2 state that A2 being better than A1 and A3 is not feasible, so this particular statement must be totally rejected. The comparison between A1 and A3 is trickier. Indices 1 and 4 do not report valuable insights, since the particular measures given are inconsistent. However, indices 2 and 3 slightly report a 61.0% and 51.5% chance, respectively, of A3 performing better than A1, which is in line with the ranking obtained from the MPMI values. Although the results are not as conclusive as with alternative A2 (both A1 or A3 could feasibly perform better than the other), the higher possibility and necessary measures obtained by A3 overcoming A1 should orientate decision-makers in that direction.

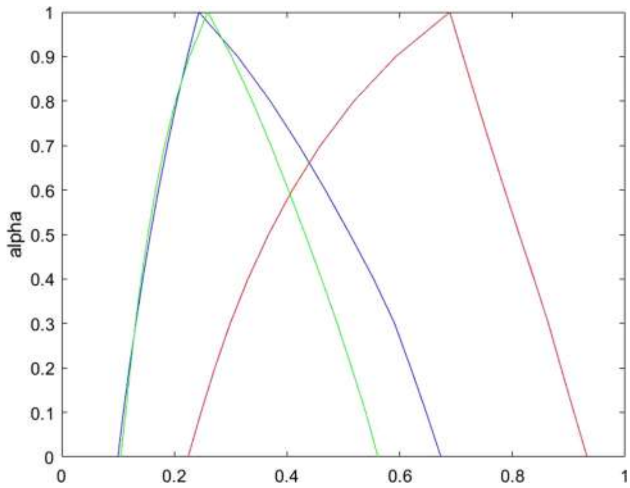

Fig. 12. Fuzzy numbers representing the overall distance from alternatives A1 (blue), A2 (red) and A3 (green).

Table 10
Crisp and fuzzy results for the analysis.

Crisp analysis

	A1	A2	A3
^1L_i	0.243	0.689	0.259

Fuzzy analysis

	A1	A2	A3
$MPMI_i$	0.329	0.603	0.294

Index 1	A1	A2	A3
A1	-	0.662	0.014
A2	0	-	0
A3	0	0.591	-

Index 2	A1	A2	A3
A1	-	1	0.390
A2	0	-	0
A3	0.610	1	-

Index 3	A1	A2	A3
A1	-	0.956	0.485
A2	0.044	-	0.063
A3	0.515	0.937	-

Index 4	A1	A2	A3
A1	-	1	1
A2	0.338	-	0.409
A3	0.986	1	-

With all this information, decision-makers would now know that, despite A1 achieving the best performance when looking only at the crisp values given by the experts, A3 performs better if confidence is considered. Thus, decision-makers can interpret A3 as a more reliable choice. This example case has validated the soundness of MIMDU for easily modelling uncertain opinions, ranking the available alternatives and assisting decision-making with useful and intuitive information.

4.4. Sensitivity analysis. Effect of confidence on the results

It has been claimed previously that A3 is better ranked than A1 due to higher confidence in the initial evaluation. To prove this, Appendix A provides a mathematical reasoning on how confidence when evaluating an alternative can affect the final ranking. Apart from that, this section performs a sensitivity analysis to quantitatively show the outcomes of confidence variations in the experts' responses. Thus, greater understanding of the connection between the initial assessment and the final ranking of alternatives can be achieved; consequently permitting greater traceability of the whole decision-aid process. The sensitivity analysis is carried out by modifying the evaluations of A3 according to C3 performed by experts 2 and 3. In particular, both experts are considered to evaluate A3 according to C3 with the same reference values (see Table 4: expert 2: 3; expert 3: 2), but each with the 5 options of confidence: CS, S, I, U, VU (5*5 = 25 scenarios).

The MIMDU methodology is applied to the 25 confidence scenarios. The confidence level has a clear effect in the two more significant indices to compare A1 and A3: index 2 (Table 11) and index 3 (Table 12). Since the ex-

Table 11
Effect of changes in the confidence of experts E2 and E3 on the possibility measure (index 2) of A3 overcoming A1.

E2 \ E3	CS	S	I (original)	U	VU
CS	0.675	0.652	0.631	0.610	0.590
S (original)	0.652	0.631	0.610	0.590	0.577
I	0.631	0.610	0.590	0.577	0.552
U	0.610	0.590	0.577	0.552	0.535
VU	0.590	0.577	0.552	0.535	0.518

Table 12
Effect of changes in the confidence of experts E2 and E3 on the necessity measure (index 3) of A3 overcoming A1.

E2 \ E3	CS	S	I (original)	U	VU
CS	0.399	0.440	0.479	0.515	0.549
S (original)	0.440	0.479	0.515	0.549	0.580
I	0.479	0.515	0.549	0.580	0.608
U	0.515	0.549	0.580	0.608	0.634
VU	0.549	0.580	0.608	0.634	0.657

Table 13
Effect of changes in the confidence of experts E2 and E3 on the MPMI values of A3.

E2 \ E3	CS	S	I (original)	U	VU
CS	**0.288[1]**	**0.290[2]**	**0.292[3]**	**0.294[4]**	**0.296[5]**
S (original)	0.290	0.292	0.294	0.296	**0.298[6]**
I	0.292	0.294	0.296	0.298	**0.300[7]**
U	0.294	0.296	0.298	0.300	**0.302[8]**
VU	0.296	0.298	0.300	0.302	**0.305[9]**

perts' evaluations are aggregated with (eq. (14)), the worsening of the possibility and necessity measures behaves symmetrically regardless of the expert considered. Depending on the attitude of a decision-maker, more optimistic or pessimistic, he/she will feel more comfortable choosing A3 over A1 based on the confidence level with which A3 has been evaluated. In detail, the higher the confidence, the higher the possibility measure of A3 strictly overcoming A1 (index 2), but at the same time the lower the certainty of being equal or better than A1 (index 3). Oppositely, a less confident evaluation offers a solid ground to base the decision, since both indices agree that A3 is a better option than A1.

When it comes to analyzing the effect of confidence in the performance of an alternative however, despite the higher ground for certainty that can be observed with index 3, the MPMI value firmly concludes that alternatives evaluated with higher confidence obtain better ranking results (Table 13). Indeed, Table 13 shows the better non-performance value of the distance of alternative A3 to the ideal solution for all confidence scenarios. It can be seen that the lowest distance, and thus the best value of alternative A3, is obtained when both experts E2 and E3 are completely sure (CS) of evaluating A3. Those values can be compared with the MPMI value of A1, which remains unchanged: while the MPMI value for A3 in the VU-VU confidence case is a 7.29% better than the one for A1 (0.305 against 0.329; Tables 13 and 10); it increases up to a 12.46% better for the CS-CS case (0.288 against 0.329; Tables 13 and 10). This means there is a difference of a 70.92% that can definitely convince decision-makers for A3 in front of A1 if A3 has been more confidently evaluated.

The worsening in the performance of A3 when decreasing the confidence with which it is evaluated, appreciated in Table 13, is caused by a shift of the α-cuts that compose $\tilde{L}_3$ to the right, as proved in Appendix A. To illustrate this effect, Fig. 13 shows all $\tilde{L}_3$ fuzzy numbers for each case highlighted in black and numbered (1 to 9) in Table 13. Following the demonstration in Appendix A, a lower confidence in the initial evaluation of A3 causes an increase of the fuzzy number's support on both sides, although sharper on the right. Consequently, the whole fuzzy number is shifted to the right and the final performance of A3 is deteriorated. In contrast, the crisp value (${}^1L_3$) remains unchanged, as it is not affected by uncertainty. This justifies the comparison between the crisp and the fuzzy analyses performed in phase 3 and remarks the decisive influence of confidence when evaluating the alternatives in the final ranking results. Indeed, this behaviour allows understanding the scope of the changes that can be expected when modifying the level of confidence, which eases the discussion of results even for decision-makers who are unused to such decision processes.

4.5. Comparison of the MIMDU methodology and the F-VIKOR method

To end this illustration, the use of the MIMDU methodology and its results are compared with the common expression of F-VIKOR, vastly used in the literature [25–27,34,38,39], and founded in the same ground of finding the most

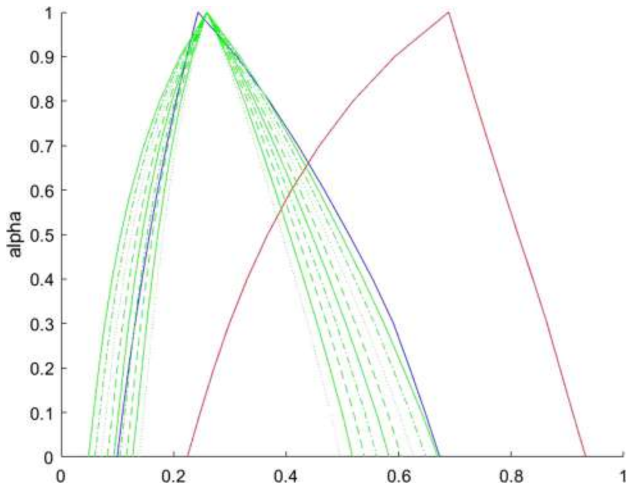

Fig. 13. Effect of changes in the confidence of experts E2 and E3 evaluating A3 on the final fuzzy distance of alternatives A1 (blue), A2 (red) and A3 (green).

Table 14
Fuzzy numbers used in the F-VIKOR calculation.

Answer in P1, step 1	Linguistic equivalence	Triangular fuzzy number
0	Very low	(0,0,1)
1	Low	(0,1,2)
2	Slightly low	(1,2,3)
3	Slightly high	(2,3,4)
4	High	(3,4,5)
5	Very high	(4,5,5)

compromised solution. First, the procedure to get the final ranking of the alternatives following F-VIKOR is presented (4.5.1) to finally discuss the differences between both methods (4.5.2).

4.5.1. *Results of the case example with F-VIKOR*

Naturally, the same input data is used to calculate the results with F-VIKOR so far as it allows. Indeed, as it has been discussed in subsections 2.1 and 3.1, F-VIKOR uses fuzzy numbers that are defined in beforehand and are therefore less adjusted to the responses provided. Consequently, as performed in the referenced F-VIKOR-based studies in the literature, the same support, excepting truncations, is assigned to all options of fuzzy numbers that can determine the importance of a criterion or the adequacy of an alternative according to one criterion (Table 14).

Literature cited usually employs a special arithmetic for triangular fuzzy numbers based on their key points (extreme values of the support and core of the fuzzy number) to aggregate the initial evaluations and get the results. However, to allow the comparison with the MIMDU methodology, the same procedure for arithmetic operations using α-cut described in phase 2 (P2) has been used. Thus, no modifications on the final results are introduced due to the different treatment of the input data.

The F-VIKOR method utilizes the same fuzzy version of equation (2) to calculate the distance of each alternative to the overall ideal solution employing metric $p = 1$, to state the "maximum group utility" (or the majority rule for all criteria) and $p = \infty$, to state the minimum individual regret (or the maximum deviation for a criterion) [3]. Those two distances are in F-VIKOR called S and R, respectively (eq. (17)):

$$\begin{aligned} {}^{\alpha}S_i &= {}^{\alpha}L_{i,1} = \sum_{j=1}^{n} {}^{\alpha}W_j \cdot \left(\frac{{}^{\alpha}F_j^* - {}^{\alpha}f_{ij}}{{}^{\alpha}F_j^* - {}^{\alpha}f_j^*} \right) \\ {}^{\alpha}R_i &= {}^{\alpha}L_{i,\infty} = \max_{j=1..n} \left[{}^{\alpha}W_j \cdot \left(\frac{{}^{\alpha}F_j^* - {}^{\alpha}f_{ij}}{{}^{\alpha}F_j^* - {}^{\alpha}f_j^*} \right) \right] \end{aligned} \tag{17}$$

Table 15
Results of the F-VIKOR for the illustration example.

α	$^{\alpha}S_i$						$^{\alpha}R_i$						$^{\alpha}Q_i$					
	A1		A2		A3		A1		A2		A3		A1		A2		A3	
0	0.075	1.026	0.235	1.449	0.068	0.990	0.075	0.413	0.083	0.523	0.040	0.377	0.038	0.733	0.105	1	0	0.682
0.1	0.084	0.966	0.266	1.399	0.078	0.933	0.084	0.395	0.095	0.507	0.044	0.358	0.045	0.715	0.126	1	0	0.663
0.2	0.094	0.904	0.302	1.350	0.089	0.875	0.094	0.378	0.109	0.491	0.049	0.339	0.053	0.695	0.152	1	0	0.641
0.3	0.105	0.841	0.343	1.303	0.103	0.817	0.105	0.361	0.125	0.475	0.053	0.321	0.063	0.672	0.185	1	0	0.615
0.4	0.118	0.777	0.390	1.256	0.119	0.759	0.118	0.344	0.144	0.460	0.059	0.301	0.074	0.644	0.226	1	0	0.584
0.5	0.133	0.709	0.446	1.211	0.137	0.699	0.133	0.327	0.167	0.445	0.072	0.308	0.082	0.609	0.273	1	0.002	0.579
0.6	0.149	0.638	0.513	1.167	0.160	0.636	0.149	0.310	0.194	0.431	0.086	0.287	0.092	0.565	0.335	1	0.005	0.531
0.7	0.168	0.56	0.594	1.124	0.187	0.571	0.168	0.293	0.226	0.417	0.104	0.265	0.102	0.508	0.418	1	0.010	0.469
0.8	0.190	0.473	0.694	1.081	0.222	0.501	0.190	0.277	0.266	0.404	0.126	0.242	0.115	0.431	0.535	1	0.018	0.384
0.9	0.214	0.372	0.824	1.040	0.267	0.422	0.214	0.260	0.315	0.391	0.154	0.217	0.129	0.320	0.710	1	0.032	0.260
1	0.243	0.243	1	1	0.330	0.330	0.243	0.243	0.378	0.378	0.189	0.189	0.144	0.144	1	1	0.057	0.057

Table 16
MPMI values for the distance of the alternatives to the ideal solution.

$MPMI_i$	A1	A2	A3
$\tilde{S}_i$	0.415	0.857	0.422
$\tilde{R}_i$	0.144	0.190	0.189
$\tilde{Q}_i$	0.323	0.674	0.260

Then, instead of computing the average value of those distances as performed with the F-CRM employed in this study (eq. (10)), F-VIKOR computes a weighted standardization of the maximum group utility and the minimum individual regret distances for all alternatives (eq. (18)), usually weighting both terms equally ($\nu = 0.5$)

$$^{\alpha}Q_i = \nu \cdot \frac{^{\alpha}S_i - min(^{\alpha}S_i)}{max\,(^{\alpha}S_i) - min(^{\alpha}S_i)} + (1-\nu) \cdot \frac{^{\alpha}R_i - min(^{\alpha}R_i)}{max\,(^{\alpha}R_i) - min(^{\alpha}R_i)} \tag{18}$$

Thus, Table 15 presents the results of F-VIKOR for the illustration example considered by solving equations (eq. (17)-(18)) and Table 16 displays the best non-fuzzy performance values for the distances of alternatives A1, A2 and A3 to the overall ideal solution by means of the Middle Point of the Mean Interval.

Alternatives are finally ranked in increasing order of Q. F-VIKOR claims that the alternative with the least Q (called $Q_i^{(1)}$) can be chosen over the rest if the following two conditions are fulfilled:

1. It has enough difference with the alternative ranked in second place: $Q_i^{(1)} - Q_i^{(2)} \geq \frac{1}{m} - 1$; being m the number of alternatives.
2. The alternative is stable within the decision-making: the alternative best ranked in Q is also the best ranked in S and/or R.

The best-ranked alternative, A3, does not fulfil the first necessary condition and cannot be claimed as the indistinctively best alternative. Indeed, even A2 cannot be discarded since it is closed enough to A3 and A1 with the current ranking of alternatives according to the first condition.

4.5.2. Comparison of MIMDU and F-VIKOR

The comparison of both methods, MIMDU and F-VIKOR, is presented in the framework of the following three categories:

- Modelling of experts' opinions: As mentioned before in the paper, MIMDU allows to better estimate the opinion of an expert since fuzzy numbers are not defined in beforehand, but adjusted to the confidence level recognized by the respondent. Thus, a more precise fuzzy number can be established around the reference value in its core according to the confidence level of the expert about the answer provided. Also, the pressure an expert can feel when stating the importance of a criterion or the evaluation of an alternative on a criterion is reduced when he/she has the chance to recognize the potential lack of confidence experienced.
- Ranking of alternatives: The similarity of the formulation to obtain the alternatives ranking (eq. (10) and eq. (17)-(18)) eases obtaining similar results between MIMDU and F-VIKOR for a given case study. In the example,

both methods agree with the fuzzy ranking of alternatives reached: since both state the best alternative is A3, followed by A1 and by A2 at a greater distance.

- Information given for decision making: The other significant difference between MIMDU and F-VIKOR is the information available for decision-makers. While F-VIKOR only provides a fuzzy ranking based on defuzzified distances of the alternatives to the ideal solution, the MIMDU methodology allows a comparison between a crisp ranking (without considering any uncertainty; or in case all experts are "completely sure" in every single response) and a fuzzy analysis, which is also equipped with pair-wise comparisons of the alternatives based on possibility and necessity measures. Thus, decisions can be performed according to the particular reasoning of each decision-maker, for example, according to: the consistency of the crisp and the fuzzy analysis with the MPMI values; the consistency of the ranking with the MPMI values and some pair-wise indices; or the compliance with a determined threshold when comparing the best alternative to the others with the possibility and necessity pair-wise comparisons. In the case example considered, a proper discussion has been realized to prefer A3 over A1 based on the consistency of the whole fuzzy analysis; while the strict application of F-VIKOR does not allow to reach such a conclusion. Overall, a decision-maker using MIMDU is provided with more useful and complimentary information to call for a final decision.

5. Conclusions

This study presents MIMDU: a novel Methodology for Integrated Multicriteria Decision-making with Uncertainty, which allows an accurate modelling of experts' opinions (fuzzy quantifying human responses and considering confidence) and provides useful information to ease decision-making. The methodology also allows to see the effect that a lack of confidence in the evaluation of one alternative can have in its final ranking. It is divided into three phases:

1. In phase 1, experts' opinions are quantified with a novel procedure based on FRS. First, the experts rate the importance of criteria and the adequacy of alternatives according to criteria on a 0-5 scale. Second, the experts express their confidence in the above responses from five options: *completely sure*, *sure*, *indecisive*, *unsure* and *very unsure*. As a result, triangular fuzzy numbers are defined according to the level of confidence.
2. In phase 2, a fuzzy formulation of the compromised ranking method (F-CRM) is standardized using the α-cut approach to deal with the fuzzy numbers obtained in phase 1 and classify the alternatives according to their distance to the ideal solution.
3. In phase 3, a systematic procedure is presented to provide information to decision-makers in order to choose the best alternative. This includes a comparison between a crisp ranking of alternatives (without considering confidence) and a fuzzy analysis (considering confidence). The fuzzy analysis includes pair-wise comparisons of the alternatives based on possibility and necessity measures which allows selecting or discarding alternatives under a certain threshold.

To facilitate understanding, MIMDU is applied to a generic example case. Results show that the proposed procedure helps decision-makers to choose the most reliable alternative, as significant differences in the ranking without and with uncertainty can be highlighted. Specifically, in the example case used, the crisp ranking states that alternative A1 is 6.58% better than alternative A3; when confidence is considered, A3 turns out to be 10.64% better considering the best non-fuzzy performance calculations. Also, the effect of lower or higher confidence in the response is tackled within a sensitivity analysis. Results show that increasing the confidence when evaluating an alternative can significantly improve its performance in the final ranking. A final comparison with F-VIKOR proves the soundness of MIMDU to better capture confidence in responses and facilitates decision-making through numerous complementary indicators.

Future work will focus on applying the methodology to real case studies, aiming to confirm its ability to ease the response process of experts, to successfully embed uncertainty in the responses and to report useful information to facilitate decision-making. Case studies from different contexts will be sought to prove cross-sector feasibility.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

The methodology designed obtains worse results for alternatives evaluated with lower confidence. This statement is proved through two propositions. The first focuses on analyzing the neutral effect of a confidence decrease when dealing with sum and subtraction interval operations. The second proves that a decrease in the confidence when evaluating an alternative worsens its final ranking, since there are multiplications involved.

Proposition 1. *A less confident evaluation of an alternative according to a criterion does not affect the average value of interval sum and subtraction operations when there are no truncations.*

Proof 1. Let ${}^{\alpha}f_{ij} = [a, b]$ be the evaluation of an alternative i according to criterion j, and ${}^{\alpha}f_{i'j} = [a', b']$ the evaluation of alternative i' according to criterion j. The average value (*avg*) of the sum of both evaluations is:

$$avg\left({}^{\alpha}f_{ij} + {}^{\alpha}f_{i'j}\right) = avg\left([a,b] + [a',b']\right) = avg\left(\left[a + a', b + b'\right]\right) = \frac{a + a' + b + b'}{2}$$

Let now *inc* be a value representing a quantification of the confidence decrease when evaluating the alternative i' according to criterion j (for example, changing from *indecisive* to *unsure*). Then, ${}^{\alpha}f_{i'j} = [a' - inc,\ b' + inc]$ and the average value (*avg*) of the sum of both evaluations is:

$$avg\left({}^{\alpha}f_{ij} + {}^{\alpha}f_{i'j}\right) = avg\left([a,b] + [a' - inc, b' + inc]\right) = avg\left(\left[a + a' - inc, b + b' + inc\right]\right) = \frac{a + a + b + b'}{2}$$

which has not changed. Therefore, a slight decrease of confidence in a response does not affect the average value of the sum interval operations. The same conclusion can be extracted for subtraction interval operations. However, when applying (eq. (8)), there are also interval multiplications. So:

Proposition 2. *A less confident evaluation of an alternative according to a criterion results in a higher overall distance of the alternative to the ideal solution.*

Proof 2. Let ${}^{\alpha}W_j = [a, b]$ be an α-cut interval of the weight of criterion j, and ${}^{\alpha}dn_{ij} = [a', b']$ an α-cut interval of the distance of alternative i to the ideal value of criterion j. Then, the multiplication of both intervals following (eq. (8)) is:

$${}^{\alpha}W_j \cdot {}^{\alpha}dn_{ij} = [a, b] \cdot \left[a', b'\right] = [aa', bb']$$

Let now *inc* be again a value representing a quantification of the confidence decrease when evaluating the alternative i according to criterion j. Since the distance is achieved only by interval sum and subtraction operations, it symmetrically affects: ${}^{\alpha}dn'_{ij} = \left[a' - inc,\ b' + inc\right]$ (Proposition 1). However, the multiplication of both intervals following (eq. (8)) is now:

$${}^{\alpha}W_j \cdot {}^{\alpha}dn_{ij} = [a, b] \cdot \left[a' - inc, b' + inc\right] = \left[a \cdot \left(a' - inc\right), b \cdot \left(b' + inc\right)\right] = [aa' - a \cdot inc, bb' + b \cdot inc]$$

which modifies the average value of the resulting interval because $a < b$ and, consequently, $a \cdot inc < b \cdot inc$. As a result, the average value moves to the right (increase), and so will the distance to the ideal solution.

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6. PAPER 4. A robust multicriteria analysis for the post-treament and agriculture reuse of digestate from small-scale digesters. A case study in Colombia

ABSTRACT

Small-scale farms located in rural and underprivileged areas are increasingly relying on low-tech digesters to produce a clean and renewable fuel (biogas), which can be used for cooking and heating. Apart from biogas, the degradation of organic waste in the digesters also produces a liquid effluent (digestate), which can be reused in agriculture as a biofertilizer. The direct application of digestate to the soil to increase crops productivity may not be either feasible due to regulations or safe due to its quality. In this context, different post-treatment options might improve digestate quality to make it appropriate for agriculture reuse. The aim of this study is to define a multicriteria analysis to select the most suitable and sustainable solution for the post-treatment and reuse of digestate from low-tech digesters implemented in small-scale farms. The potential solutions studied are: degassing tank, sand filter, vermifilter, digestate recirculation, facultative pond, or a combination of them. 10 criteria and 21 sub-criteria including technical, environmental and socio-economic aspects are defined and weighted considering the opinion of 16 experts in the field. According to the experts' opinion, the socio-economic criteria are the most important. The subsequent analysis employs triangular fuzzy numbers to embed the inherent uncertainty in the decision-making process and increase the robustness of the results. The analysis is validated using three case studies of small-scale farms in Colombia. The post-treatment alternatives are designed using data collected in-situ and robustly ranked with the fuzzy multicriteria assessment. Results confirm the robustness of the rankings and show that vermifiltration is the best alternative for digestate post-treatment in small-scale farms, followed by sand filter, recirculation and degassing tank coupled with vermifiltration. In particular, vermifiltration shows to be an appropriate technology that can contribute to boosting the circular bioeconomy and improving the standard of living of small-scale farms in low-income countries.

6.1 INTRODUCTION

At present, the rural population in low-income countries mainly relies on traditional biomass (especially firewood, charcoal, dung and agricultural residues) to meet their daily heating and cooking needs [World Bank, 2018; Pizarro-Loiza et al., 2021]. The use of traditional biomass in unimproved stoves is responsible for serious impacts on the environment and on people's health, due to harmful gases (e.g. carbon monoxide (CO), nitrous oxide (N_2O)) and particulate matter emissions

[Bhattacharya et al., 2000; Miah et al., 2009]. For these reasons, local authorities and international organisations have fostered the implementation of small-scale and low-tech digesters [Thu et al., 2012] as a simple and effective technology to meet daily energy needs in remote and rural areas lacking energy infrastructure [Iannou-Ttofa et al., 2021].

In low-tech digesters, organic matter, generally cattle or pig manure, is biodegraded by bacteria in anaerobic conditions, producing biogas, mainly composed of CH_4 and carbon dioxide (CO_2), that can be used for cooking or heating. Apart from biogas, a liquid effluent (digestate) is also produced which can be reused in agriculture as a biofertilizer [Ferrer et al., 2011; Ferrer-Martí et al., 2018]. While significant attention has been given in the literature to the potential of biogas as a renewable energy source [Serrano et al., 2020], many questions about the treatment and valorisation of the digestate remain unanswered [Jimenez et al., 2017]. Indeed, some studies have already pointed out that digestate is more homogeneous and can penetrate soil faster than manure [Garfi et al., 2016]. Moreover, it reduces odours and weed germination when compared to dung and can replace chemical fertilizer, which is more expensive and likely to cause long-term degradation of the soil quality [Sapp et al., 2015].

The direct application of digestate in soil may not be safe, particularly when the digester works at short hydraulic retention times (HRT) and under psychrophilic conditions [Kearney et al., 1993; Garfi et al., 2011a, Garfí et al., 2011b Surendra et al., 2014]. In fact, digestate can still contain pathogens and other harmful substances for soil and human health [Chong et al., 2022]. In particular, previous studies showed that nutrients and heavy metals concentration in digestates from low-tech digesters implemented in Colombia were suitable for agricultural reuse. However, lack of organic matter stabilization and pathogens presence represented the main issues [Cucina et al., 2021]. Indeed, the former can lead to soil quality depletion while the latter can cause severe illness. Thus, digestate needs to be properly treated before its application to the soil in order to prevent health and environmental risks and improve its quality [Garfi et al., 2016; Cucina et al., 2021].

The main techniques studied and commercialized to remove part of the undesired compounds (e.g. pathogens, heavy metals) of the digestate and enrich it for further utilization are drying and stripping systems, and membranes [Bolzonella et al., 2018]. However, such techniques require infrastructure and resources not available in small-scale farms located in rural underprivileged areas. Alternatively, low-tech and low-cost solutions should be coupled with low-tech digesters for digestate post-treatment in small-scale farms. In this study, 5 solutions are considered which mainly aim to further stabilise the organic matter and reduce pathogens concentration. They are as follows: i) a degassing tank; ii) a sand filter; iii) a vermifilter; iv) digestate recirculation in the digester; and v) a facultative pond. Moreover, options combining a degassing tank with a sand filter, a vermifilter and a facultative pond are also considered due to the complementary nature of the actions carried out by each of the techniques.

Selecting the most appropriate technique for digestate post-treatment in small-scale farms of low-income countries is not an easy task. Indeed, different aspects should be taken into account: technical aspects (e.g. heavy metal and nutrients content); environmental aspects (e.g. emission of gases or particles); social aspects (e.g. adequacy with the social context of the region); and economic aspects (i.e. capacity to pay and potential revenues generation) [Garfi et al., 2019]. Thus, multicriteria decision tools are needed to support the assessment and design of these solutions [Ferrer-Martí et al., 2018]. Moreover, uncertainty can arise when ranking and selecting the best alternative for a particular case [Juanpera et al., 2021], since the relative importance of one criterion front of another may not be clear [Chen & Hong, 2014], or its evaluation may be difficult to quantify [Domenech et al., 2018]. In those cases, different experts are consulted to account for distinctive opinions, and fuzzy numbers are embedded into the multicriteria decision-making to collect the vagueness of human reasoning [Zadeh, 1975] and their potential lack of confidence [Juanpera et al., 2021].

Different studies in the literature have focused individually on sand filters, vermifiltration and facultative ponds, in order to provide recommendations for their design based on real case studies. For example, Patil & Husain [2019] use a sand filter for the filtration of digestate coming from the anaerobic digestion of kitchen waste and provide a valuable database regarding the reduction of the organic content of the effluent and the lifespan of the system. Similarly, Sari et al., [2019] perform different experiments to state the variability in the capacity of removing the content of heavy metals and ammonia using quartz sand-based filters. Krishnasamy et al., [2013] offer a detailed review of studies on vermifiltration and recommend adjusting key parameters for their design in different contexts and climates, such as worm species, HRT or hydraulic loading rate (HLR). Arora & Saraswat [2021] focus on factors affecting the performance of vermifilters under different scenarios related to the treatment mechanism. Regarding facultative ponds, the Environmental Protection Agency from the United States (EPA), provides an extended manual to assist with the design and construction criteria that define effective pond performance, discussing their capability to reduce nutrient concentrations [EPA, 2011]. However, as far as the authors are concerned, no work still offers an overall comparison of different alternatives within a multicriteria approach to better enhance the particularities of digestate post-treatment from low-tech digesters implemented in small-scale farms of underprivileged countries.

In Colombia, low-tech digesters are increasingly used in small-scale farms [Garfi et al., 2019]. Around 50% of the population in this country live below the poverty threshold, and their economy is based on self-sufficient agriculture and family farming [World Bank, 2018]. The main energy sources used in these areas are, according to the economic capacity, firewood for the poorest households, and liquefied petroleum gas (LPG) for those who can afford it [World Bank, 2014]. Alternatively, low-tech digesters have been implemented since the 80s, to cover the energy needs of small-scale farms and households increasing their living conditions [Garfi et al., 2011a]. However, there are still no studies which investigate the appropriateness of different post-treatment alternatives to increase the efficiency and the quality of the digestate.

In this context, this work aims to define a fuzzy multicriteria analysis to robustly select the best alternative for digestate post-treatment from low-tech digestate implemented in small-scale farms, which are: i) degassing tank, ii) sand filter, iii) vermifilter, iv) digestate recirculation, v) facultative pond, and combinations of them. 10 criteria and 21 sub-criteria including technical, environmental and socio-economical aspects have been defined and weighted considering the opinion of 16 experts in the field. The assessment has been validated using three case studies of low-tech digesters implemented in small-scale farms in Colombia. All the studied alternatives have been designed using data collected in-situ, assessed and ranked with the multicriteria analysis employing fuzzy numbers to integrate uncertainty. Moreover, a sensitivity analysis has been performed to analyse the influence on the results of the different experts' profiles and to confirm their robustness.

The paper is structured as follows: in section 6.2, the different alternatives for digestate post-treatment are described; section 6.3 defines the criteria selected for the analysis and presents the methodology used; in section 6.4, the three case studies are introduced, the alternatives are appropriately evaluated and ranked and a discussion of the results is provided; finally, section 6.5 shows the conclusions of the work.

6.2 ALTERNATIVES FOR DIGESTATE POST-TREATMENT

In this work five options for digestate post-treatment from low-tech digesters implemented in small-scale farms are analysed in order to improve its quality before its reuse in agriculture:

- *Degassing tank*

A degassing tank is a tank implemented after the digester that aims to treat its effluent (digestate), recovering the residual diluted methane and stabilising its residual organic matter by producing more biogas [Brusi et al., 2017]. In this study, the degassing tank has been designed as a smaller tubular digester. Thus, it consists of a tubular polyethylene bag buried in a trench [Garfí et al., 2016]. The digestate must remain a sufficient period of time into the tank to ensure the residual methane is recovered and the post-treated digestate is ready to be applied to agricultural soil (Figure 6.1a).

- *Sand filter*

A sand filter is used to reduce the digestate turbidity and remove suspended solids and pathogens through both physical and biological processes without needing additional chemical products or energy inputs [SSWM, 2020]. The digestate flows across the layers of the sand filter at slow speed (7-14 $m^3/m^2 \cdot d$), leaving the suspended solids of greater size retained in the sand grains [Otero, 2006]. Also, a biological layer (composed of microorganisms) is formed on the top of the filter, stimulating pathogens removal [Patil & Husain, 2019] (Figure 6.1b).

- *Vermifilter*

The vermifilter is a biofilter with earthworms to accelerate the decomposition process of the incoming organic matter through vermicomposting (Figure 6.1c). It can treat both solid and liquid wastes thanks to the presence of different beds [Krishnasamy et al., 2013]: one upper bed, where solid wastes are biodegraded with earthworms (vermicomposting); and lower sand and gravel beds, where the liquid wastes are treated [Hughes et al., 2009]. The biodegradation taking place in the upper bed create a layer of humus material rich in stabilised organic matter and nutrients, which increases the porosity and the hydraulic conductivity of the upper bed [Taylor et al., 2004] and leads to the removal of contaminants, such as heavy metals and pathogens [Hughes et al., 2009]. Moreover, worms' activity creates air spaces through movement, producing aerobic conditions throughout the beds of the vermifilter, avoiding unpleasant odours and ultimately accelerating the biological decomposition of the wastes.

- *Recirculation*

Digestate recirculation in the digester helps to recover the remaining methane and stabilize the organic matter in the digestate (Figure 6.1d). Thus, the microbial community in the digestate is recirculated in the digester, increasing the HRT. Moreover, the microbial community is capable of hydrolyzing the organic compounds and producing hydrogen, contributing to the production of methane and maintaining an optimal pH for the proper functioning of the digester. Also, it reduces water consumption since less water can be used for the dilution of the feedstock (livestock manure) for digester feeding.

- *Facultative pond*

The facultative ponds are shallow basins which aim to remove pathogens, transform ammoniacal nitrogen, reduce solids content and clarify the effluent [CNA, 2007] (Figure 6.1e). A high environmental temperature positively affects the physical and biochemical reactions taking place in the pond, increasing, therefore, the degradation speed. Also, solar radiation rises bacterial activity, while rainfalls dilute the concentration of microbial agents and difficult consequently its activity [Peña et al., 2003; Treviño & Cortés, 2016].

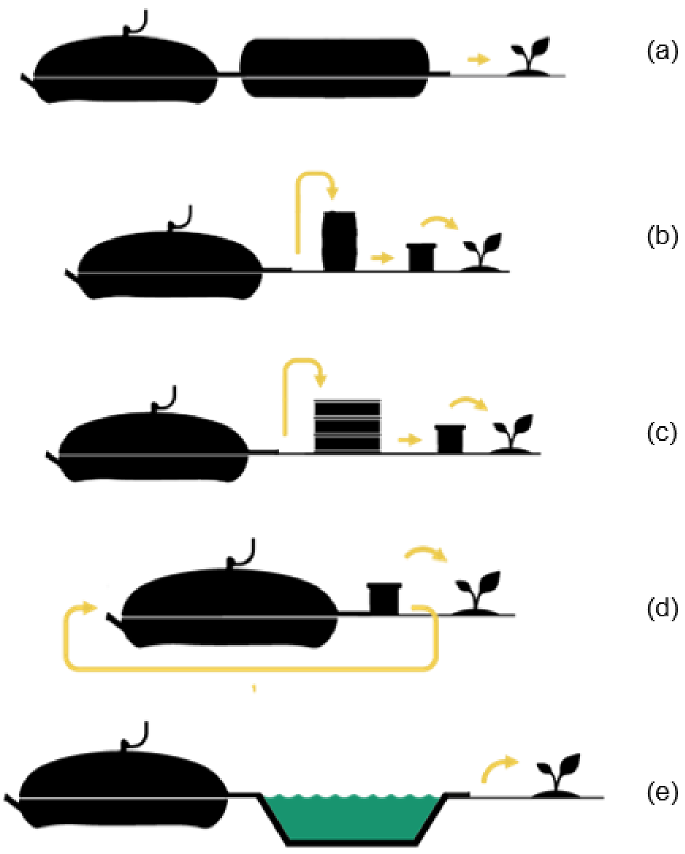

Figure 6.1 Graphical representation of the five alternatives considered for digestate post-treatment before its reuse in agriculture. Adapted from Monteagudo [2020]

6.3 FUZZY MULTICRITERIA ANALYSIS FOR DIGESTATE POST-TREATMENT SELECTION

Multicriteria analysis is a decision aid tool that allows the generation of preferences from the available alternatives [Awashti et al., 2018] to finally select the best one [Melvin, 2012]. It is specifically needed when multiple aspects should be considered; for instance, general interests, such as environmental issues, economic development or gender equity [Garfi et al., 2009; Garfi & Ferrer-Martí, 2011c; Sánchez-López et al., 2012]. Its application is especially useful in human development programs to support the assessment and design of the projects [Ferrer-Martí et al., 2018].

In any multicriteria analysis, a 4-step structure is usually used [Wang et al., 2009]: first, a set of appropriate criteria for the particular application is defined; second, the criteria are weighted according to their relative importance [Opricovic & Tzeng, 2004]; third, the alternatives are evaluated according to each criterion; and fourth, a global score is calculated by aggregating the previous two steps [Wang et al., 2009] and the alternatives are consequently ranked. In this study, steps 2 to 4 are integrated into the Methodology for Integrated Multicriteria Decision-making with Uncertainty (MIMDU) [Juanpera et al., 2021], which provides two rankings: a crisp one, without considering any uncertainty, and a fuzzy one, which includes uncertainties. So far, the crisp one has been the unique source of information in relevant multicriteria applications focusing on energy access [Domenech et al., 2015; Ferrer-Martí et al., 2018]. On the other hand, the fuzzy ranking takes into account uncertainties due to experts' lack of confidence or difficulty in quantifying alternatives. Therefore, in the MIMDU methodology, the crisp ranking is complemented with the fuzzy one, obtaining a whole robust analysis and allowing decision-makers to base the decision on more reliable results.

The following sections aim to present in detail the criteria defined for this work (section 6.3.1) and to describe how criteria are weighted and alternatives are evaluated and ranked employing the MIMDU methodology (section 6.3.2).

6.3.1 Criteria definition

10 criteria and 21 sub-criteria have been defined in order to evaluate the effectiveness of the different alternatives for digestate post-treatment and reuse in agriculture (Table 6.1). These criteria and sub-criteria have been grouped in 3 aspects: technical, environmental and socio-economic aspects. The next paragraphs focus on defining each aspect.

The technical aspect evaluates the suitability of the post-treated digestate and the adaptability of the solutions to the context of small-scale farms in low-income countries from a technical perspective. Therefore, it includes the following criteria:

- Digestate characteristics (T1), including the content of heavy metals (T1.1, especially Zn and Cu, the most present in cattle manure), pathogens (T1.2), dry and organic matter and nutrients (T1.3-T1-5) and the presence of diluted methane (T1.6) in the digestate. It is relevant to highlight that the maximum concentration of heavy metals and pathogens in the digestate is usually set by the country regulation. Moreover, the lower their content the better the digestate quality.

- Management (T2), which takes into account the complexity of implementation and operation of the alternatives. In detail, this criterion considers the potential need for skilled labour (T2.1), and the ease of construction and maintenance (T2.2 and T2.3).
- Surface area requirement (T3), which considers the land area required for the implementation of the solution, since it is an issue of concern in small-scale farms.
- The lifespan of the alternative (T4), which considers the durability of the alternatives.

Despite the importance of having a digestate with suitable values of pH and electric conductivity for agricultural purposes (around 7 and between 5 and 8 µS/cm, respectively [Hanc & Vasak, 2014]), they have not been included as specific criteria in the assessment, since all the post-treatment alternatives considered do not cause any significant change in their values.

The environmental aspect aims to evaluate the effect of the considered alternatives on the environment. It includes:

- Air pollution (E1), which includes the contamination caused by particulate matters (e.g. PM10 and PM2.5), greenhouse gases (e.g. methane, carbon dioxide, nitrogen dioxide) and sulphur oxides (E1.1), and the emission of odours that can cause discomfort (E1.2).
- Resources consumption (E2), which considers the use of sustainable and local materials (E2.1), and the amount of water (E2.2) and energy (E2.3) used or potentially saved during alternatives' operation.

The socio-economic aspect evaluates the social and economic impact or benefits of the digestate post-treatment solutions for people living and working in small-scale farms. It considers:

- Costs (S1), which include the initial investment for the implementation of the solutions (S1.1) and the operational and maintenance costs (S1.2).
- Benefits (S2), which include both the potential income generation (S2.1) and savings (S2.2) due to digestate sales or improved crops production, respectively.
- Equity and standard of living (S3), which take into account the potential improvement in wealth.
- Social acceptance (S4), which takes into account the acceptance of the solutions in the considered context.

Table 6.1 summarizes the aspects and criteria definition through the expression of each sub-criterion. Indeed, each sub-criterion is evaluated through an indicator, which can be quantitative (QT) or qualitative (QL), and beneficial (+) or harmful (-) for the project.

Table 6.1. Definition of criteria and indicators

Aspects	Criteria		Sub-criteria		Indicators	Unit	QT/ QL	+/-
Technical	T1	Digestate characteristics	T1.1	Heavy metals content	Content of Cu and Zn in the digestate	mg/ kg of dry matter	QT	-
			T1.2	Pathogens content	Content of total coliforms in the digestate	CFU/g	QT	-
			T1.3	Dry matter content	Content of total solids (TS) in the digestate	%	QT	+
			T1.4	Organic matter content	Content of volatile solids (VS) in the digestate	%	QT	+
			T1.5	Nutrients content	Content of Total Kjeldahl Nitrogen (TKN) in the digestate	%	QT	+
			T1.6	Residual biomethane	Quantity of biomethane that can be still released from the digestate	m^3/day	QT	+
	T2	Management	T2.1	Skilled labour	Need of skilled labour to implement and operate the solution	-	QL	-
			T2.2	Ease of construction and maintenance	Access to local resources to implement the solution and simplicity of the design	-	QL	+
			T2.3	Ease of maintenance	Simplicity and time saved for maintenance tasks	-	QL	+
	T3	Surface area requirement	-	Surface area requirement	Land area needed to implement the solution	m^2	QT	-
	T4	Lifespan	-	Lifespan	Expected lifetime of the materials for the implementation of the alternative	years	QT	+
Environmental	E1	Air pollution	E1.1	Emissions of particulate matter, greenhouse gases and sulphur oxides	Estimated emissions particulate matter (e.g. PM10, PM2.5), greenhouse gases (e.g. methane, carbon dioxide) and sulphur oxides	-	QL	-
			E1.2	Emissions of odours	Estimated emissions of odoriferous gases such as hydrogen sulphide and ammonia	-	QL	-
	E2	Resources consumption	E2.1	Sustainability of materials	Use of sustainable local materials		QL	+
			E2.2	Water consumption	Amount of water needed for both the digestate post-treatment alternative and the digester operation	l/day	QT	-
			E2.3	Energy consumption	Amount of energy needed for alternative operation	kWh/ day	QT	-
Socio-economic	S1	Costs	S1.1	Initial investment	Total cost for alternative implementation	$	QT	-
			S1.2	Maintenance costs	Total costs for operation and maintenance	$	QT	-
	S2	Benefits	S2.1	Income generation	Economic benefit that can be generated in the farms (e.g. digestate sale, increasing of crops production)	-	QL	+
			S2.2	Savings	Savings due to digestate reuse instead of chemical fertilizer	-	QL	+
	S3	Standard of living	-	Equity and standard of living	Improvement of gender equity and standard of living	-	QL	+
	S4	Social acceptance	-	Social acceptance	Beneficiaries' acceptance of the alternative	-	QL	+

6.3.2 MIMDU methodology application

The Methodology for Integrated Multicriteria Decision-making with Uncertainty (MIMDU) [Juanpera et al., 2021] is applied to perform a robust assessment of the considered alternatives for digestate post-treatment according to the defined criteria. This methodology employs triangular fuzzy numbers (TFN) instead of deterministic values to consider uncertainty in the quantifications of both the relative importance of the criteria and the evaluation of each alternative. Figure 6.2 shows the differences between deterministic and fuzzy evaluations with TFN. In detail, a deterministic value c is represented in blue: for example, the importance of one criterion could be evaluated with a 3 in a scale of 0 to 5. However, as mentioned above, different kinds of uncertainties can make such deterministic evaluations unrealistic [Cheng & Hong, 2014]. Thus, more values around the reference c are included within the same evaluation. However, those nearby values are included with a lower possibility measure α, which states how much feasible is that each value determines the real value of the evaluation. For the example in Figure 6.2, it is completely feasible that the importance of one criterion is determined by c, while it is very unlikely to be set by a or b. Indeed, each TFN is represented by three crisp values (a, c, b), being a and b the smallest and highest, respectively, possible value that belongs to the fuzzy number and can therefore determine the evaluation, and c the most promising value. The possibility measure α allows cutting the fuzzy numbers at different levels, determining the interval of values that achieve at least that measure. For example, in Figure 6.2, the values compressed between a' and b' reach the possibility measure $\alpha = 0.5$. The extreme cases are $\alpha = 0$, which constitutes the *support* of the fuzzy number (the interval $[a, b]$, in red in Figure 6.2), and $\alpha = 1$, which only includes the reference value c and is, therefore, equivalent to a deterministic scenario. The intervals generated by different cuts on α are called α-cut intervals and will be used to operate with the TFN within the MIMDU methodology (sections 6.3.2.2 and 6.3.2.3).

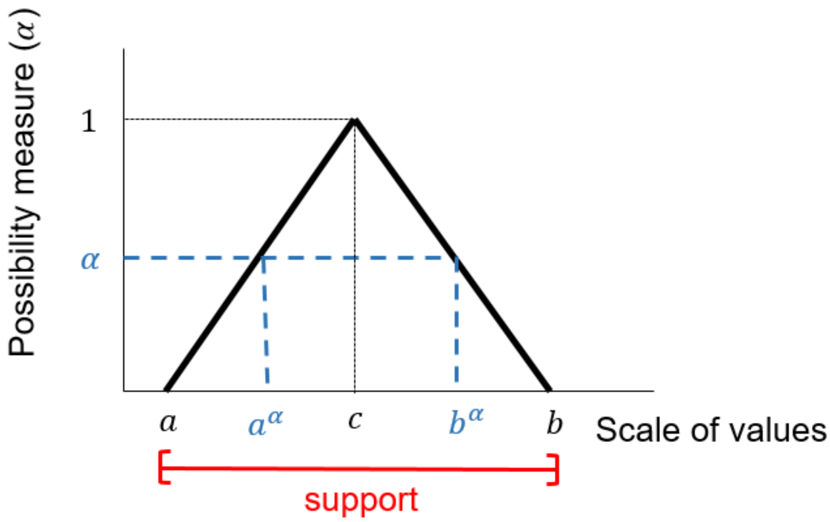

Figure 6.2. General expression of a crisp (in blue) and a fuzzy evaluation through a triangular fuzzy number (in black)

As mentioned above, the weights of the criteria and the evaluations of the alternatives are determined by TFN to embed uncertainty. In order to operate with them towards an alternatives' ranking, eq. 1 is applied for different values of α to express each TFN as a sequence of their α-cut intervals $[a^\alpha, b^\alpha]$ (Figure 6.3). These α-cut intervals define the lowest and the highest value that achieves a certain possibility measure α. Indeed, 11 eleven values of α are taken, from 0 to 1 with increments of 0.1, as recommended in Ranjbar et al., [2020], in order to balance a good approximation of the fuzzy numbers and a relatively quick calculation process. It is worthy to mention that the 1-cut intervals ($\alpha = 1$) correspond to the crisp intervals $[c, c]$ (eq. 6.1), which are equivalent to crisp evaluations (Figure 6.2, in blue) and allow calculating the crisp ranking of alternatives. On the other hand, the fuzzy rankings take into account all 11 values of α and help to complement the crisp one in a whole robust assessment.

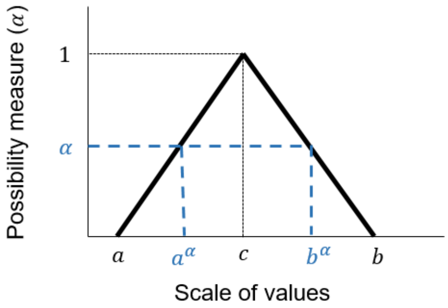

Figure 6.3. Representation of an α-cut interval of a triangular fuzzy number

$$^{\alpha}TFN = [a^{\alpha}, b^{\alpha}] = [a + (c - a) \cdot \alpha \, , b - (b - c) \cdot \alpha] \quad \text{(eq. 6.1)}$$

The remaining part of the methodology description is divided in detail: how the criteria are weighted (6.3.2.1), and the equations and procedures to evaluate (6.3.2.2) and rank (6.3.2.3) the alternatives.

6.3.2.1 Criteria weighting

To weight the importance of each aspect and sub-criterion, a survey has been carried out and answered by 16 experts from the Network for Biodigesters in Latin America and the Caribbean (RedBioLAC). All the experts were professionals working in non-governmental organizations, public administration, universities and companies in several countries of Europe and America (i.e. Spain, Bolivia, Costa Rica, Colombia, Mexico, Argentina, Ecuador, Chile, Peru, Brazil, Cuba and United States).

Each expert has been asked to provide a punctuation from 0 to 5 to evaluate the importance of each criterion (0 being not important, and 5 being essential). To consider the potential lack of confidence in this evaluation, the expert was also asked to state his/her level of confidence when evaluating the importance of each criterion, within 5 possibilities (Table 6.2): completely sure, sure, indecisive, unsure and very unsure. This level of confidence is used to define the support ($[a^{\alpha}, b^{\alpha}]$, with $\alpha = 0$) of the fuzzy number for each expert evaluation. The higher the lack of confidence then, the bigger the support. Thus, a fuzzy number with a different support is generated for each answer considering the information (value and confidence) provided by each expert.

Table 6.2. Options to express the level of confidence and support related to the range of the answer (0-5)

Confidence in the response	Relative support
Completely sure (CS)	0%
Sure (S)	15%
Indecisive (I)	30%
Unsure (U)	45%
Very unsure (VU)	60%

Then, the TFN defined for the 16 experts' evaluation are aggregated to conform to the standardized weights of both aspects and sub-criteria (Table 6.3). Each weight displayed in Table 6.3 expresses, therefore, with a TFN (a, c, b), the average opinion of all experts regarding the relative importance of the criterion. As it can be seen, in the crisp scenario, the opinions of the 16 experts give higher priority to the socio-economic aspect (35.4%), followed by the environmental and the technical ones (32.7% and 31.9%, respectively). Further information on the methods for fuzzy aggregation to calculate the standardized weights can be found in [Juanpera et al., 2021].

Table 6.3. Weights of aspects and sub-criteria

Aspects	Aspects weights	Sub-criteria		Sub-criteria weights
Technical	(0.283, 0.319, 0.357)	T1.1	Heavy metals content	(0.072, 0.087, 0.105)
		T1.2	Pathogens content	(0.096, 0.111, 0.127)
		T1.3	Dry matter content	(0.623, 0.077, 0.095)
		T1.4	Organic matter content	(0.623, 0.077, 0.095)
		T1.5	Nutrients content	(0.097, 0.109, 0.126)
		T1.6	Residual biomethane	(0.088, 0.097, 0.110)
		T2.1	Skilled labour	(0.069, 0.081, 0.096)
		T2.2	Ease of construction and maintenance	(0.083, 0.096, 0.111)
		T2.3	Ease of maintenance	(0.096, 0.108, 0.123)
		T3	Surface area requirement	(0.061, 0.077, 0.095)
		T4	Lifespan	(0.074, 0.089, 0.107)
Environ-mental	(0.290, 0.327, 0.367)	E1.1	Emissions of particulate matter, greenhouse gases and sulphur oxides	(0.166, 0.201, 0.241)
		E1.2	Emissions of odours	(0.160, 0.190, 0.227)
		E2.1	Sustainability of materials	(0.170, 0.202, 0.242)
		E2.2	Water consumption	(0.192, 0.221, 0.256)
		E2.3	Energy consumption	(0.157, 0.186, 0.222)
Socio-economic	(0.318, 0.354, 0.394)	S1.1	Initial investment	(0.159, 0.179, 0.200)
		S1.2	Maintenance costs	(0.133, 0.149, 0.167)
		S2.1	Income generation	(0.137, 0.155, 0.175)
		S2.2	Savings	(0.144, 0.163, 0.187)
		S3	Equity and standard of living	(0.151, 0.175, 0.201)
		S4	Social acceptance	(0.165, 0.180, 0.200)

6.3.2.2 Alternatives evaluation

The alternatives are evaluated through quantitative or qualitative indicators:

- Quantitative criteria are evaluated with the data taken from the case studies. Inherent data uncertainty (i.e. 5% or 10% of the nominal value) is considered through fuzzy numbers to obtain a robust evaluation.
- Qualitative criteria are assessed using linguistic scales that define, for a single evaluation, how the alternative fulfills the purpose of the criterion (i.e. completely, very good, neutral, not so

good, etc.) [Xu et al., 2017; Shojaie et al., 2018; Ziemba, 2018; Abdel-Baset et al., 2019; Kilic & Yalcin, 2020]. Afterwards, this assessment is translated into a real-values scale (i.e. 0-5). To obtain a robust evaluation, inherent opinion uncertainty is introduced with a margin in the numerical scale (i.e. +/- 1).

Once each criterion is weighted and each alternative is assessed regarding each criterion, a global assessment of the alternatives is obtained with the fuzzy formulation of the compromised ranking method (F-CRM) [Juanpera et al., 2021]. Thus, the crisp ($\alpha = 1$) and fuzzy (considering all α) rankings of the alternatives (eq. 6.2) are obtained. This method calculates the distance from each alternative to an ideal, utopian solution that performs optimally for all criteria [Yu, 1973; Zeleny, 1973]. The closer the alternative is to the ideal solution, the better it is considered.

First of all, the specific distance from the evaluation of an alternative i according to a criterion j to the ideal value of the criterion j (numerator of eq. 6.2) is calculated. In order to aggregate these specific distances, they have to be previously standardized (denominator of eq. 6.2). Then, the aggregated distance ${}^{\alpha}L_{i,p}$ is calculated taking into account the weights of each criterion and the metric p, which indicates the importance assigned to the maximum deviation from the ideal value of a criterion [Hashimoto & Wu, 2004]. The formula is as follows:

$$ {}^{\alpha}L_{i,p} = \left[\sum_{j=1}^{n} ({}^{\alpha}W_j)^p \cdot \left(\frac{{}^{\alpha}F_j^* - {}^{\alpha}f_{ij}}{{}^{\alpha}F_j^* - {}^{\alpha}f_j^*}\right)^p\right]^{1/p} \qquad \text{(eq. 6.2)} $$

where *n* is the number of criteria; ${}^{\alpha}W_j$ is the fuzzy weight of the criterion *j*; ${}^{\alpha}f_{ij}$ is the fuzzy evaluation of alternative i for criterion j; ${}^{\alpha}F_j^*$ is the ideal value for criterion j (the best-achieved value among all the alternatives); and ${}^{\alpha}f_j^*$ is the anti-ideal value for criterion j (the worst value among all alternatives). As it can be observed, all these parameters are expressed using their α-cut intervals (eq. 6.2). The final global score of one alternative (${}^{\alpha}L_i$) can be obtained with a linear combination of metrics 1 and ∞, as recommended in Díaz-Balteiro & Romero [2004] (eq. 6.3).

$$ {}^{\alpha}L_i = 0.5 \cdot {}^{\alpha}L_{i,1} + 0.5 \cdot {}^{\alpha}L_{i,\infty} \qquad \text{(eq. 6.3)} $$

6.3.2.3 Alternatives ranking

Fuzzy numbers allow to capture the uncertainty in any decision-making process, however, the translation of the final scores into a comprehensive ranking can be challenging. First of all, the overall scores for $\alpha = 1$ (${}^{1}L_i$) are already crisp intervals (and thus, deterministic numbers) that can easily be sorted to obtain the crisp ranking of alternatives. Secondly, in order to obtain the fuzzy ranking, the complete fuzzy numbers (${}^{\alpha}L_i$) are defuzzified into crisp values using the technique of the Middle Point of the Mean Interval (MPMI) (eq. 6.4) [Yager, 1981], recommended by Dubois [2006]. This technique takes into account, for each level of α, the average between the lowest and highest value of the corresponding α-cut:

$$MPMI_i = \int_0^1 \frac{min\ ^{\alpha}L_i + max\ ^{\alpha}L_i}{2} d\alpha \quad \text{(eq. 6.4)}$$

Further information on the fuzzy calculation to obtain the final ranking and its interpretation can be found in Juanpera et al., [2021].

6.4 CASE STUDY: SELECTION OF ALTERNATIVES FOR THE POST-TREATMENT AND AGRICULTURAL REUSE OF DIGESTATE FROM LOW-TECH DIGESTERS IN SMALL-SCALE FARMS IN COLOMBIA

In this section, the fuzzy multicriteria analysis for the selection of alternatives for digestate post-treatment and reuse in agriculture (section 6.3) is applied to three case studies in Colombia. First, the three case studies are introduced and the potential solutions for digestate post-treatment are designed for each case study (section 6.4.1). Then, the results about the evaluations of the alternatives according to each criteria and the alternatives' global ranking are displayed and discussed (section 6.4.2). Such results and discussion allows to remark the most suitable solutions for the reuse of digestate from low-tech digesters in small-scale farms.

6.4.1 Introduction to the case studies and alternatives design

The three case studies (CS1, CS2 and CS3) consider full-scale low-tech (plastic tubular) digesters implemented in three small-scale farms located in the Colombian Andean region. The plastic tubular digesters are fed with cattle manure (CM), pig manure (PM) and cattle manure in co-digestion with cheese whey (CM-CW) in CS1, CS2 and CS3, respectively. A previous study which analysed these digestates pointed out that all the digestates were characterized by physico-chemical characteristics and nutrients concentration suitable for their reuse in agriculture [Cucina et al., 2021]. However, these digestates may only partially replace a mineral fertilizer due to the high nutrients dilution. Heavy metals were present at low concentrations in all the digestates and under the limit set by the Colombian regulation (Royal Decree 1287, 2014). Biodegradable organic matter and pathogens (coliform, helminths and Salmonella spp.) analysis proved that all the digestates should be post-treated before soil application to prevent environmental and health risks, and also to reduce residual phytotoxicity effects [Cucina et al., 2021]. Table 6.4 summarizes the digesters operational parameters and digestates characteristics for each case study. It is worthy to mention that, among all the heavy metals, only zinc (Zn) and copper (Cu) were reported and considered in the present study, which are the most relevant heavy metals in small-scale (non-industrialised) farms. Further information regarding the case study and digestate characteristics can be found in Cucina et al. [2021].

Table 6.4. Digesters operational parameters and digestates characteristics

	Parameters	Notation	Unit	Case study 1 (CS1)	Case study 2 (CS2)	Case study 3 (CS3)
Digester	Feedstock composition (after dilution) (w/w)			100% CM	100% PM	30% CM; 70% CW
	Total inflow	Q	l/day	200	2800	70
	Water used for the dilution	QW	l/day	150	-*	60
	Manure/water ratio (w/w)	r	-	1:3	-*	1:6
	Average ambient temperature	T	ºC	23	17	17
	Hydraulic Retention Time	HRT	days	35	25	75
	Useful volume	UV	m^3	7.1	70.9	5.2
Digestate	Total solids	TS	%	2.1 ± 0.1	4.1 ± 0.5	2.2 ± 0.1
	Volatile solids	VS	%	1.4 ± 0.1	3.2 ± 0.4	1.6 ± 0.1
	Chemical oxygen demand	COD	g/L	17 ± 0.1	26.1 ± 1.1	25.8 ± 2.4
	Biochemical methane potential	BMP	m^3_{CH4}/kg_{VS}	0.077 +- 0.001	0.07 +- 0.009	0.066 +- 0.002
	Total Zn	Zn	mg/kg	15.4 ± 1	85.3 ± 1	12.1 ± 1
			mg/kg_{DM}***	376.6	2080.5	550
	Total Cu	Cu	mg/kg	< 5**	5.3 ± 1	< 5*
			mg/kg_{DM}	< 122	129.3	< 228
	Total Coliforms	COLI	CFU/g	435000 ± 50000	2970 ± 379	3450 ± 350
	Total Kjeldahl Nitrogen	TKN	%	0.04	0.17	0.68

*the digester is fed with water from stall floor drainage after cleaning; ** Detection limit of the method, adapted from Cucina et al. [2021]; *** DM: Dry matter.

Five basic alternatives (A1-A5) have been designed to treat the digestate from each case study (Table 6.5). Also, three additional alternatives are defined as a combination of a degassing tank and sand filter, vermifilter or a facultative pond (A1+A2, A1+A3, A1+A5, Table 6.5) in series. These combinations are more expensive than the single alternative, but combine the positive effects of two techniques obtaining a better quality digestate. It is worthy to mention that recirculation (A4) is not feasible for CS2 since the digester is fed with water from stall floor drainage after cleaning, thus water could not be saved by recirculating the digestate. For the other case studies (CS1 and CS3), 50% of the water volume needed for feedstock dilution is saved by recirculating the corresponding amount of digestate (Table 6.5).

Table 6.6 shows the lifespan, the amount of each material needed for the implementation of all the alternatives (A1 to A5), the unit cost of the materials and the total costs afforded during the whole life of the project. The unit costs of materials were provided by local suppliers. In order to calculate the total cost of the alternatives, including capital and maintenance costs, a period of 20 years is considered. Thus, the total costs comprised the capital costs plus the cost of the materials that are replaced during the 20 years, considering their lifespan (Table 6.6). The total costs of the alternatives in series (A1+A2, A1+A3, A1+A5, Table 6.5) are calculated as the sum of the single alternatives considered.

Table 6.5. Design and operational parameters of the digestate post-treatment alternatives for each case study

Alternative	Parameter	Unit	Case study 1 (CS1)	Case study 2 (CS2)	Case study 3 (CS3)
	Digestate inflow	l/day	200	2800	70
A1: Degassing tank	Useful volume	m^3	3.75	37.88	3
	Hydraulic Retention Time (HRT)	days	18	13	38
	Biogas production rate	m^3_{biogas}/ $m^3_{digester}$ day	0.05	0.15	0.02
	Organic loading rate (OLR)	kg_{VS}/m^3day	0.39	1.26	0.22
A2: Sand filter	Surface x Depth	m^2 x m	1.4 x 0.7	16.1 x 0.7	0.4 x 0.7
	Sand volume	m^3	0.97	11.24	0.28
	Organic loading rate (OLR)	g_{BOD}/cm^2day	0.27	0.27	0.27
A3: Vermifilter	Surface x Depth	m^2 x m	0.25 x 1	2.8 x 1	0.1 x 1
	Number of beds	number	3	3	3
	Earthworms	number/ m^2	20000	20000	20000
	Hydraulic Loading Rate (HLR)	m^3/m^2 day	1	1	1
A4: Recirculation	Recirculated digestate	l/day	75	-*	30
A5: Facultative pond	Length x Width x Depth	m x m x m	4.5 x 2 x 1	14.8 x 7.5 x 1	2.5 x 1.2 x 1
	Organic loading rate (OLR)	g_{BOD}/m3 day	400	400	400

**the digester is fed with water from stall floor drainage after cleaning; recirculation is not possible*

Note: CS1, digester fed with cattle manure (CM); CS2: digester fed with pig manure (PM), CS3: digester fed with cattle manure in co-digestion with cheese whey (CM-CW). A1 designed considering half of the useful volume of the digester; A2 designed according to Patil & Husain, 2019; A3 designed according to Krishnasamy et al. [2013]; A4 designed considering the replacement of 50% of water volume needed for feedstock dilution by the digestate recirculation; A5 designed according to CNA [2007] and Mara [2003]

Table 6.6. Materials, amount and costs needed for the implementation of each alternative

<table>
<tr><th rowspan="2">Alternative</th><th rowspan="2">Material</th><th>Lifespan</th><th colspan="3">Amount</th><th>Unit cost</th><th>Total cost over</th></tr>
<tr><th>(years)</th><th>CS1</th><th>CS2</th><th>CS3</th><th>($/unit)</th><th>20 years ($)</th></tr>
<tr><td rowspan="3">A1</td><td>Polyethylene (m^2)</td><td>5</td><td>15.70</td><td>157.00</td><td>12.56</td><td>3.87</td><td rowspan="3">CS1: 403.04
CS2: 2591
CS3: 354.48</td></tr>
<tr><td>Plastic pipeline (unit)</td><td>5</td><td>1</td><td>1</td><td>1</td><td>40</td></tr>
<tr><td>Stones (bags)</td><td>20</td><td>20</td><td>20</td><td>20</td><td>0</td></tr>
<tr><td rowspan="2">A2</td><td>Container (unit)</td><td>5</td><td>1</td><td>1</td><td>1</td><td>20</td><td rowspan="2">CS1: 84.85
CS2: 216.2
CS3: 81.39</td></tr>
<tr><td>Sand, gravel and small rocks (m^3)</td><td>8</td><td>0.97</td><td>11.24</td><td>0.28</td><td>2</td></tr>
<tr><td rowspan="3">A3</td><td>Wood boxes (unit)</td><td>5</td><td>4</td><td>4</td><td>4</td><td>7.5</td><td rowspan="3">CS1: 127.30
CS2: 219.2
CS3: 122.5</td></tr>
<tr><td>Sand, gravel and small rocks (m^3)</td><td>8</td><td>0.20</td><td>2.24</td><td>0.06</td><td>2</td></tr>
<tr><td>Earthworms (kg)*</td><td>20</td><td>1.14</td><td>16</td><td>0.40</td><td>5.50</td></tr>
<tr><td>A4</td><td>Plastic bucket</td><td>5</td><td>1</td><td>-**</td><td>1</td><td>10</td><td>CS1: 40
CS3: 40</td></tr>
<tr><td rowspan="2">A5</td><td>Polyethylene for waterproofing (m^2)</td><td>5</td><td>22.49</td><td>154.04</td><td>9.69</td><td>3.87</td><td rowspan="2">CS1: 348.3
CS2: 2385
CS3: 150.1</td></tr>
<tr><td>Stones (bags)</td><td>20</td><td>20</td><td>20</td><td>20</td><td>0</td></tr>
</table>

** 1kg is assumed to include 3500 earthworms; **the digester is fed with water from stall floor drainage after cleaning; recirculation is not possible*

Note: *Note: CS1, digester fed with cattle manure (CM); CS2: digester fed with pig manure (PM), CS3: digester fed with cattle manure in co-digestion with cheese whey (CM-CW); A1: Degassing tank; A2: Sand filter; A3: Vermifiltration; A4: Recirculation; A5: Facultative pond*

6.4.2 Results and discussion

Once the alternatives for digestate reuse in agriculture have been designed for each case study, they can be evaluated according to each criterion (section 6.4.2.1) towards a final ranking that takes into account the weights of the criteria and the uncertainty in the whole decision-process (section 6.4.2.2). Finally, a sensitivity analysis is performed to confirm the robustness of the results (section 6.4.2.3).

6.4.2.1 Alternatives evaluation

The alternatives for digestate post-treatment in each case study are evaluated with TFN according to the defined criteria and the fuzzy procedure explained in section 6.3 (Tables 6.8-6.10 for each case study). In particular, Table 6.7 provides important information for the quantification of technical criteria regarding digestate characteristics (Table 6.1) for all the alternatives. For criteria T1.1-T1.5, the content of the parameters considered (i.e. heavy metals, Total Coliforms, TS, VS, and Nitrogen) in the treated digestate or vermicompost, is calculated considering the removal efficiency (or percentage increase) from the literature, or mass balance calculations (Table 6.7). For the alternatives which combine different technologies (A1+A2, A1+A3 and A1+A5) the evaluation of the technical criteria is made by combining in series the alternatives and considering the effect of the single alternative in series.

Heavy metals (Zn and Cu) content in the treated digestate or vermicompost is constant or reduced in most of the studied alternatives (A1, A2, A3, A5). However, it can increase in A4 (recirculation) due to their accumulation in the digester. All the alternatives considered are characterized by high removal efficiency (from 97 to 99.9%) of Total Coliforms (T1.2). Regarding the contents of TS, stabilized organic matter and nutrients (T1.3-T1.5), which are desired to be maximized (Table 6.1), the alternatives present uneven results. In fact, vermifiltration (A3) produces vermicompost which is characterized by a high content of TS, VS and Nitrogen (T1.3-T1.5). On the other hand, the degassing tank (A1), which mainly aims to increase biogas production, slightly decreases their content in the treated digestate (Table 6.7). Moreover, sand filtration (A2) reduces the content of TS, VS, and Nitrogen in the treated digestate. Regarding biogas production (T1.6), it can be increased only if digestate is post-treated by a desgassing tank (A1) or recirculated (A4). For all these technical criteria, vermifiltration (A3) shows to be the best alternative, since it produces a product (vermicompost) with high-quality characteristics for agricultural reuse, such as high content of TS and Nitrogen and high content of stabilized organic matter, and low concentration of pathogens, overcoming the drawbacks of the digestate [Cucina et al., 2021].

Table 6.7. Summary of the calculations used for the quantification of the technical criteria regarding digestate characteristics for all the alternatives

Criteria		Unit	Effect on digestate parameter: reduction (-) or increment (+)				
			A1	A2	A3	A4	A5
T1.1	Heavy metals content	mg/kg_{DM}	- (mass balance)	-95% [Sari et al., 2019]	-55% [Garg et al., 2006]	+60% for CS1 +75% for CS3 (mass balance)	-10% for Zn -30% for Cu [Kaplan et al., 1987]
T1.2	Pathogens content	CFU/g	-97% [Garfi et al., 2011a; Garfi et al., 2019]	-99% [Torres-Parra et al., 2013]	-99.9% [Droppelmann, 2009]	-97% (mass balance)	-97% [CNA, 2007]
T1.3	Dry matter content	%TS	-10% [Cucina et al., 2021]	-89% [Patil & Husain, 2019]	60% [Garg et al., 2006]	- (mass balance)	+30% [Mara, 2003]
T1.4	Organic matter content	%VS	-10% [Cucina et al., 2021]	-65% [Patil & Husain, 2019]	50% [Garg et al., 2006]	- (mass balance)	-30% [CNA, 2007]
T1.5	Nutrients content	%TKN	- (mass balance)	-15% [Patil & Husain, 2019]	3% [Kalantari et al., 2010; Arévalo, 2017]	+60% for CS1 +75% for CS3 (mass balance)	-10% [Mara, 2003]
T1.6	Residual biomethane	m^3/day	$OLR \cdot BMP \cdot UV$	0	0	$kg_{VS}/day \cdot BMP$	0

Note: A1: Degassing tank; A2: Sand filter; A3: Vermifiltration; A4: Recirculation; A5: Facultative pond. For the calculation of T1.6, it is considered the Organic Loading Rate (OLR) and Useful Volume (UV) of the tank (Table 6.5), and the Biochemical Methane Potential (BMP) of the digestate (Table 6.4)

Regarding the other quantitative criteria, the surface area requirement (T3), the lifespan (T4), the water consumption (E2.2) and the investment and maintenance costs (S1.1 and S1.2) (Table 1), are calculated considering the design of the alternative (Table 6.5 and Table 6.6). Regarding energy consumption (E2.3), it was non-existent in all the alternatives and each case study, since the solutions considered are low-tech and working manually or by gravity. For these criteria, recirculation (A4) show to be the best alternative, since it does not require any material or energy for its implementation and save water. On the other hand, the desgassing tank in series with the pond (A1+A5) is the alternative with the highest surface area requirement and costs.

All the other criteria (T2.1-T2.3, E1.1, E1.2, E2.1, S2.1, S2.2, S3 and S4; Table 6.1) are evaluated qualitatively considering the opinion of different experts, as described in Section 6.3.2.2. Experts' evaluation is considered to be the same in the three case studies for these criteria (Tables 6.8-6.10). The evaluations of the alternatives differ significantly for some criteria such as for the need for skilled labour (T2.1), the sustainability of materials used (E2.1) and the degree of acceptability (S4). For these criteria, recirculating the digestate (A4) offers globally the best results, for the aforementioned reasons. On the other hand, all the alternatives obtain similar or equal values (i.e. emission of odours; E1.2, equity and life quality; S3). Despite both S3 and E2.3 are not decisive to select the best alternative, they were included among the criteria since they can be relevant in other regions and contexts.

As mentioned above, a TFN is defined for each evaluation based on the nominal value calculated from the collected data and an uncertainty margin to account for a robust analysis (Tables 6.8-6.10). Indeed, two types of fuzzy evaluations are considered:

- A +/- 10% uncertainty margin is considered, as in similar studies [Garfi et al., 2019], in the quantitative criteria, except for the lifespan criterion (T4). In this criterion, +/- 1 year is used as the uncertainty margin, according to experts' opinions.
- Regarding the qualitative criteria, a 0-5 scale of real values are used, with a +/- 1 uncertainty margin [Juanpera et al., 2021].

Table 6.8. Fuzzy evaluations for case study 1

CASE STUDY 1			A1	A2	A3	A4	A5	A1+A2	A1+A3	A1+A5
TEC.	T1.1	-	(338, 375.6, 413.2)	(16.9, 18.78, 20.66)	(152.1, 169, 185.9)	(540.9, 601, 661.1)	(304.2, 338, 371.9)	(16.9, 18.78, 20.66)	(152.1, 169, 185.9)	(304.2, 338, 371.9)
	T1.2	-	(11745, 13050, 14355)	(3915, 4350, 4785)	(391.5, 435, 478.5)	(11745, 13050, 14355)	(11745, 13050, 14355)	(117.5, 130.5, 143.6)	(11.75, 13.05, 14.36)	(352.4, 391.5, 430.7)
	T1.3	+	(3.32, 3.69, 4.06)	(0.40, 0.45, 0.50)	(54, 60, 66)	(3.69, 4.1, 4.51)	(4.80, 5.33, 5.86)	(0.37, 0.41, 0.45)	(54, 60, 66)	(4.32, 4.80, 5.28)
	T1.4	+	(4.13, 4.59, 5.05)	(1.61, 1.79, 1.96)	(45, 50, 55)	(4.59, 5.1, 5.61)	(3.21, 3.57, 3.93)	(1.45, 1.61, 1.77)	(45, 50, 55)	(2.89, 3.21, 3.53)
	T1.5	+	(0.032, 0.036, 0.040)	(0.028, 0.031, 0.034)	(2.7, 3, 3.3)	(0.052, 0.058, 0.063)	(0.029, 0.032, 0.036)	(0.028, 0.031, 0.034)	(2.7, 3, 3.3)	(0.029, 0.032, 0.036)
	T1.6	+	(0.60, 0.67, 0.74)	(0, 0, 0)	(0, 0, 0)	(0.45, 0.5, 0.55)	(0, 0, 0)	(0.60, 0.67, 0.74)	(0.60, 0.67, 0.74)	(0.60, 0.67, 0.74)
	T2.1	-	(1, 2, 3)	(1, 2, 3)	(2, 3, 4)	(0, 1, 2)	(1, 2, 3)	(2, 3, 4)	(3, 4, 5)	(2, 3, 4)
	T2.2	+	(3, 4, 5)	(2, 3, 4)	(2, 3, 4)	(4, 5, 5)	(3, 4, 5)	(1, 2, 3)	(1, 2, 3)	(2, 3, 4)
	T2.3	+	(3, 4, 5)	(3, 4, 5)	(2, 3, 4)	(2, 3, 4)	(3, 4, 5)	(2, 3, 4)	(1, 2, 3)	(2, 3, 4)
	T3	-	(5.4, 6, 6.6)	(1.30, 1.45, 1.60)	(0.225, 0.25, 0.275)	(0, 0, 0)	(8.1, 9, 9.9)	(6.705, 7.45, 8.195)	(5.625, 6.25, 6.875)	(13.5, 15, 16.5)
	T4	+	(4, 5, 6)	(7, 8, 9)	(7, 8, 9)	(4, 5, 6)	(4, 5, 6)	(5.5, 6.5, 7.5)	(5.5, 6.5, 7.5)	(4, 5, 6)
ENV.	E1.1	-	(1, 2, 3)	(0, 1, 2)	(0, 1, 2)	(0, 1, 2)	(1, 2, 3)	(1, 2, 3)	(1, 2, 3)	(2, 3, 4)
	E1.2	-	(0, 0, 1)	(1, 2, 3)	(1, 2, 3)	(1, 2, 3)	(2, 3, 4)	(1, 2, 3)	(1, 2, 3)	(2, 3, 4)
	E2.1	+	(2, 3, 4)	(3, 4, 5)	(4, 5, 5)	(4, 5, 5)	(3, 4, 5)	(2, 3, 4)	(2, 3, 4)	(2, 3, 4)
	E2.2	-	(135, 150, 165)	(135, 150, 165)	(135, 150, 165)	(67.5, 75, 82.5)	(135, 150, 165)	(135, 150, 165)	(135, 150, 165)	(135, 150, 165)
	E2.3	-	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)
SOC-ECO.	S1.1	-	(90.69, 100.8, 110.8)	(19.75, 21.94, 24.13)	(33.02, 36.69, 40.36)	(9, 10, 11)	(78.36, 87.07, 95.78)	(110.4, 122.7, 135)	(123.7, 137.5, 151.2)	(169.1, 187.8, 206.6)
	S1.2	-	(362.8, 403.1, 443.4)	(76.37, 84.85, 93.34)	(114.6, 127.3, 140)	(36, 40, 44)	(313.4, 348.3, 383.1)	(439.2, 488, 536.7)	(477.4, 530.4, 583.4)	(676.2, 751.4, 826.5)
	S2.1	+	(1, 2, 3)	(1, 2, 3)	(3, 4, 5)	(1, 2, 3)	(1, 2, 3)	(1, 2, 3)	(3, 4, 5)	(1, 2, 3)
	S2.2	+	(4, 5, 5)	(3, 4, 5)	(3, 4, 5)	(2, 3, 4)	(3, 4, 5)	(4, 5, 5)	(4, 5, 5)	(4, 5, 5)
	S3	+	(4, 5, 5)	(4, 5, 5)	(4, 5, 5)	(4, 5, 5)	(4, 5, 5)	(4, 5, 5)	(4, 5, 5)	(4, 5, 5)
	S4	+	(3, 4, 5)	(2, 3, 4)	(3, 4, 5)	(3, 4, 5)	(2, 3, 4)	(2, 3, 4)	(3, 4, 5)	(2, 3, 4)

Note: A1: Degassing tank; A2: Sand filter; A3: Vermifiltration; A4: Recirculation; A5: Facultative pond.

Table 6.9. Fuzzy evaluations for case study 2

CASE STUDY 2			A1	A2	A3	A5	A1+A2	A1+A3	A1+A5
TEC.	T1.1 Zn	-	(1872, 2080, 2289)	(93.62, 104, 114.40)	(842.6, 936.2, 1029.8)	(1685, 1872, 2060)	(93.62, 104.03, 114.4)	(842.6, 936.2, 1029.8)	(1685, 1872, 2060)
	T1.1 Cu		(116.3, 129.3, 142.2)	(5.82, 6.46, 7.11)	(52.35, 58.17, 64.00)	(81.44, 90.49, 99.54)	(5.82, 6.46, 7.11)	(52.35, 58.17, 64.00)	(81.44, 90.49, 99.54)
	T1.2	-	(80.19, 89.10, 98.01)	(26.73, 29.70, 32.67)	(2.67, 2.97, 3.27)	(80.19, 89.10, 98.01)	(0.80, 0.89, 0.98)	(0.080, 0.089, 0.098)	(2.41, 2.67, 2.94)
	T1.3	+	(3.14, 3.48, 3.83)	(0.406, 0.451, 0.496)	(54, 60, 66)	(4.80, 5.33, 5.86)	(0.345, 0.383, 0.422)	(54, 60, 66)	(4.08, 4.53, 4.98)
	T1.4	+	(2.363, 2.848, 3.13)	(1.01, 1.12, 1.23)	(45, 50, 55)	(2.02, 2.24, 2.46)	(0.897, 0.997, 1.096)	(45, 50, 55)	(1.79, 1.99, 2.19)
	T1.5	+	(0.153, 0.170, 0.187)	(0.130, 0.144, 0.159)	(2.7, 3, 3.3)	(0.138, 0.153, 0.168)	(0.130, 0.144, 0.159)	(2.7, 3, 3.3)	(0.138, 0.153, 0.168)

	T1.6	+	(4.84, 5.38, 5.91)	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)	(4.84, 5.38, 5.91)	(4.84, 5.38, 5.91)	(4.84, 5.38, 5.91)
	T2.1	-	(1, 2, 3)	(1, 2, 3)	(2, 3, 4)	(1, 2, 3)	(2, 3, 4)	(3, 4, 5)	(2, 3, 4)
	T2.2	+	(3, 4, 5)	(2, 3, 4)	(2, 3, 4)	(3, 4, 5)	(1, 2, 3)	(1, 2, 3)	(2, 3, 4)
	T2.3	+	(3, 4, 5)	(3, 4, 5)	(2, 3, 4)	(3, 4, 5)	(2, 3, 4)	(1, 2, 3)	(2, 3, 4)
	T3	-	(54, 60, 66)	(14.4, 16, 17.6)	(2.7, 3, 3.3)	(99, 110, 121)	(68.4, 76, 83.6)	(56.7, 63, 69.3)	(153, 170, 187)
	T4	+	(4, 5, 6)	(7, 8, 9)	(7, 8, 9)	(4, 5, 6)	(5.5, 6.5, 7.5)	(5.5, 6.5, 7.5)	(4, 5, 6)
ENV.	**E1.1**	-	(1, 2, 3)	(0, 1, 2)	(0, 1, 2)	(1, 2, 3)	(1, 2, 3)	(1, 2, 3)	(2, 3, 4)
	E1.2	-	(0, 0, 1)	(1, 2, 3)	(1, 2, 3)	(2, 3, 4)	(1, 2, 3)	(1, 2, 3)	(2, 3, 4)
	E2.1	+	(2, 3, 4)	(3, 4, 5)	(4, 5, 5)	(3, 4, 5)	(2, 3, 4)	(2, 3, 4)	(2, 3, 4)
	E2.2	-	(2520, 2800, 3080)	(2520, 2800, 3080)	(2520, 2800, 3080)	(2520, 2800, 3080)	(2520, 2800, 3080)	(2520, 2800, 3080)	(2520, 2800, 3080)
	E2.3	-	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)
SOC-ECO.	**S1.1**	-	(582.97, 647.74, 712.51)	(56.24, 62.49, 68.74)	(110.2, 122.5, 134.7)	(536.6, 596.3, 655.9)	(639.2, 710.2, 781.3)	(693.2, 770.2, 847.2)	(1120, 1244, 1368)
	S1.2	-	(2331.9, 2591, 2850.1)	(194.6, 216.2, 237.8)	(197.3, 219.2, 241.1)	(2147, 2385, 2624)	(2526, 2807, 3088)	(2529, 2810, 3091)	(4478, 4976, 5474)
	S2.1	+	(1, 2, 3)	(1, 2, 3)	(3, 4, 5)	(1, 2, 3)	(1, 2, 3)	(3, 4, 5)	(1, 2, 3)
	S2.2	+	(4, 5, 5)	(3, 4, 5)	(3, 4, 5)	(3, 4, 5)	(4, 5, 5)	(4, 5, 5)	(4, 5, 5)
	S3	+	(4, 5, 5)	(4, 5, 5)	(4, 5, 5)	(4, 5, 5)	(4, 5, 5)	(4, 5, 5)	(4, 5, 5)
	S4	+	(3, 4, 5)	(2, 3, 4)	(3, 4, 5)	(2, 3, 4)	(2, 3, 4)	(3, 4 5)	(2, 3, 4)

Note: A1: Degassing tank; A2: Sand filter; A3: Vermifiltration; A5: Facultative pond. Recirculating the digestate (A4) is not possible in CS2.

Table 6.10. Fuzzy evaluations for case study 3

CASE STUDY 3			**A1**	**A2**	**A3**	**A4**	**A5**	**A1+A2**	**A1+A3**	**A1+A5**
TEC.	**T1.1**	-	(495, 550, 605)	(24.75, 27.5, 30.25)	(222.8, 247.5, 272.3)	(866.3, 962.5, 1058.8)	(445.5, 495, 544.5)	(24.75, 27.5, 30.25)	(222.7, 247.5, 272.3)	(445.5, 495, 544.5)
	T1.2	-	(93.15, 103.5, 113.9)	(31.05, 34.5, 37.95)	(3.105, 3.45, 3.795)	(93.15, 103.5, 113.85)	(93.15, 103.5, 113.85)	(0.932, 1.035, 1.139)	(0.093, 0.104, 0.114)	(2.795, 3.105, 3.416)
	T1.3	+	(0.653, 0.726, 0.799)	(0.218, 0.242, 0.266)	(54, 60, 66)	(1.98, 2.2, 2.42)	(2.57, 2.86, 3.15)	(0.072, 0.080, 0.088)	(54, 60, 66)	(0.849, 0.944, 1.038)
	T1.4	+	(0.446, 0.496, 0.546)	(0.504, 0.56, 0.616)	(45, 50, 55)	(1.44, 1.6, 1.76)	(1.008, 1.12, 1.232)	(0.156, 0.174, 0.191)	(45, 50, 55)	(0.313, 0.347, 0.382)
	T1.5	+	(0.061, 0.068, 0.075)	(0.052, 0.058, 0.064)	(2.7, 3, 3.3)	(0.107, 0.119, 0.131)	(0.055, 0.061, 0.067)	(0.052, 0.058, 0.064)	(2.7, 3, 3.3)	(0.055, 0.061, 0.067)
	T1.6	+	(0.055, 0.062, 0.068)	(0, 0, 0)	(0, 0, 0)	(0.048, 0.053, 0.058)	(0, 0, 0)	(0.055, 0.062, 0.068)	(0.055, 0.062, 0.068)	(0.055, 0.062, 0.068)
	T2.1	-	(1, 2, 3)	(1, 2, 3)	(2, 3, 4)	(0, 1, 2)	(1, 2, 3)	(2, 3, 4)	(3, 4, 5)	(2, 3, 4)
	T2.2	+	(3, 4, 5)	(2, 3, 4)	(2, 3, 4)	(4, 5, 5)	(3, 4, 5)	(1, 2, 3)	(1, 2, 3)	(2, 3, 4)
	T2.3	+	(3, 4, 5)	(3, 4, 5)	(2, 3, 4)	(2, 3, 4)	(3, 4, 5)	(2, 3, 4)	(1, 2, 3)	(2, 3, 4)
	T3	-	(4.32, 4.8, 5.28)	(0.36, 0.4, 0.44)	(0.09, 0.1, 0.11)	(0, 0, 0)	(2.7, 3, 3.3)	(4.68, 5.2, 5.72)	(4.41, 4.9, 5.39)	(7.02, 7.8, 8.58)
	T4	+	(4, 5, 6)	(7, 8, 9)	(7, 8, 9)	(4, 5, 6)	(4, 5, 6)	(5.5, 6.5, 7.5)	(5.5, 6.5, 7.5)	(4, 5, 6)
ENV	**E1.1**	-	(1, 2, 3)	(0, 1, 2)	(0, 1, 2)	(0, 1, 2)	(1, 2, 3)	(1, 2, 3)	(1, 2, 3)	(2, 3, 4)
	E1.2	-	(0, 0, 1)	(1, 2, 3)	(1, 2, 3)	(1, 2, 3)	(2, 3, 4)	(1, 2, 3)	(1, 2, 3)	(2, 3, 4)

	E2.1	+	(2, 3, 4)	(3, 4, 5)	(4, 5, 5)	(4, 5, 5)	(3, 4, 5)	(2, 3, 4)	(2, 3, 4)	(2, 3, 4)
	E2.2	-	(54, 60, 66)	(54, 60, 66)	(54, 60, 66)	(27, 30, 33)	(54, 60, 66)	(54, 60, 66)	(54, 60, 66)	(54, 60, 66)
	E2.3	-	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)
SOC-ECO.	**S1.1**	-	(79.76, 88.62, 97.48)	(18.50, 20.56, 22.62)	(29.08, 32.31, 35.54)	(9, 10, 11)	(33.77, 37.52, 41.27)	(98.26, 109.18, 120.1)	(108.8, 120.9, 133.0)	(113.5, 126.1, 138.7)
	S1.2	-	(319.03, 354.48, 389.93)	(73.25, 81.39, 89.53)	(110.2, 122.5, 134.7)	(36, 40, 44)	(135.1, 150.1, 165.1)	(392.3, 435.9, 479.5)	(429.3, 477.0, 524.7)	(454.1, 501.6, 555.0)
	S2.1	+	(1, 2, 3)	(1, 2, 3)	(3, 4, 5)	(1, 2, 3)	(1, 2, 3)	(1, 2, 3)	(3, 4, 5)	(1, 2, 3)
	S2.2	+	(4, 5, 5)	(3, 4, 5)	(3, 4, 5)	(2, 3, 4)	(3, 4, 5)	(4, 5, 5)	(4, 5, 5)	(4, 5, 5)
	S3	+	(4, 5, 5)	(4, 5, 5)	(4, 5, 5)	(4, 5, 5)	(4, 5, 5)	(4, 5, 5)	(4, 5, 5)	(4, 5, 5)
	S4	+	(3, 4, 5)	(2, 3, 4)	(3, 4, 5)	(3, 4, 5)	(2, 3, 4)	(2, 3, 4)	(3, 4 5)	(2, 3, 4)

Note: A1: Degassing tank; A2: Sand filter; A3: Vermifiltration; A4: Recirculation; A5: Facultative pond.

Once the evaluations are obtained, the MIMDU method [Juanpera et al, 2021] is applied to aggregate all the evaluations considering the weights of the criteria in order to obtain a final ranking and, subsequently, the best alternatives.

6.4.2.2 Fuzzy alternatives ranking

As mentioned above, after the application of the MIMDU methodology [Juanpera et al., 2021], two rankings of the alternatives are obtained: a crisp one, which does not take into account any uncertainty in the results aggregation, and a fuzzy ranking, which considers uncertainty in both the weighing and the evaluation process (Table 6.11 for CS1, Table 6.12 for CS2 and Table 6.13 for CS3). Both rankings completely match in the case studies CS1 and CS3 and are very similar in CS2. Indeed, the vermifilter (A3) is considered to be the best post-treatment alternative for the digestate from low-tech digesters implemented in the three small-scale farms studied. In CS1 and CS3, it is followed by recirculation (A4) and sand filter (A2). In CS2, where recirculation is not feasible, the vermifilter (A3) is followed by the degassing tank in series with vermifilter (A1+A3) and the sand filter (A2). The similarity between the crisp and the fuzzy rankings confirms the robustness of the results and increase the confidence of decision-makers in the results achieved.

A detailed tracking of the MIMDU application towards the final rankings can be found in Appendix A.

Table 6.11. Crisp and fuzzy ranking of alternatives for CS1

	A1	A2	**A3**	A4	A5	A1+A2	A1+A3	A1+A5
Crisp analysis: ${}^{1}L_i$	0.334	0.308	**0.183**	0.275	0.425	0.396	0.315	0.487
Fuzzy analysis: $MPMI_i$	0.345	0.309	**0.210**	0.291	0.412	0.375	0.313	0.451
Ranking:	5	3	**1**	2	7	6	4	8

Note: A1: Degassing tank; A2: Sand filter; A3: Vermifiltration; A4: Recirculation; A5: Facultative pond.

Table 6.12. Crisp and fuzzy ranking of alternatives for CS2

	A1	A2	**A3**	A5	A1+A2	A1+A3	A1+A5
Crisp analysis: ${}^{1}L_i$	0.287	0.285	**0.140**	0.399	0.337	0.236	0.433
Fuzzy analysis: $MPMI_i$	0.310	0.263	**0.166**	0.368	0.322	0.241	0.410
Ranking:	4	3	**1**	6	5	2	7

Note: A1: Degassing tank; A2: Sand filter; A3: Vermifiltration; A4: Recirculation; A5: Facultative pond. Recirculating the digestate (A4) is not possible in CS2

Table 6.13. Crisp and fuzzy ranking of alternatives for CS3

	A1	A2	**A3**	A4	A5	A1+A2	A1+A3	A1+A5
Crisp analysis: ${}^{1}L_i$	0.348	0.309	**0.186**	0.272	0.406	0.414	0.331	0.486
Ranking:	5	3	**1**	2	6	7	4	8
Fuzzy analysis: $MPMI_i$	0.358	0.293	**0.213**	0.288	0.394	0.391	0.329	0.450
Ranking:	5	3	**1**	2	7	6	4	8

Note: A1: Degassing tank; A2: Sand filter; A3: Vermifiltration; A4: Recirculation; A5: Facultative pond.

Overall, vermifiltration (A3) stands out as the best alternative. Indeed, from a technical point of view, it treats digestates increasing the content of TS, stabilized organic matter and nutrients (T1.3-T1.5), generating a final product (vermicompost) which is easier to manage and transport and, at the same time, it is a high-quality biofertilizer, overcoming digestate drawbacks [Cucina et al., 2021]. Also, the vermifilter accounts for the best evaluation in some of the environmental and socio-economic criteria, such as the sustainability of materials needed for its implementation (E2.1) and its capacity of generating an income for the beneficiary population (S2.1). In fact, the vermifilter is usually implemented using sustainable materials (e.g. wood) and it produces a high-quality compost that can increase crops productivity or can be sold increasing farmers' income. This is in accordance with previous studies which highlighted the high removal efficiency of heavy metals and pathogens of vermifiltration. These studies also pointed out the potential benefits of reusing the vermicompost in agriculture in rural areas of Asia [Kannadasan et al., 2021; Kumar et al., 2014 and 2015].

Besides, recirculating the digestate (A4) is easy to implement and it does not require skilled labour (T2.1, T2.2). Also, this alternative obtains the best score in three out of the four environmental criteria (E1.1, E2.1 and E2.2). As mentioned above, this solution does not require any materials, energy, surface area for its implementation and it is the least expensive alternative. Moreover, recirculating the digestate reduces the amount of water used for digesters feeding by 50%.

The sand filter (A2) is also well ranked mainly due to its heavy metals removal efficiency (T1.1) despite not achieving outstanding results in the environmental and socio-economic criteria. These results are in accordance with previous studies in which sand filters were shown to be robust technology with a long lifespan, easy to implement and maintain, and low-cost solutions appropriated for rural underprivileged areas [Patil & Husain, 2019; Torres-Parra, et al., 2013]. The degassing tank (A1) and the facultative pond (A5), are the lowest-ranked due to their low efficiency in improving digestate characteristics (e.g. Total coliforms removal, nutrients content), which is not compensated by particularly good environmental or socio-economic benefits compared to the other alternatives, as pointed out by previous studies [Kaplan et al., 1987; Mara, 2003].

Finally, despite the common drawback of higher investment and maintenance costs, the alternatives which consider two technologies in series (A1+A2, A1+A3, A1+A5) obtain uneven ranking results.

Indeed, combining a degassing tank with the vermifilter (A1+A3) highly increase the quality of the digestate (T1.2-T1.8). On the other hand, the desgassing tank coupled with a sand filter (A1+A2) and a facultative pond (A1+A5) are not appropriate choices with respect to the majority of technical, environmental and socio-economic criteria.

6.4.2.3 Sensitivity analysis

A sensitivity analysis is performed to analyse the influence of the experts' profiles (groups) or the uncertainty margin considered on the criteria evaluations (scenarios). In detail, 3 groups (i.e. all the experts, technicians and academics) of 4 scenarios (i.e. crisp and fuzzy 5, 10, and 20%) are considered for each case study (Table 6.14, Table 6.15 and Table 6.16, respectively). Regarding the 3 groups, the experts with a technical background belong to several companies and NGOs and have long-term experience in the implementation of digesters and biogas programs in Latin America. On the other hand, academics belong to 7 different universities of Spain, Colombia and Ecuador. Both technicians and academics gave higher weights to the socio-economic criteria (36.00% and 36.07%, respectively). In the case of technicians, socio-economic criteria were followed by technical and environmental criteria (with weights of 32.12% and 31.88%). On the contrary, in the case of academics, socio-economic criteria were followed by environmental criteria first (32.53%), and then by the technical ones (31.40%). For each of the 3 groups, 4 scenarios (and therefore 4 rankings are calculated): one for the crisp analysis, without considering any uncertainty, and the three others with a 5%, 10% and 20% uncertainty margin, respectively, in the evaluation of the quantitative criteria.

The results of the sensitivity analysis show that the vermifilter (A3) stands out as the best alternative for all scenarios and case studies. This alternative can be therefore seen as a very solid option for digestate post-treatment in small-scale farms located in Colombia. Apart from that, slight differences introduced by the experts' profile and the uncertainty consideration can be observed:

1. Regarding CS1 (Table 6.14), the results obtained considering only academics' opinion show that the vermifilter (A3) is followed by the sand filter (A2) instead of the recirculation (A4). This was mainly due to the higher weights given by academics to the environmental criteria instead of technical criteria. Also, the sand filter (A2) and recirculation (A4) can be considered equivalent options due to the small differences in their assessments that make one stand over the other and vice versa across the crisp and fuzzy rankings for each profile.
2. Regarding CS2 (Table 6.15), no remarkable difference is appreciated in this ranking regarding groups or scenarios. The order of the alternatives is therefore very robust.
3. Regarding CS3 (Table 6.16), although slight differences in the final ranking are obtained due to the effect of the fuzzy analysis and the experts' profiles, vermifiltration (A3) is always the best alternative. Next, the sand filter (A2), recirculation (A4), and the degassing tank coupled with vermifilter (A1+A3) always obtain the following positions.

Table 6.14. Results of the sensitivity analysis on the alternatives ranking of CS1

CASE STUDY 1		A1	A2	A3	A4	A5	A1+A2	A1+A3	A1+A5
All experts	Crisp	5	3	**1**	2	7	6	4	8
	Fuzzy (5%)	5	3	**1**	2	7	6	4	8
	Fuzzy (10%)	5	3	**1**	2	7	6	4	8
	Fuzzy (20%)	5	3	**1**	2	7	6	4	8
Technicians	Crisp	5	4	**1**	2	7	6	3	8
	Fuzzy (5%)	5	4	**1**	2	7	6	3	8
	Fuzzy (10%)	5	4	**1**	2	7	6	3	8
	Fuzzy (20%)	5	4	**1**	2	7	6	3	8
Academics	Crisp	5	3	**1**	2	7	6	4	8
	Fuzzy (5%)	5	2	**1**	3	7	6	4	8
	Fuzzy (10%)	5	2	**1**	3	7	6	4	8
	Fuzzy (20%)	5	2	**1**	3	7	6	4	8

Note: A1: Degassing tank; A2: Sand filter; A3: Vermifiltration; A4: Recirculation; A5: Facultative pond.

Table 6.15. Results of the sensitivity analysis on the alternatives ranking of CS2

CASE STUDY 2		A1	A2	A3	A5	A1+A2	A1+A3	A1+A5
All experts	Crisp	4	3	**1**	6	5	2	7
	Fuzzy (5%)	4	3	**1**	6	5	2	7
	Fuzzy (10%)	4	3	**1**	6	5	2	7
	Fuzzy (20%)	4	3	**1**	6	5	2	7
Technicians	Crisp	4	3	**1**	6	5	2	7
	Fuzzy (5%)	4	3	**1**	6	5	2	7
	Fuzzy (10%)	4	3	**1**	6	5	2	7
	Fuzzy (20%)	4	3	**1**	6	5	2	7
Academics	Crisp	4	3	**1**	6	5	2	7
	Fuzzy (5%)	4	3	**1**	6	5	2	7
	Fuzzy (10%)	4	3	**1**	6	5	2	7
	Fuzzy (20%)	4	3	**1**	6	5	2	7

Note: A1: Degassing tank; A2: Sand filter; A3: Vermifiltration; A4: Recirculation; A5: Facultative pond. Recirculating the digestate (A4) is not possible in CS2.

Table 6.16. Results of the sensitivity analysis on the alternatives ranking of CS3

CASE STUDY 3		A1	A2	A3	A4	A5	A1+A2	A1+A3	A1+A5
All experts	Crisp	5	3	**1**	2	6	7	4	8
	Fuzzy (5%)	5	3	**1**	2	7	6	4	8
	Fuzzy (10%)	5	3	**1**	2	7	6	4	8
	Fuzzy (20%)	5	3	**1**	2	7	6	4	8
Technicians	Crisp	5	3	**1**	4	6	7	2	8
	Fuzzy (5%)	5	2	**1**	4	6	7	3	8
	Fuzzy (10%)	5	2	**1**	4	6	7	3	8

	Fuzzy (20%)	5	2	**1**	4	6	7	3	8
Academics	Crisp	4	3	**1**	5	6	7	2	8
	Fuzzy (5%)	5	2	**1**	4	7	6	3	8
	Fuzzy (10%)	5	2	**1**	4	7	6	3	8
	Fuzzy (20%)	5	2	**1**	4	7	6	3	8

Note: A1: Degassing tank; A2: Sand filter; A3: Vermifiltration; A4: Recirculation; A5: Facultative pond.

6.5 CONCLUSIONS

This work defines and validates a fuzzy multicriteria analysis to robustly select the best alternative for the post-treatment and agricultural reuse of digestate from low-tech digesters implemented in small-scale farms. The solutions studied are: degassing tank, sand filter, vermifilter, digestate recirculation, facultative pond, or a combination of them. 10 criteria and 21 sub-criteria including technical, environmental and socio-economic aspects are defined and weighted considering the opinion of 16 experts in the field. According to the experts' opinion, the socio-economic criteria are the most important. In order to evaluate the alternatives, the MIMDU methodology is used, since it provides solid results due to the consideration of inherent uncertainty in criteria weighting and evaluations of alternatives.

Moreover, the analysis is validated using three case studies of low-tech digesters implemented in small-scale farms in Colombia. Results confirm the robustness of the rankings and show that vermifiltration is the best alternative for digestate post-treatment in small-scale farms, followed by sand filters, digestate recirculation and degassing tank coupled with vermifiltration. This is mainly due to the fact that vermifiltration generate a high-quality product (vermicompost) that can be used as biofertilizer. In particular, the vermicompost has high total solids, stabilised organic matter and nutrients content, but low pathogens concentration. Moreover, it is not only safer than the digestate, but it is also easier to manage, transport and apply to the soil due to its high total solids content. Thus, the vermicompost can be used in the same farms improving crops' productivity or it might be sold, increasing, in both cases, farmers' income. In addition, the vermifilter is an environmentally-friendly technology, implemented using sustainable materials (e.g. wood), that can contribute to boosting the circular bioeconomy and improving the standard of living of small-scale farms in low-income countries.

APPENDIX A

Tables 6.17-6.19 display the fuzzy numbers, through their α-cut intervals, reflecting the distance of each alternative to the ideal solution in each case study. These numbers allow to calculate the crisp ranking, which is easily determined by the 1-cut of each fuzzy number, and the fuzzy ranking with eq. 6.4. Also, a graphical representation of the fuzzy numbers is offered in Figure 6.4, which allows a fast determination of a crisp and fuzzy alternatives order.

Table 6.17. Results of CS1. α-cut of the fuzzy distances $\widetilde{L_\iota}$

alpha	A1	A2	A3	A4	A5	A1+A2	A1+A3	A1+A5
0	(0.180, 0.547)	(0.153, 0.492)	(0.081, 0.397)	(0.150, 0.477)	(0.216, 0.619)	(0.173, 0.576)	(0.132, 0.517)	(0.219, 0.664)
0.1	(0.190, 0.526)	(0.163, 0.474)	(0.087, 0.378)	(0.158, 0.457)	(0.229, 0.599)	(0.187, 0.557)	(0.143, 0.497)	(0.235, 0.645)
0.2	(0.202, 0.505)	(0.173, 0.456)	(0.095, 0.358)	(0.167, 0.438)	(0.243, 0.579)	(0.201, 0.538)	(0.156, 0.478)	(0.253, 0.626)
0.3	(0.214, 0.485)	(0.185, 0.438)	(0.103, 0.339)	(0.177, 0.419)	(0.259, 0.559)	(0.217, 0.520)	(0.169, 0.458)	(0.272, 0.607)
0.4	(0.227, 0.465)	(0.197, 0.420)	(0.111, 0.319)	(0.187, 0.400)	(0.276, 0.540)	(0.235, 0.502)	(0.184, 0.439)	(0.293, 0.589)
0.5	(0.241, 0.444)	(0.211, 0.402)	(0.121, 0.299)	(0.198, 0.380)	(0.294, 0.521)	(0.255, 0.484)	(0.201, 0.420)	(0.317, 0.571)
0.6	(0.256, 0.424)	(0.226, 0.384)	(0.131, 0.278)	(0.211, 0.361)	(0.315, 0.501)	(0.276, 0.467)	(0.219, 0.400)	(0.343, 0.553)
0.7	(0.273, 0.403)	(0.243, 0.365)	(0.142, 0.257)	(0.224, 0.341)	(0.337, 0.482)	(0.301, 0.449)	(0.239, 0.380)	(0.372, 0.536)
0.8	(0.291, 0.381)	(0.261, 0.347)	(0.155, 0.234)	(0.239, 0.320)	(0.363, 0.463)	(0.328, 0.432)	(0.261, 0.360)	(0.405, 0.519)
0.9	(0.312, 0.359)	(0.283, 0.328)	(0.168, 0.210)	(0.256, 0.298)	(0.391, 0.444)	(0.360, 0.414)	(0.286, 0.338)	(0.443, 0.503)
1	(0.334, 0.334)	(0.308, 0.308)	(0.183, 0.183)	(0.275, 0.275)	(0.425, 0.425)	(0.396, 0.396)	(0.315, 0.315)	(0.487, 0.487)

Note: A1: Degassing tank; A2: Sand filter; A3: Vermifiltration; A4: Recirculation; A5: Facultative pond.

Table 6.18. Results of CS2. α-cut of the fuzzy distances $\widetilde{L_\iota}$

alpha	A1	A2	A3	A5	A1+A2	A1+A3	A1+A5
0	(0.161, 0.512)	(0.096, 0.433)	(0.057, 0.333)	(0.162, 0.563)	(0.150, 0.503	(0.088, 0.422)	(0.206, 0.614)
0.1	(0.169, 0.492)	(0.105, 0.418)	(0.061, 0.315)	(0.175, 0.547)	(0.160, 0.487)	(0.097, 0.405)	(0.219, 0.595)
0.2	(0.178, 0.471)	(0.115, 0.403)	(0.067, 0.298)	(0.189, 0.530)	(0.171, 0.470)	(0.107, 0.387)	(0.233, 0.577)
0.3	(0.188, 0.450)	(0.127, 0.389)	(0.072, 0.281)	(0.204, 0.513)	(0.184, 0.454)	(0.117, 0.370)	(0.249, 0.559)
0.4	(0.199, 0.429)	(0.140, 0.375)	(0.078, 0.263)	(0.222, 0.497)	(0.198, 0.438)	(0.129, 0.353)	(0.267, 0.541)
0.5	(0.210, 0.408)	(0.156, 0.360)	(0.086, 0.245)	(0.242, 0.481)	(0.213, 0.422)	(0.142, 0.335)	(0.286, 0.523)
0.6	(0.223, 0.386)	(0.173, 0.346)	(0.094, 0.227)	(0.264, 0.465)	(0.231, 0.405)	(0.156, 0.317)	(0.308, 0.506)
0.7	(0.237, 0.364)	(0.194, 0.331)	(0.103, 0.207)	(0.290, 0.449)	(0.251, 0.389)	(0.173, 0.299)	(0.332, 0.488)
0.8	(0.252, 0.340)	(0.218, 0.316)	(0.113, 0.187)	(0.320, 0.433)	(0.275, 0.372)	(0.191, 0.280)	(0.360, 0.470)
0.9	(0.268, 0.315)	(0.248, 0.301)	(0.126, 0.165)	(0.356, 0.416)	(0.303, 0.355)	(0.212, 0.259)	(0.393, 0.452)
1	(0.287, 0.287)	(0.285, 0.285)	(0.140, 0.140)	(0.399, 0.399)	(0.337, 0.337)	(0.236, 0.236)	(0.433, 0.433)

Note: A1: Degassing tank; A2: Sand filter; A3: Vermifiltration; A4: Recirculation; A5: Facultative pond. Recirculating the digestate (A4) is not possible in CS2.

Table 6.19. Results of CS3. α-cut of the fuzzy distances $\widetilde{L_\iota}$

alpha	A1	A2	A3	A4	A5	A1+A2	A1+A3	A1+A5
0	(0.189, 0.565)	(0.124, 0.470)	(0.082, 0.401)	(0.147, 0.474)	(0.204, 0.596)	(0.195, 0.587)	(0.142, 0.537)	(0.219, 0.664)
0.1	(0.200, 0.544)	(0.134, 0.454)	(0.089, 0.381)	(0.155, 0.454)	(0.217, 0.576)	(0.208, 0.568)	(0.154, 0.517)	(0.235, 0.644)
0.2	(0.211, 0.523)	(0.145, 0.438)	(0.096, 0.362)	(0.164, 0.435)	(0.231, 0.557)	(0.222, 0.550)	(0.167, 0.497)	(0.252, 0.625)
0.3	(0.224, 0.502)	(0.158, 0.422)	(0.104, 0.342)	(0.174, 0.416)	(0.246, 0.538)	(0.237, 0.533)	(0.181, 0.478)	(0.272, 0.607)
0.4	(0.237, 0.481)	(0.172, 0.406)	(0.113, 0.322)	(0.184, 0.397)	(0.262, 0.519)	(0.254, 0.515)	(0.197, 0.458)	(0.293, 0.588)
0.5	(0.252, 0.460)	(0.187, 0.390)	(0.123, 0.302)	(0.196, 0.377)	(0.280, 0.500)	(0.273, 0.498)	(0.214, 0.438)	(0.317, 0.571)
0.6	(0.268, 0.439)	(0.205, 0.374)	(0.133, 0.281)	(0.208, 0.358)	(0.299, 0.481)	(0.294, 0.481)	(0.233, 0.418)	(0.343, 0.553)

0.7	(0.285, 0.418)	(0.225, 0.359)	(0.144, 0.259)	(0.222, 0.338)	(0.321, 0.463)	(0.317, 0.464)	(0.253, 0.398)	(0.372, 0.536)
0.8	(0.304, 0.396)	(0.248, 0.343)	(0.157, 0.237)	(0.236, 0.317)	(0.346, 0.444)	(0.344, 0.447)	(0.276, 0.377)	(0.405, 0.519)
0.9	(0.325, 0.373)	(0.276, 0.326)	(0.170, 0.212)	(0.253, 0.295)	(0.374, 0.425)	(0.376, 0.431)	(0.302, 0.355)	(0.443, 0.503)
1	(0.348, 0.348)	(0.309, 0.309)	(0.186, 0.186)	(0.272, 0.272)	(0.406, 0.406)	(0.414, 0.414)	(0.331, 0.311)	(0.486, 0.486)

Note: A1: Degassing tank; A2: Sand filter; A3: Vermifiltration; A4: Recirculation; A5: Facultative pond.

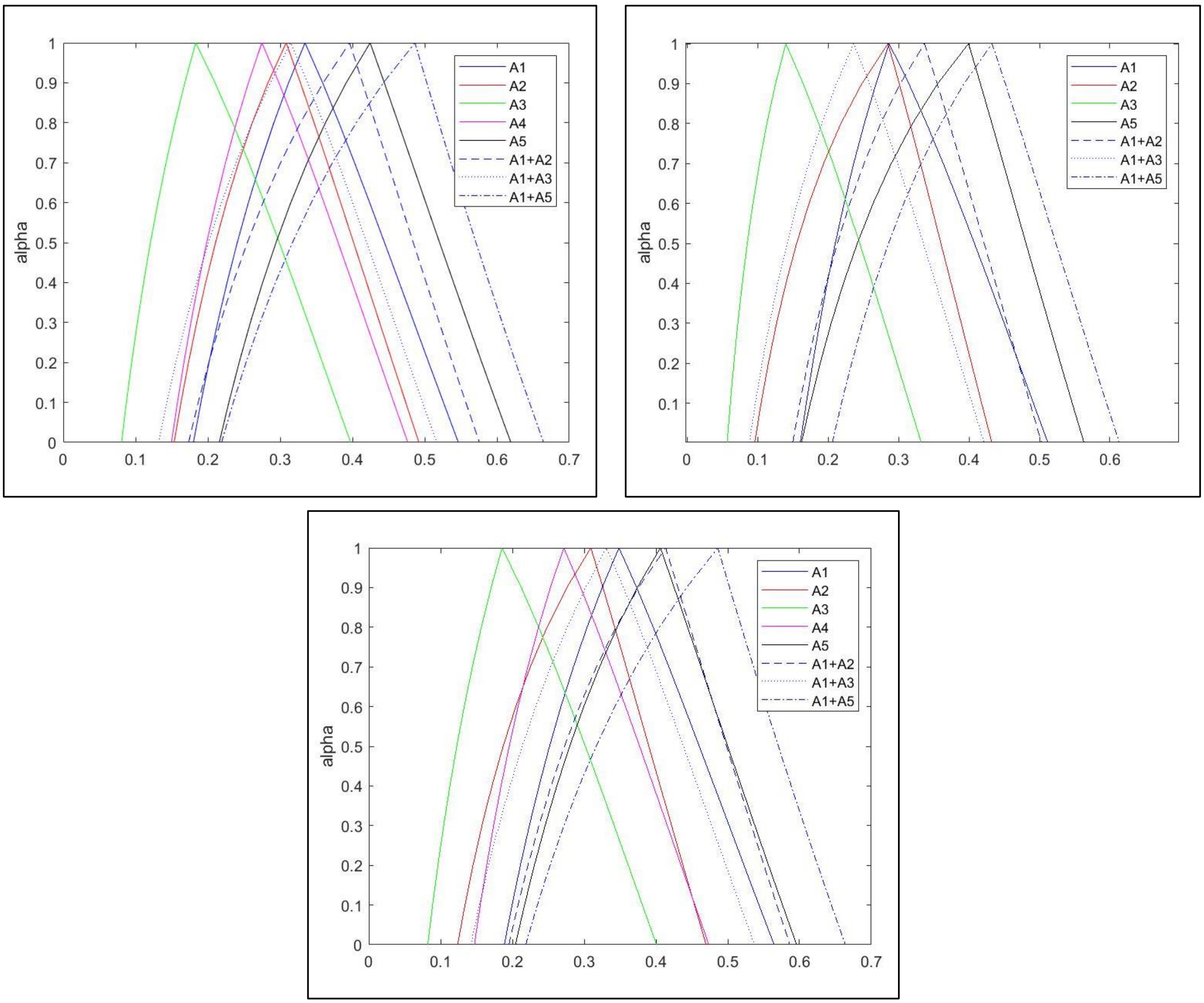

Figure 6.4. Fuzzy numbers of the distance of each alternative to an ideal solution for the case studies CS1 (top left), CS2 (top right) and CS3 (bottom). Note: A1: Degassing tank; A2: Sand filter; A3: Vermifiltration; A4: Recirculation; A5: Facultative pond.

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7. CONCLUSIONS AND FUTURE RESEARCH

This section first concludes the work by reviewing the methodology presented and the work carried out in this PhD thesis, detailing the procedures developed and highlighting the particular outcomes of the results obtained (section 7.1). Then, proposals for further researches in line with the thesis presented are introduced (section 7.2).

7.1 CONCLUSIONS

This PhD thesis had the objective of developing multicriteria procedures considering uncertainty to ensure robust rankings of alternatives able to ease decision-making. These procedures have been applied to the promotion of the development of rural areas through fostering their access to energy services. The work begins with two multicriteria procedures for the evaluation and design, respectively, of electrification projects for rural communities located in Peru and Nigeria. Both studies provide valuable insights for local authorities and other promoters of electrification systems in similar contexts, but allow some room for improvement regarding the robustness of the results. Thus, a methodology for multicriteria decision-making considering uncertainty is developed to include the lack of confidence experts might have when weighting a criterion or evaluating an alternative. This methodology is finally applied to a real case study to robustly select the best alternative for digestate post-treatment before its use in agriculture. Next, the papers included in this thesis are now summarized, with a special emphasis on the main conclusions reached.

Two multicriteria procedures have been developed for the evaluation and design, respectively, of electrification projects for rural communities:

- In the evaluation procedure, nine electrification projects implemented some years ago in six Peruvian communities employing different renewable options for electricity generation (solar PV, wind, micro-hydro or combinations) and distribution (individual systems, microgrids or combinations) have been analyzed. The analysis took into account detailed surveys delivered to technical operators and family beneficiaries of the systems and evaluated the systems according to several sustainable objectives and indicators grouped into 4 dimensions: technical, social, economic and environmental. Results provided special requirements regarding community cohesion and organization, internal knowledge and access to appropriate maintenance and demand flexibility to lead the selection of a design using particular technologies for electricity generation and distribution. Also, the need of an effective management models in which local and national institutions take active support has been detected as essential.
- In the design procedure, a two-phased methodology is presented to elaborate a design of an electrification system for a rural community. First, design alternatives are generated considering different technologies for electricity generation (renewables, diesel or a combination) and

distribution (on-grid or off-grid). Then, a final design is selected according to multiple suitable criteria grouped into 4 dimensions: economic, technical, socio-institutional and environmental. Experts on the field were contacted to particularize criteria weights and contribute to the alternatives evaluation for the particular case study in Nigeria. Results of the case study highlighted the adequacy of off-grid designs based on only solar PV and batteries for communities far from the national grid and with sufficient power demand.

Then, the Methodology for Integrated Multicriteria Decision-making with Uncertainty (MIMDU) is developed to ensure a major robustness of the results by considering the potential lack of confidence of experts and users when asked to weight a criterion or to evaluate one alternative. This confidence's consideration can help to reduce the pressure of the respondents and to penalize an alternative more hesitantly evaluated towards a more robust final ranking. Fuzzy numbers are employed and a systematic procedure has been defined within this study to i) quantify the answers given with uncertainty, ii) obtain numerous rankings of alternatives and iii) provide valuable and complementary information to decision-makers with the comparison of crisp and fuzzy-based rankings in order to robustly choose the best alternative. A generic case example has been used to illustrate the potential of the methodology to consider uncertainty and ease decision-making in any given sector. Also, a sensitivity analysis performed has revealed that increasing the confidence when evaluating an alternative can significantly improve its performance in the final ranking, making the selection easier to a decision-maker.

Finally, MIMDU has been applied to select the best post-treatment for digestate for real small-scale farms in Colombia before its use in agriculture as a fertilizer. Different treatments have been considered: a degassing tank, a sand filter, a vermifilter, recirculating the digestate into the digester, a facultative pond, or combinations of them. To account for an appropriate selection of a treatment, several criteria and sub-criteria have been defined and grouped into 3 dimensions: technical, environmental and socio-economic. Real data from three small-scale farms acting as case studies have been used together with experts' opinions on the field to weight the criteria and evaluate the alternatives considering uncertainty with fuzzy numbers. The use of MIMDU enabled the achievement of more reliable results due to the consideration of the experts' confidence and the alignment of all crisp and fuzzy rankings calculated. In these rankings, vermifiltration stands out as the best alternative, followed by digestate recirculation and sand filter.

Three major benefits can be extracted from the use of MIMDU for multicriteria decision-making in energy problems within rural and underprivileged areas. First, considering the lack of confidence of the respondents can reduce the pressure they might feel when providing an answer without complete knowledge. Second, opinions can be more accurately quantified, modifying the shape of the fuzzy number with the confidence expressed, and clearly identifying an alternative less confidently evaluated with a worse ranking position. And third, more robust decisions can be taken due to the major accuracy in the modelling of opinions and the possibility of comparing crisp and fuzzy-based rankings of the alternatives.

7.2 FUTURE RESEARCH

Multicriteria procedures with uncertainty have been proved along this PhD thesis to provide valuable and complementary information for decision-makers to reach robust decisions in the framework of access to energy. Thus, the work presented establishes a basic knowledge about, among others, how the data coming from experts and users should be gathered, which alternatives and criteria can be of interest when evaluating and designing energy appliances for poor areas, and how to process the input data towards the presentation of robust rankings to ease decision-making. This basic knowledge is pretended to be confirmed and developed further with other problems focused on access to electricity and also in the framework of the water-energy-food nexus:

- Regarding the access to electricity, this thesis has focused on evaluating and designing electrification systems at a community scale. Therefore, a follow-up work can focus on defining the extension of the electricity access over a region with hundreds of disperse communities. This problem arises new interesting questions: to which communities extend the national grid, in which communities implement a microgrid, which sources use, etc. Also, the electrification plan should order the actions taken to extend the electricity access over time, deciding at each point of time which communities electrify and with which configuration. Potential configurations for one community may involve only grid extension, or implementing on-grid or off-grid microgrids, with specific renewable and non-renewable sources. Electrification planners currently available in literature usually focus on ensuring economic and technical feasibility, and omit social, environmental and institutional aspects that have been taken into account in this thesis. At the same time, the opinion of experts and users should be robustly considered to assign higher priority to the most relevant criteria and precisely evaluate the feasible sources and configurations for electricity extension now at a regional scale. This thesis can therefore be a starting point for the development of quantitative methods involving robust multicriteria decision-making to plan the extension of the electricity access to a region of communities.

- The methodology developed in this thesis can be used as a starting point to solve other problems that depend highly on the opinions of stakeholders or final users, since the uncertainty in their responses should be considered. In particular, related to the water-food-energy nexus, the optimization of different parts of the food supply chain can be addressed, from the agricultural field to the final distribution of food to individuals. Such optimization requires a precise modelling of the consumption preferences of the individuals in order to obtain the major waste reduction possible. The role of the food banks in this waste reduction can be specifically studied. In this regard, several specific questions can arise: how much distances can be reduced in favour of a shorter and more sustainable supply chain (from producers to consumers), which is the role of food banks to avoid food waste and efficiently supply to beneficiaries in need, how this whole flow of food should be organized, etc. To answer these questions, not only economic, but also social and environmental issues are increasingly being taken into account due to a major environmental concern of population. In consequence, robust quantitative methods with a multicriteria focus can be developed from the results of this thesis to optimize the processes of food banks within the food supply chain.

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