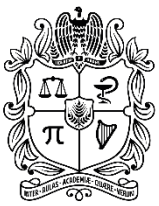

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Modelo de decisión para el diseño conceptual de un sistema de suministro sostenible de energía para la Sede Leticia de la Universidad Nacional de Colombia.

Luis Carlos López Rojas

Universidad Nacional de Colombia

Facultad de Ingeniería, Departamento de Ingeniería Química y Ambiental

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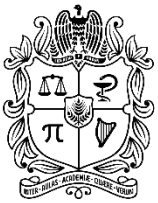

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Facultad de Ingeniería, Departamento de Ingeniería Química y Ambiental

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Don't part with your illusions. When they are gone, you may still exist, but you have ceased to live.

Mark Twain

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Initially, I want to thank God for giving me health and life to be able to complete this master's degree. I would like to thank my alma mater, the National University of Colombia, for providing me with a new opportunity to change, to reborn, to start over through this degree. The teaching assistant scholarship deserves a special mention for the financial support and for allowing me to discover and perform a beautiful vocation as teaching.

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Abstract

Decision methodology for the conceptual design of a sustainable energy supply system for the Leticia Campus of the Universidad Nacional De Colombia.

The decentralized model of energy generation has emerged as a solution to provide electricity to isolated areas, ensuring energy security and increasing coverage. This model frequently leads to a dependency on a unique energy source; thus, it is necessary to change the paradigm of energy generation by adding other more sustainable sources. Unfortunately, there is not a well-defined route to establish which energy sources should be linked and in what way, making this restructuring a very complex problem involving a decision-making process. Generally, decisions are made only considering the economic or technical dimensions, ignoring the other dimensions such as environmental, social, and political, which could provide a more contextualized perspective.

The aim of this study is to develop and test a methodology to find an optimal arrangement of energy sources in a decentralized electricity production model considering all sustainability dimensions. A methodology as the proposed in this work can support the stakeholders during the planning stages of energy supply systems. The methodology was applied to a specific case in Colombia, the campus Amazonia of the Universidad Nacional de Colombia, located in Leticia, a municipality where on-site generators are employed due to the difficulty of access. As a result, the proposed methodology generated nine different scenarios of energy arrangements according to an evaluation of energy sources using a sustainability approach that considered context aspects along with a carefully selected set of indicators and stakeholders' preferences.

Keywords: Energy system design, Sustainability, Multi-criteria Decision Analysis, Decision-Making, Optimization.

Resumen

Modelo de decisión para el diseño conceptual de un sistema de suministro sostenible de energía para la sede Leticia de la Universidad Nacional de Colombia.

El modelo descentralizado de generación de energía surgió como una solución para el suministro de energía en áreas aisladas, asegurando la seguridad energética e incrementando la cobertura. No obstante, este modelo frecuentemente conlleva a una dependencia a una única fuente de energía, por lo que es necesario cambiar el paradigma de la generación de energía añadiendo otras fuentes más sostenibles. Desafortunadamente, no existe una ruta definida para establecer cuales fuentes de energía deben ser agregadas y de qué manera, convirtiendo esta reestructuración en un problema muy complejo que involucra la toma de decisiones. Generalmente, estas decisiones se toman considerando aspectos económicos o técnicos, dejando de lado otras dimensiones como la ambiental, social y política, que podrían proporcionar una perspectiva más contextualizada.

El objetivo de este estudio es desarrollar y probar una metodología que permita encontrar un arreglo óptimo de fuentes de energía en un modelo de producción de electricidad descentralizado teniendo en cuenta todas las dimensiones de la sostenibilidad. La metodología propuesta en este trabajo puede ayudar a los principales involucrados durante las fases de planeación de sistemas de suministro de energía. Esta metodología fue aplicada a un caso específico en Colombia, la sede Amazonas de la Universidad Nacional de Colombia, ubicada en Leticia, un municipio donde generadores in situ son empleados debido al difícil acceso. Como resultado, la metodología propuesta generó nueve escenarios diferentes de arreglos energéticos de acuerdo a una evaluación de fuentes de energía en un enfoque de sostenibilidad considerando

aspectos de contexto junto a una selección cuidadosa de indicadores y las preferencias de las partes interesadas.

Palabras clave: Diseño de sistemas energéticos, Sostenibilidad, Análisis de decisiones multicriterio, Toma de decisiones, Optimización.

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Introduction

Electricity has played an important role in the development of humanity. Since its discovery, it has changed mankind's way of life, becoming a fundamental pillar not only for technological advancement in sectors such as transport and telecommunications, but also in the social sphere, where its inclusion has increased wellness. Nowadays, electric power is the most consumed type of energy in the world. Its consumption has increased year after year due to various factors, especially the increasing population, reaching a level where it is either necessary to produce large volumes of energy, make better use of the existing resources, or explore new methods to meet the demand.

Since the 20th century, energy has been commonly generated in large power plants, from where it is transferred to consumers through transmission and distribution networks. Despite the growth of electricity production, because of the model previously described, there is not full coverage of this service worldwide, particularly in rural areas of countries with high poverty index. It has generated a global social problem since electricity is required to satisfy basic needs including food, water, health, and education. In this regard, Colombia is not the exception, and there are zones where the electricity distribution network does not have enough capacity. These zones are known as Non-Interconnected Zones (ZNI).

In order to overcome the problem of electricity supply in ZNI, on-site generators are used around the world to generate energy in these isolated areas, leading to a new way to supply electricity, denominated as decentralized. The main advantage of this alternative is that power generation units are close to the consumption points, increasing coverage. Unfortunately, most of the decentralized generators use fossil fuels, releasing a high amount of greenhouse gases (GHE), causing a huge environmental impact and, in parallel, leading to dependency on a single fuel with limitations on energy accessibility due to the availability of these sources. In addition, the transport costs associated with these fossil fuels increase the price the users have to pay to obtain that public service, reinforcing inequity and poverty.

Thus, the current approach to change the paradigm of energy generation is to increase the production capacity of renewable energies by taking advantage of natural resources in a specific region, allowing policymakers and energy companies to modify the energy matrix with the addition of new sustainable sources. Different worldwide initiatives have been implemented in this way to increase the coverage of this service, besides improving efficiency in energy spending, reducing pollution, and meeting the requirements of demand with a view to ensuring future energy security. Nonetheless, an adequate infrastructure must be available to fulfill this function, able to answer specific demands related to the territory of emplacement.

Restructuring the energy matrix seems to be a decision-making problem where it is essential to establish which energy sources should be linked and in what way, considering economic, environmental, and social factors. Unfortunately, there is still no defined route to take since each case has a set of specificities that make it singular because of its high dependence on the social, political, economic, and environmental context.

The above arguments lead to think that determining an optimal arrangement of technologies and their operating scheme is crucial in the design of an energy distribution system.

Thus, finding a method to define a sustainable energy matrix is essential. Nevertheless, most of the studies in this field are focused on new technological developments to improve performance or on seeking new alternatives for energy production. In some cases, it is stated that a combination of various energy sources could lead to new benefits by exploiting the advantages of each form of energy to counteract the disadvantages of another to have an improved supply system, either with lower costs and emissions or with an increase in system efficiency. However, these decisions are mostly supported from an economic or technical point of view, ignoring other dimensions such as environmental, social, and political, which could provide a more contextualized perspective.

Therefore, the aim of this study is to propose a methodology to find an optimal arrangement of energy sources in a decentralized electricity production model with

sustainability criteria, facing the current lack of methodologies to help the decision-making problem associated with energy planning. The approach of this methodology is purely conceptual and will be a support tool so that the stakeholders can apply it in the planning phases of energy supply systems to understand, evaluate, and finally decide what is most convenient for the sake of having a design that satisfactorily and sustainably responds to the demands. As case study, the methodology was applied to the campus Amazonia of the Universidad Nacional de Colombia, located in one of the major cities of the Non-Interconnected Zones of Colombia, the municipality of Leticia, the capital and largest city of the department of Amazonas.

The conception and application of the proposed model are presented in this document. Some important concepts are introduced in the first chapter in an effort to give the reader context to better understand what is exposed throughout the entirety of the document. The second chapter describes the state of the art related to energy design problems based on similar publications around the world along with Colombian context. Later, in the third one, the methodology designed and implemented to define the approach and the variables considered in the development of the proposed model is exposed. The fourth chapter emphasizes the context of the case study, giving an insight into the situation of the municipality of Leticia as well as the campus of the National University of Colombia. There, energy demand and potential in renewable energies are estimated. Finally, the model proposed for the contemplated case study is applied in the fifth chapter, illustrating how it works and leading to a discussion about the outputs produced: various scenarios were generated using the model depending on stakeholders' preferences, and a description as well as an analysis of the operating schemes is included. Once the research findings are reviewed, a reflection is made to recognize the contributions according to the results; likewise, certain conclusions and possible perspectives are presented with a view to carrying out future work that could upgrade the scope adopted in this study.

As a result of this work, a research internship was carried out in the ERPI (Équipe de Recherche sur les Processus Innovatifs) group of the University of Lorraine and an oral presentation was given at the 2020 AIChE Annual Meeting.

1 Conceptual Framework

1.1 Needs Analysis

The definition of need is essential in order to implement needs analysis. Need is commonly defined as a gap between the current conditions and a desired condition as shown in Figure 1-1 [**1**]. Needs help to guide the decision process, and they determine what actions should be implemented to achieve a result which could be material or immaterial [**2**].

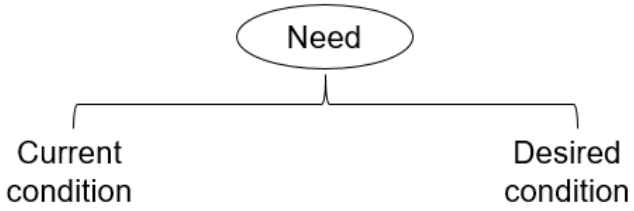

Figure 1-1. Need definition [**2**].

One of the first researchers who studied the notion of need was Abraham Maslow. He proposed a hierarchy of needs with the Maslow's pyramid, ranging the basic or lower order needs (food, water, shelter), through the higher order needs such as safety and belonging needs, rising with recognition needs and self-actualization [**3**]. Maslow also stated that lower needs should be attempted before passing to the higher needs in a linear way.

A need arises if any of the following occurs [**4**]:

- Need of addition: Non-existent resource whose establishment has a positive impact on the system.
- Need of improvement: Not satisfying resource whose improvement is appreciated by people.
- Need of substitution: Replacement of an existing resource by something new, more interesting, and more efficient.
- Need of fusion: Gather existing elements to achieve a new product with a defined function.

A need can be perceived (what individuals feel), requested (what individuals desire), mandatory (demanded by standards, regulatory entities) or comparative (resulting from comparison with other fields or contexts). The satisfaction of a need leads to a good performance of the activities, keeping or even improving the level of the results; on the contrary, the failure to satisfy a need can lead to a malfunction in the activities, which has negative consequences on performance. Thus, there is dependence between performance and need [**5**].

To satisfy a need, a solution can be selected to close the gap. For example, initiatives as human learning, training and performance apparently are the solution to achieve it. However, experts agree that this process should begin with a needs analysis [**1**]. Needs analysis or needs assessment is a process for figuring out how to close learning or performance gap, this process includes comparing the current condition to the desired condition, determining how specific behaviors or mechanisms can be changed to achieve the desired condition. It is a systematic process to guide decision process with the aim of making better decisions [**2**].

Since the 1960s, needs assessment has become a common business practice [**2**]. Needs analysis associates data to view a situation from the full spectrum, identifying problems or opportunities of interest to build relationships among people who are interested in the issue and intending to negotiate among different points of view. It also provides the first step for the subsequent improvement actions, prioritizing needs, aligning resources with strategy, sharing knowledge and resources clarifying the scenario for decision making

process to help the decision makers to create solutions that are practical, credible, and appropriate for the situation [**1**].

In the same way, needs analysis identifies appropriate interventions, influence points, and resources for making changes: establishes objectives for initiatives, prioritizes actions, determines who must be involved to be successful, and provides data for evaluations aimed at addressing those needs. As a result, needs are identified with a better understanding of the existing context, the reason why there is an improvement on the quality of the decisions. Many actions could be implemented from needs analysis such as new initiatives, engage people, enhance work design, supply tools or technology or implementing learning programs which will be better targeted and aligned with the needs [**1**,**2**].

Determining needs is a subjective process as different people have different visions of what is required. If several stakeholders such as community members, or subject experts are involved in the needs analysis a full range of deficiencies will be identified. In addition, the tools can offer a replicable model that can be applied in similar scenarios either by novices or experts using the lessons learned from previous decisions or independent systems with an identical approach [**2**,**5**].

1.2 Decision Making Process

Decision-making can be associated to a cognitive process where, for various reasons, it leads to a path or response. In the search to ensure the best results, during the Second World War a discipline called operations research emerged. That discipline is responsible for applying various methodologies to be able to choose the best scenario, considering the implications of all factors in a logical way. Operations research proposes conceptual models to know and analyze any situation, to then allow the decision makers to understand, evaluate, and finally decide what is most convenient for each case, all with the support of mathematical models and simulation tools [**6**]. Today, this discipline is applied in different fields, including project management, logistics, finance, computer science, process design, among others [**7**].

To solve an operations research problem, it is necessary to use decision models. These are mathematical or theoretical descriptions of a set of variables that together represent an entire system [**6**]. Many of these models are solved analytically or using optimization tools, so they include an objective function, decision variables, and constraints. A good decision model should provide as much information as possible in the simplest way to understand the problem as easily as possible. Thus, a suitable approach could be defined to find the solution [**7**].

1.3 Multi-Criteria Decision Analysis (MCDA)

Multiple-Criteria Decision-Making (MCDM) or Multiple-Criteria Decision Analysis (MCDA) is a branch of operations research which deals with decision problems under the presence of a number of decision criteria [**8**,**9**]. It describes several methods developed for aiding decision makers in reaching better decisions [**10**]. These methods organize and structure complex and uncertain decision-making problems characterized by multiple objectives, different forms of data and information related to various interests and perspectives [**9**,**11**,**12**,**13**].

Hence, a multi-criteria decision problem essentially consists of a set of alternatives that are evaluated on the basis of criteria (often diverse and conflicting) and according to decision maker preferences, there is not a single solution; generally a compromise among the dimensions involved in the decision process is required [**9**,**10**,**14**]. In most of the cases, different groups of decision-makers are involved in the process. For example, a utility company may be more concerned with the plant performance and return on capital whereas a community group that uses the utility might be more concerned with social, economic and environ-mental impacts [**15**]. Each group brings along different criteria and points of view, which must be resolved within a framework of understanding and mutual compromise. The best alternative is usually selected by making comparisons among alternatives with respect to each attribute [**9**].

MCDA methods are frequently used in the decision processes [**12**]. The reason for using the statement “decision analysis” is to emphasize that the methods cannot make decisions. In contrast, the aim of MCDA methods is to help decision makers feel

comfortable and confident so that they make better decisions, reducing the post-decision regret [**10**].

In general, any multi-criteria decision problem includes four stages: first, the alternatives are formulated; second, a set of criteria is selected and data related to these criteria are collected and, if required, indicators are calculated; third, criteria weights are determined to show the relative importance of each one, and finally, the alternatives are ranked and ordered by MCDA methods with criteria weights [**13**]. The detailed steps in undertaking MCDA are presented in Figure 1-2.

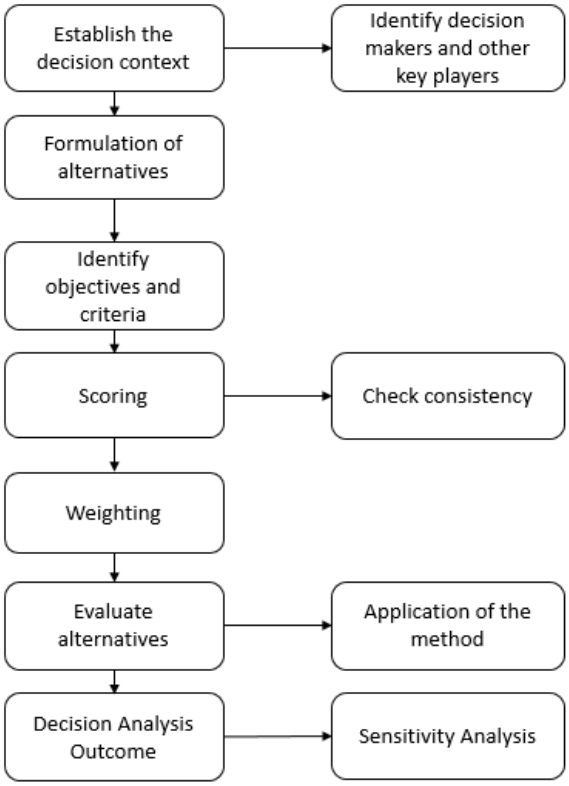

Figure 1-2. Series of action involved in MCDA process.

Scoring and weighting are two important steps in MCDA. The first refers to the assessment of the expected performance of each option/alternative against the criteria [**16**], while the second is relative to the importance of each criterion compared with the others reflecting their relative significance in the decision [**9**]. Three factors are usually

considered to obtain the weights: the variance degree of criteria, the independency of criteria, and the subjective preference of the decision-makers [**13**].

MCDA approach can deal with many problems on different fields. In this regard, Cajot [**12**] made a classification related to the type of solution found by the methodology:

- Choice problem: Selection of the “best” alternative, by reducing the set of alternatives to a smallest subgroup.
- Sorting problem: Classify alternatives according to predefined categories, helping the decision maker to know which treatment to give to the grouped alternatives.
- Ranking problem: List the alternatives by order of preference.
- Portfolio problem: Choose a subset of alternatives and account for possible interactions between them.
- Design problem: Propose new solutions based on the knowledge gained from the MCDA process.
- Description problem: Identify the paths where the problem could be achievable.

Many arguments exist to use MCDA as a tool to obtain a satisfying decision-making result. The first advantage is the use of multiple criteria which allow the decision makers to evaluate a wider range of objectives [**13**]. Second, it could solve conflicting interests reaching compromises in a simple way, synthesizing multiple aspects in a single decision output [**15**]. Third, promotion of public participation in decision-making processes by the inclusion of multiple stakeholders facilitating multidisciplinarity, and finally, MCDA can also handle and aggregate qualitative and quantitative information [**12**,**15**]. On the other hand, MCDA has some drawbacks, particularly, the dependency of the results on the method selected to perform the assessment, a subjective factor included in the decision maker preferences, and the difficulty to quantify environmental or social impacts [**17**].

There exist numerous MCDA methods. According to some studies, there are nearly 30 different MCDA methods that can be applied in varied problems [**12**]. The most common are shown in Table 1-1. However, considering the new computational developments, other methods are becoming popular, for example, multi objective programming and fuzzy methods [**9**].

Table 1-1. Most common MCDA methods [**18**].

Method	Author(s)	Year
Weighted Product Model	Bridgman	1922
ELECTRE	Benayoun et al.	1966
Weighted Sum Model	Fishburn	1967
AHP	Saaty	1970
TOPSIS	Hwang & Yoon	1981
MAUT	Edwards & Newman	1982
PROMETHEE	Brans & Vincke	1985
VIKOR	Opricovic	1998

MCDA methods could be categorized in many ways. Regarding a classification proposed by various authors [**10**,**12**,**19**], the methods are divided in five categories as presented in Table 1-2.

Table 1-2. Classification of MCDA methods [**12**]

Category	Fundamental	Examples
Value measurement models.	Assign numerical scores to each alternative by aggregating criteria and weights	Weighted Sum Approach (WSM) or Analytical Hierarchy Process (AHP)
Goal, aspiration, and reference level models.	Goal programming	Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS)
Outranking models.	Distinction of alternatives in a pairwise fashion for each criterion.	ELECTRE
Multi-Objective Decision Making (MODM)	Programming and optimization techniques to make the best choice	Multi-objective linear programming (MOLP)
Other	Other techniques developed	Fuzzy set theory (FST)

Literature does not discuss which method is most suitable for each case. No single MCDA model can be ranked as the best or the worst [**12**]. Every method has its own strengths and weaknesses, so it is not possible to affirm that one of the methods is generally more suitable than the others. As a consequence, the choice is made depending on its application because different methods will probably give different recommendations [**10**,**18**]. Unfortunately, selecting appropriate methods for different problem types is still an open research question [**12**]. It could be said that it is a multi-criteria problem [**10**], where the existence of multiple MCDA methods suggests a growing in the research area, but at the same time decreases the ease of choosing one by novices [**12**].

The main argument to choose a MCDA method is the perceived popularity. The second most frequent argument is simplicity, which was also expressed as user-friendliness or intuitiveness. If the decision maker does not understand what is happening inside the methodology, there is possibility of mistrust making meaningless applying this method [**10**]. The third is the ability to handle qualitative and quantitative values. Those arguments explain the reason why AHP, WSM, TOPSIS, and VIKOR are very popular and indicate that decision makers prefer to trust a method that has been intensively studied and applied by peers [**12**].

Some authors identified a possible solution for facing the problem of method selection, with the combination of methods to tackle a similar problem taking advantage of one to afford the weaknesses from the other [**10**,**20**]. Despite, the majority of studies rely on a single main MCDA method, there is a growing trend to combine several methods [**9**,**18**].

1.3.1 MCDA and energy planning

Nowadays, many problems related to energy production and supply have led to a new trend towards the diversification of the energy matrix with the inclusion of renewable energy sources. Unfortunately, there is not a well-defined route to establish which energy sources should be linked and in what way. The decision makers sometimes judge the feasibility based on only one criterion, which may lead to the improper scheme [**21**]. Multi-Criteria Decision Analysis (MCDA) techniques are gaining popularity in energy planning because they enable users to better understand the decision problem, negotiate, communicate preferences, and make decisions more explicitly and rationally [**10**,**19**].

MCDA methods has been successfully used in energy planning processes and are considered as one of the most suitable methods for solving issues related to energy [**18**]. In energy projects, these methods have succeeded because they manage numerous scenarios with multiple criteria, sometimes implying a high degree of uncertainty and incommensurable units [**9**,**18**]. The main energy issues addressed using MCDA include energy planning and selection [**22**,**23**,**24**,**25**,**26**], energy resource allocation [**27**,**28**], energy exploitation [**29**,**30**], energy policy [**31**,**32**], building energy management [**33**,**34**,**35**], transportation energy systems [**36**] and others [**9**,**13**].

1.4 Sustainability Triple Bottom Line (TBL)

Few works were made in planning of energy systems before the oil crisis in the 1970s. This event boosted studies to find new ways to produce energy in an efficient way. However, most of the studies were only based on cost minimization. In the 1980s, society became more aware of environmental issues [**9**,**10**], and as time passed, the studies included other criteria, resulting in the first definitions related to the sustainability concept, such as sustainable development, defined in 1987 by the United Nations as the "development that meets the needs of the present generations without compromising the ability of the future generations to meet their own needs" [**37**]. Likewise, the Triple Bottom Line (TBL) was proposed by Elkington in 1997 [**38**] as a new framework expressing the need of expansion of the development in a way working on economic, environmental and social lines measuring the performance of new processes in these aspects [**39**].

Recently, the Triple Bottom Line was reformulated to propose the Triple Bottom Line Extended (TBL+), as an attempt to broaden the scope including the political and technological dimensions, which have become important in the last years [**40**]. Despite the majority of studies on energy planning are based on technical or economic criteria, being cataloged as "reductionist", there is a new trend trying to integrate environmental, social and political considerations, giving a perspective from the point of view of the communities who are the most interested and affected for these developments. Within this new trend, energy planning aims to find environmentally friendly, institutionally sound, socially acceptable and cost-effective solutions of the best mix of energy supply and

demand options for a defined area to support long-term regional sustainable development [**12**].

1.5 Optimization Overview

Since the beginning of its existence, humankind has sought the best option. The process of search the optimal or optimum to a problem is known as optimization. This word comes from the Latin word *optimus,* which means best. An optimization process involves the maximization or minimization of a function representing the performance of some system; this process is carried out by finding the values that lead to an optimal value [**41**]. The objective function is usually subject to different constraints that define the possible values of the optimization variables.

The general representation of a typical optimization problem is:

$$\min f(x)$$

$$subject\ to \quad h_i(x) = 0, \quad i = 1, \dots, \dots, m$$

$$g_j(x) \leq 0, \quad j = 1, \dots, \dots, p$$

Where f(x) is the objective function, $h_i(x)$ are the equality constraints and $g_j(x)$ the inequality constraints. Additionally, m and p are the quantity of equality and inequality constrains respectively. By convention, the standard form defines a minimization problem; a maximization problem can be formulated negating the objective function.

In the case where the vector X satisfies all the constraints, it can be said that the vector is a feasible point. The combination of all feasible vectors is a feasible region, here, represented by S. The solution to this problem is a vector called optimum and is written X* and it must satisfy the next condition:

$$f(X^*) \leq f(X) \quad \forall \quad X \in S$$

There are optimization problems in all disciplines, particularly computer science, engineering, economics, etc. Also, in mathematics the development of new solution methods has been a subject of interest in research.

1.5.1 Multi-objective optimization

Optimization has become a major research area in science and engineering. It has evolved from a methodology of academic interest into a technology with significant impact in industry [**42**]. Nowadays, in science and engineering, many problems demand a simultaneous optimization of more than one function objective, resulting in what is known as multi-objective optimization.

Usually, in multi-objective optimization, there should be one solution that satisfies the different objective functions. However, no element produces an optimal value for both objective functions. This condition occurs due to the presence of conflicting objectives; the improvement of one of them leads to a worsening of another one. Therefore, a compromise situation must be reached, in which all the objectives are satisfied to an acceptable degree, from the design point of view. Unlike single-objective optimization problems, the concept of optimum is now relative, and it will be necessary to decide what is the best solution (or the best solutions) to the problem.

The mathematical formulation of multi-objective optimization is:

$$\min(f_1(\underset{x}{\rightarrow}), f_2(\underset{x}{\rightarrow}), \dots, f_n(\underset{x}{\rightarrow}))$$
$$s.t \quad \underset{x}{\rightarrow} \in X$$

Where:

- n is the number of objective functions, n ≥ 2.
- $\underset{x}{\rightarrow}$ is the decision variable vector, $\underset{x}{\rightarrow} = (x_1, x_2, \dots, x_r)$
- X is the feasible set of decision vectors, it also considers constrains $g_j(x) \leq 0$, $j=1,2,\dots,m$ and $h_i(x) = 0$, $i = 1,2,\dots,p$.

As previously explained, there is no feasible solution that simultaneously minimizes all objective functions. As a result, the concept of non-dominated or Pareto optimal solution must be introduced. A Pareto optimal solution is one that cannot be improved in any of the objectives without compromising at least one of them.

In mathematical terms, a feasible solution $\underset{x_1}{\rightarrow}$ dominates the solution $\underset{x_2}{\rightarrow}$, if it meets the two next conditions:

$$f_i(\underset{x_1}{\rightarrow}) \leq f_i(\underset{x_2}{\rightarrow}) \quad \forall \ i$$
$$f_j(\underset{x_1}{\rightarrow}) \leq f_j(\underset{x_2}{\rightarrow}) \quad \forall \ j$$

The Pareto front or Pareto frontier is given by the set of the objective functions in the solution space whose vectors $f(\underset{x}{\rightarrow})$. From the mathematic point of view, all Pareto optimal solutions are considered equally good, for that reason, once the optimization has been completed, a subjective preference choice should be made by a human decision maker to satisfy the different objectives [**43**].

1.5.2 Multi-period optimization

Many problems could be solved considering one-period concept. However, this kind of formulations disconnect the possible future affectations and, sometimes, the decision makers need to make decisions at more than one point in time, specially, knowing that decisions made during the current period influence decisions during future periods [**7**].

In the traditional industries, processes operate with invariable streams, but this is not the case for processes involved in the agricultural or food industries due to the prevailing seasonal variations [**44**]. In these cases, a new problem appears. It consists of determining how many units must be produced, and, of course, the answer changes if there is a fluctuation in demand. In one case, the production could not be enough, or, on the contrary, there would be an extra production that could be used at another time. These interactions can be represented very easily with optimization models, resulting in an important branch known as multi-period optimization [**7**,**45**]. This approach minimizes the impact of change over time by anticipating production and storing products for future periods.

Multi-period models for planning over time represent the real world by partitioning time into a defined number of periods. These periods are normally linked by an inventory variable such as a transfer of material between periods. In the same way, it should exist constraints related to this condition, the most important is the called “material balance”

whose definition is “beginning inventory + production = ending inventory + goods sold” [**45**].

Multi-period models are solved in a “rolling” format, so the model is solved at the beginning of each period, once the solution of the first period is found, the model slid forward to the next period using the information previously obtained to solve all equations and so on until the whole process is solved [**45**].

Sometimes multi-period operation is confused with batch operation but they are different, multi-period is an approach to find the best answer to occasional external changes, for example demand, in contrast, the batch operation is related to the nature of some process that could not be carried out in continuous, here, a process involving charge, execution and discharge is repeated as many times as required [**44**].

2 State of the art

2.1 Background

2.1.1 World Energy Outlook

The development of society is linked with the understanding of elements that nature places at disposal and their possible transformation to make a better use [**46**]. Since its discovery, electricity has changed mankind way of life, becoming a fundamental pillar not only for technological advancement in sectors such as transport and telecommunications, but also in the social sphere, where its inclusion has increased the wellness. Nowadays, it is difficult to conceive a life without electricity. Most of our daily actions at industrial, commercial, and residential levels depend on its use.

Electricity is the most consumed type of energy for several reasons, including its low production and maintenance costs and its high versatility to be transformed into other types of energy with high efficiencies. In the same way, the flexibility in storage, easy transportation and distribution over long distances, and simple control make it ideal to be the source of energy used globally [**47**,**48**].

Worldwide, energy consumption has almost quadrupled in the last six decades [**46**]. Year after year the consumption of electrical energy has increased reaching a total consumption of 25,027 TWh for 2019 according to the International Energy Agency [**49**]. To meet this need, humankind made use of large-scale exploitation of natural resources (particularly, non-renewables), reaching a world population coverage with electric energy of 89.59%, as estimated by World Bank [**50**]. Despite this fact, coverage has not reached some places, especially in rural areas of countries with high poverty index, generating a global social problem because electricity is required to satisfy basic needs as food, water, health, and education [**51**]. Issues such as growing population demand and high

dependence on fossil resources, whose high environmental impact and limited availability are becoming evident (most of these fuels will be depleted within about 100 years [**15**]), have led to a rethinking of the energy industry, trying to restructure it towards the use of more sustainable and environmentally friendly energy sources in order to mitigate the existing impacts [**13**,**52**]

A new way for energy supply has been the subject of wide-ranging discussion and debate within government, non-government and academic circles, being a major focus of national and international agendas [**13**], concluding that evolution on energy supply implies a growing intervention of the public entities [**46**]. Consequently, many initiatives have been proposed, including the Rio Declaration (1992) that established 27 principles intended to guide countries in future sustainable development [**53**], the Kyoto Protocol (1997) that commits states to reduce greenhouse gas emissions [**54**], the Paris Agreement (2016) with the aim of keeping the global temperature rise below 2°C [**12**,**55**], the United Nations (UN) 2030 Agenda for Sustainable Development (2015), where one of its 17 objectives is ensuring access to affordable, reliable, sustainable and modern energy for humankind, promoting policies for sustainable use and production from renewable sources [**56**] and finally, Stockholm+50 (2022), a meeting that aims to accelerate a transformation that leads to sustainable and green economies, more jobs, and a healthy planet for all [**57**].

The energy sector has currently profound changes facing the new challenges generated by these actions, with many countries trying to decrease their energy demand, reduce dependency on fossil fuels, and increase the share of decentralized and renewable energy [**12**]. As a result, most of the countries are transforming their infrastructure, industries, and economies, impacting all sectors of society.

In the case of Latin America and the Caribbean, the region stands out at the international level: 30% of total primary energy comes from renewable sources, a high value compared to the 9% from the OCDE countries. Despite the significant share of renewable sources in primary energy, the proportion of renewable sources in electricity generation decreases to 17%. This level of participation has two characteristics that could influence the evolution of electricity systems in the region. First, the development of resources and technologies has been concentrated in two renewable energy sources: large-scale hydroelectricity and

biomass. Second, development of renewable sources has been particularly successful in some countries, but it is still latent in others, creating a heterogeneous degree of advancement of renewable energies in the region [**58**].

The countries of South America recently experienced a period of dynamism and now are contemplating higher energy autonomy with respect to the industrialized countries, all with the expectation of becoming a competitive economic region worldwide. For this, the Latin American Energy Organization (OLADE) pointed out the region must strengthen its planning bodies, so that they can guide the required investments according to an integrated concept of use of resources based on economic, political, social, and environmental goals, formulating energy policies in the search of sustainability incorporating the objectives set at the global initiatives. This new energy policy must evaluate different options to satisfy energy requirements. This evaluation should be based on available national resources and the eventual energy imports, considering aspects such as: energy efficiency, the role of new and renewable sources, technological development, access to energy, investment guarantees, diversification of sources and minimization of negative environmental effects [**46**].

2.1.2 Colombia Energy Outlook

Colombia has a diversified energy production with significant surpluses for export (especially oil and coal). In 2015, primary energy had a production of 141,990 ktoe/yr from which 92,261 ktoe/ yr (65%) were exported and the remaining is used in domestic supply [**59**]. A high portion of the 39,673 ktoe/ yr in the domestic market is transformed into petroleum derived fuels and electricity. This transformed energy with the initial non-converted fraction, lead to a final domestic consumption of 29,655 ktoe/yr where transportation sector represents 39.8% of total consumption, industrial sector the 26,39% followed by residential sector. There is a high difference before and after of transformation stage, in part, due to the own efficiencies of the processes, but also with non-technical losses such as theft, pipeline losses, illegal connections to electricity distribution lines and difficult to manage isolated areas or with armed conflict [**59**].

Regarding electricity, it is produced mainly through hydroelectric and thermal power plants. These facilities generate 71% and 28% of the total respectively, while 1% of the

energy is generated by wind and cogeneration plants [**60**]. According to the UPME (in English: Energy Mining Planning Unit of Colombia), 69,701 GWh of electricity were generated for 2019 [**61**]. All this energy is distributed in the country using the SIN (in English: National Interconnected System), which includes generation plants, interconnection, transmission, and distribution networks. Nowadays, SIN covers most of the country's demand. The Colombian electricity information system reported a national general coverage of 97.02%. This value is an average, but, if the data is disaggregated, the coverage in urban areas is 99.72%, while for rural areas is 87.81% [**62**].

Despite this coverage value, 427,693 homes do not have any energy service [**62**], some of them are located in the ZNI which are the cities, municipalities, townships or hamlets not connected to the SIN. The ZNI represent approximately 52% of the Colombian territory and there is an estimated population of 1.9 million inhabitants. These areas are the furthest from the major cities of the country, mainly located in border, coastal and insular areas. A map showing the location of these areas within the country is shown in Figure 2-1.

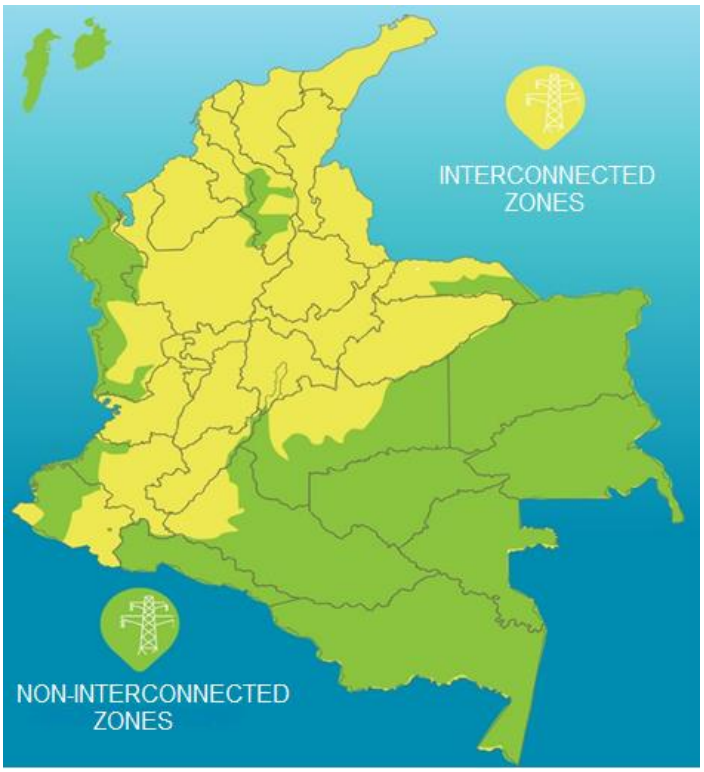

Figure 2-1. Non-Interconnected Zones in Colombia. Source: Acolgen

The main characteristics of the ZNI are [**63**]:

- Low population density (3 people/km^2)
- 71% of basic needs are unsatisfied.
- Low average electricity consumption level (essentially lighting and home appliances)
- Low ability of users to pay.
- High levels of energy losses.
- Low level of measurement accuracy.
- Biodiverse areas with the presence of ethnic communities.

These attributes combined with the deficient mobilization infrastructure and fragile political and socioeconomic conditions become logistics services complicated increasing investment and operating costs, making unattractive for private investors develop the required infrastructure, since their investment is high, and their profitability is low. Therefore, the ZNI have local generation services, usually based on diesel generation plants [**64**]. As a consequence, the cost to the final consumer is higher compared to other areas of the country connected to the network, even being 2 or 3 times higher. This elevated price makes necessary the intervention of the state helping with subsidies so that the inhabitants can pay for the service.

The Law 697 of 2001 states that rational and efficient energy use is a matter of social, public, and national interest. The ZNI situation motivated the Colombian government to propose new strategies to supply energy to these zones; multiple projects had been formulated with the aim of improving the quality of life of the people who live there. The target is the provision of the service, which tries to bring energy 24 hours a day to municipal capitals and larger towns, stimulating power generation schemes with unconventional energy sources and hybrid systems through alliances with public and private investments [**65**]. Some important actions to achieve this objectives are the creation of the IPSE (in English: Institute for Planning and Promotion of Energy Solutions for Non-Interconnected Zones), PROURE (in English: Program for Rational and Efficient Energy Use and Non-Conventional Energy Sources), FAZNI (Financial Support Fund for the Electrification of Non-Interconnected Zones), whose objective is to assure the resources for the construction and installation of the new electric infrastructure and rehabilitation of the existing, in order to implement sustainable and efficient energy

solutions, assuring access to communities with the promotion of the use of renewable energies. Likewise, Law 1715 of 2014 regulates the integration of renewable energies into the national energy system and the 2020-2050 Colombia national energy plan, describes the short, medium and long-term scenarios to improve access to energy in the country, which includes the promotion and use of renewable energies [**64**,**66**].

Currently, in Colombia there is not an applied methodology for selecting the most convenient energy alternative for a particular area, especially for ZNI [**67**]. The lack of studies and real measurements of the energy potentials of these areas makes it difficult to plan projects aimed at supplying energy by methods other than conventional ones. Therefore, the strengthening of a research and technological development plan on areas such as energy management, distributed generation and smart grids is mandatory to obtain the required information to start new power generation schemes on isolated areas.

2.1.3 Distributed Energy Systems (DES)

Since the 20th Century, energy has been commonly generated in large power plants, then transmitted and commercialized to consumers through huge transmission and distribution networks. This strategy of energy generation fulfills the demand in large population. However, it leaves the most remote regions without any system of electrical interconnection, difficulties in adapting technologies related to new energy sources, problems in expanding existing networks, high network congestion and even the risk of destruction by natural disasters or outlaw groups are giving way to a new trend in energy delivery that will permit to expand the coverage to the most isolated zones, the decentralized or distributed [**68**]. In that trend, energy generation units are close to the points of consumption, opening the possibility for buildings or even small regions to become completely self-sufficient without being part of any system [**69**] because of the increasing diffusion in recent years of various small-scale technologies for distributed generation [**21**]. Additionally, several advantages had been identified working in this way, including increased participation of locals, more agile responses to opportunities and threats, more personal investment and a clearer link between local consumption and generation [**12**].

Within this new approach emerge the *Energy hubs*, which aim to provide energy and services in a decentralized manner, maintaining a single unit capable of transforming, converting and storing various forms of energy, all through the use of various energy carriers [**52**,**70**]. Until now, conventional structures use each source independently. However, a combination of several sources could lead to new benefits by exploiting the advantages of each form of energy in order to have an improved supply system, for example, with lower costs and emissions, or by an increase of reliability and system efficiency, fulfilling local requirements [**52**,**64**,**71**].

To make new energy systems more sustainable, it is necessary to change the paradigm of energy generation by diversifying the energy matrix with local renewable energy sources [**69**]. Coupling different energy carriers means letting them act simultaneously, so there should be an adequate infrastructure has to be available to fulfill this function, capable of responding specific demands. Despite this, there is not a well-defined route to establish which energy sources should be linked and in what way. Therefore, solving this question is essential to give an indication of a proper configuration or operation scheme, concluding that restructuring the energy matrix is a new and very complex problem faced by policy makers, investors, among others which involves a decision-making process in order to compare between different options [**15**].

2.2 Related Studies

Many research efforts have been carried out focused on the search for technological solutions in energy supply issues as well as on the integration of renewable sources in energy systems. This is a very extensive research and development topic that can have different approaches, one of them is MCDA, evaluating diverse energy sources or proposed systems using qualitative or quantitative indicators. Some authors have conducted reviews about MCDA application in energy planning. These reviews emphasized on the existing methods, making an extended explanation of the main characteristics, analyzing the applicability and the rationales behind their choice. In summary, MCDA is well-suited for energy planning problems; however, the key problem to choose which the most suitable of the multitude methods [**9**,**10**,**12**].

The other path is modeling and optimization. In that, studies are oriented to develop or apply models, methods and software to find the best alternative under given constraints taking into account factors such as costs, emissions and performance [**71**,**72**]. Some applications in modeling are the understanding of the various renewables technologies and systems. Optimization could be applied to activities as sizing, operation and control, maintenance and scheduling activities with decision making situations involving renewable sources. A sizing problem deals with the kind and capacity of installations that can be employed to achieve the predetermined results, confirming that it meets all the necessary constraints in the best possible manner, whereas operation and control deals with the placement on the distribution network minimizing transmission losses and with a delivery of maximum quality power to the load, providing the strategy which works at the with ideal configuration to meet the demand [**71**].

Although there are many studies on topics such as MCDA applied to energy planning and in modeling and optimization of energy systems, there are very few that combine both topics. It should be deepened in those that not only use these topics in a combined way, but also those which include aspects of current interest such as local systems with multiple energy carriers [**10**], social and environmental aspects focused on remote territories or regions where the results obtained could be of great use as a first approach to energy transformation [**67**].

2.2.1 Studies applied in countries different to Colombia

Many models studying the implementation of energy supply systems at different scales considering multiple energy carriers have been developed. Concerning the application of combined MCDA with optimization for the design of sustainable energy systems, the subject has gained strength and is still in development, the most relevant works using the previously mentioned approach are presented. Gabrielli et al [**73**] proposed a new methodology to reduce the complexity of the optimization problem considering a year long-time horizon. With this simplification, the design of a multi-energy system of a neighborhood is proposed optimizing total annual costs and carbon dioxide emissions including seasonal storage. Fonseca et al [**74**] proposed a modeling approach for a distributed energy system considering the time-varying operation of the energy

conversion units for responding to electricity and hydrogen demands with a multi-criteria evaluation addressing economic, environmental, and social aspects. Fazlollahi et al [**75**] compared different optimization methods to solve a multi-objective energy systems design problem. In this case, diverse configurations of six energy conversion technologies were found according to the investment cost and CO_2 emissions for heat and electricity production. Ahmadi et al [**76**] presented the Pareto front from the optimization of the generation of electricity, heating, cooling, and hot water from various gas-based systems considering the exergy efficiency and the total costs. Abbes et al [**77**] developed a triple multi-objective optimization method for the sizing of a PV-wind-battery to supply the electric demand of a residential house considering economic and environmental aspects. Pelet et al [**78**] made a model for the design of the energy supply system of a remote community in the Tunisian Sahara studying the effects on the choice of power technologies when pollution and economic are considered. Li et al [**79**] assessed economic and environmental benefits to optimize the design of an electricity system coupled with district power, heating, and cooling networks at a neighborhood level in Dalian, China with a mixed-integer linear programming (MILP) model. Dorotic et al [**80**] proposed a multi-objective optimization model for the design of district heating systems with one-year time horizon to search the best compromise between economic, environmental and exergetic criteria. Dufo-Lopez et al. [**81**] presented an evolutionary algorithm for the design a system including PV, wind and diesel generation solving a triple-objective optimization problem including cost, pollutant emissions and unmet load as objective functions. Perera et al [**82**] combined a MCDA method with a multi-objective optimization technique to design hybrid energy systems considering criteria such as levelized energy cost, unmet load fraction, wasted renewable energy and fuel consumption. Wang and Singh [**83**] presented a multi-objective optimization problem to propose an adequate configuration of a hybrid system with wind turbine generators, photovoltaic panels, and storage batteries including costs, reliability and emissions.

2.2.2 Studies applied in case studies in Colombia

In the Colombian context, some works tried to propose methodologies to find adequate solutions for the supply of electricity to isolated cities, the studies of Garzón [**84**] and Gonzales [**85**] considered only the technical point of view; however, many authors started to include the economic approach. For example, some authors carried out different

analysis of some municipalities from ZNI, in which they looked for an adequate combination of energy sources that responds to the energy demands of the municipality, considering an economic optimum with costs calculation of various proposed scenarios using simulation tools or coupled optimization [**86**,**87**,**88**,**89**,**90**]. In the same way, others worked with a focus on sustainability, including environmental and social aspect, such as Rosso-Cerón [**91**], who evaluated different alternatives for a city belonging to the ZNI using various qualitative and quantitative criteria through fuzzy logic with the help of experts. Similarly, Silva [**92**] presented a model to evaluate the substitution of diesel by biomass based energy using goal programming, Quijano [**93**] created the MODERGIS model, which makes a projection of the future Colombia energy matrix taking into account the spatial and temporal energy potential of supply and demand of energy in a geographical area, using geographic information system (GIS) combined with MCDA. Chaves presents a tool to select an energization alternative, initially performing an optimization and then making the choice of the most suitable scenario using MCDA [**94**] .

3 Methodology

3.1 Decision methodology proposal

The main measure taken by the governmental entities across the world to accelerate the diversification of the energy mix is the inclusion or in some cases the increase of share of renewable energies in the energy matrix. This decision is motivated mainly by the need of assurance of future energy security and the adverse effects of conventional energy sources. However, in some regions the implementation of these new alternatives has been slowed down for various reasons, such as climate variability, vulnerability of the sources, insufficient political support, and low acceptance among the inhabitants or even low financing.

For that reason, it is necessary to find a way to make this change progressively and with the least possible impact. A way to that change is the implementation of distributed energy systems [**52**]. However, coupling different energy vectors means letting them act simultaneously with a free exchange between them, so not only there must be an adequate infrastructure to fulfill this function, but it must also be able to respond to the specific demands associated from the location territory. Despite knowing this, it is not clear which ones should be linked and how to operate the system, since each case has a set of specificities that make it unique. Therefore, solving this question is essential because the answer gives an approximation for an adequate implementation and operation configuration, so this problem should be considered fundamental in this type of projects. It could be concluded that the progress towards energy restructuring seems to be a matter of decision making.

The design of distributed energy systems is complex because of the large number of variables involved and the objectives and constrains to be considered. Determining an

optimal arrangement of technologies is essential for the conception of distributed energy systems. However, as observed in the previous section, even though there have been studies to couple different energy sources to conceive a suitable energy arrangement. It has been noticed that many of the studies are focused on seeking new energy production alternatives based mostly on technical or economic criteria, often leaving out important criteria in sustainable development such as environmental or social criteria, which could provide a different perspective. In this way, conceiving a new methodology that takes these aspects into account is a key factor for the development of new energy systems. It would be very useful for the planning phases of distributed energy systems with the aim of obtaining a design that satisfactorily respond to demands.

This work will aim to propose a decision-making methodology that will result in a sustainable arrangement of energy sources in a decentralized energy generation system, facing the current lack of methodologies that evaluate all aspects considered within sustainable development and thus apply them to the design of energy supply systems. The main objective is to develop a decision methodology that helps to define the best configuration for a power supply network for the Leticia Campus of the Universidad Nacional de Colombia. As specific objectives, first, establish the parameters, initial conditions, and restrictions for the decision model of the case study from its context; second, define the criteria that objectively evaluate the different types of energy through technological, economic, environmental, and social indicators; then, develop a decision model for the choice of an energy arrangement considering technical, economic, environmental, and social aspects, and finally, apply the model to a specific case study at the Leticia Campus of the Universidad Nacional de Colombia.

Developing a methodology like this one, will allow the decision maker to solve the question of which is the most suitable arrangement and its possible operation for a specific case study, considering not only technical and economic aspects but also the context, associating the environmental and social dimensions and evaluating combinations of different possible energy sources, including renewable and non-renewable, using the strengths of one to counteract the disadvantages of another, estimating their possible implementation potential, as well as their impact on the system

intending to make this methodology more versatile and with a more complete contribution with respect to the conventional tools, techniques and models seen in the literature.

Although there is no specific methodology for conceiving a methodology, the approach used to reach the methodological proposal of this work was based on inductive reasoning, where certain patterns could be identified from many observations to arrive at a conclusion. Thus, technological surveillance translated into a bibliographic review was established as the main action to carry out. Through this search, it was possible to start devising a standard methodology by identifying the steps and reasoning that have normally been used in the studies. Then, a compilation of these steps was made, and, taking advantage of the research group's expertise on the subject, after several sessions of discussion and analysis, a standard methodological proposal was built to identify the best energy matrix for a specific place considering its context.

According to the observed studies, the general methodology shown in Figure 3-1 is proposed, this methodology condenses the main steps seen in the literature with the addition of covering certain limitations seen during the bibliographic review. As a general rule, it is necessary to use a decision support tool, which is in charge of making the selection considering the associated weights. Likewise, the context of the project must be defined; the difference in this work is that two important factors will be taken into account, the characterization of the territory and the local resources, the first referring specifically to the demand and the second to the usable resources that can be found in the area. Finally, it is necessary to find the evaluation criteria for the project, in this case, the methodology will take into account what is proposed in the sustainability triple bottom line, where the final result will be obtained through an evaluation considering technical, economic, environmental and social criteria in a specific case study.

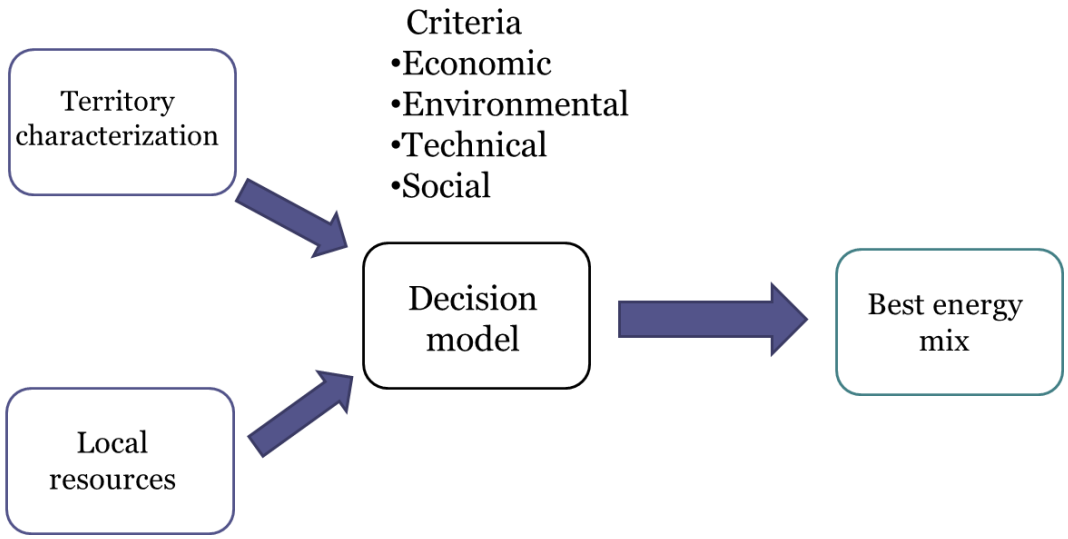

Figure 3-1. Schema of the proposed methodology.

Regarding the coverage of limitations, this methodology proposes the use of needs analysis as a new way to choose the indicators by considering the context, this tool has never been used for projects of this type but that can be very powerful. Similarly, there is a limitation where many of the studies simply list the most desirable energy sources but do not propose how they should be associated, so this methodology aims to arrive at a more realistic final decision, proposing scenarios where the temporal variability of resource availability and demand is considered, being a first approximation and the basis for a subsequent more detailed design of an energy supply network.

After all, the proposed methodology comprises three main phases, schematically presented in Figure 3-2.

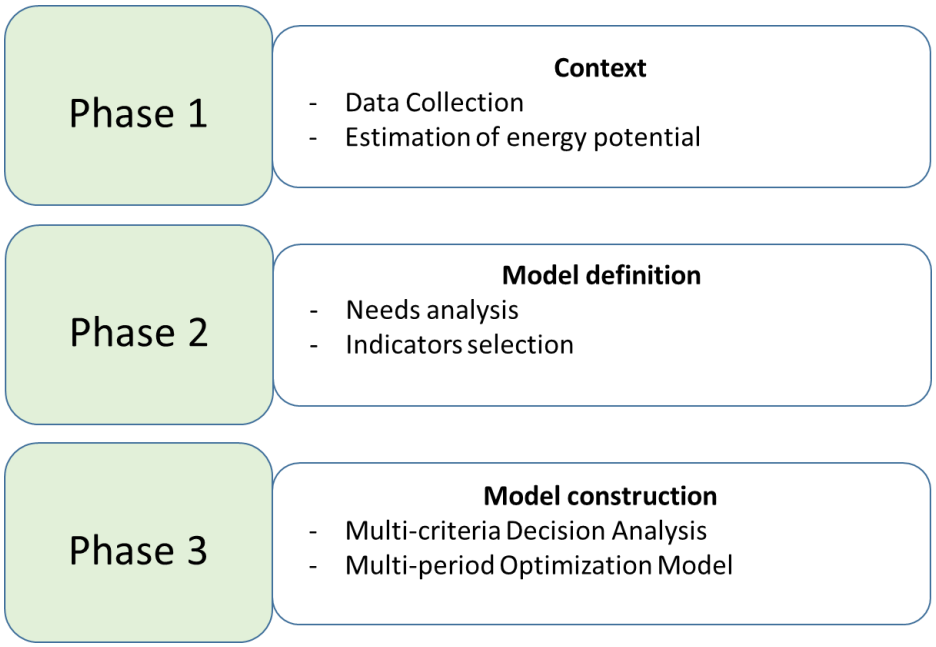

Figure 3-2. Disaggregated of the proposed methodology.

Initially, in phase 1, the context of the case study should be studied. Information corresponding to the site is gathered; such as available space, average annual consumption and, according to the location, the energy potential in renewable energies is estimated. Then, phase 2 corresponds to the selection of the various indicators. For this purpose, an exhaustive literature review of criteria used on energy system design problems should be carried out, with this information, an analysis of the different stakeholders and their emerging needs should be made with the objective of selecting the most adapted for the case study. Finally, in the last phase, with the help of the MCDA a first selection of the most convenient energy sources for then passing to a multi-period optimization model whose result will show the operating units with their respective connections according to the demand and the stakeholders' preferences.

3.2 Application of proposed methodology to case study

Even if main objective of this project is to propose a methodology able to choose the most appropriate energy arrangement for a specific site, one of the derived objectives is the application of this proposal to a particular situation study, in this case the Leticia campus of Universidad Nacional de Colombia. This section explains the different steps in the

methodology as well as the collection of the information required for the methodology application was carried out.

3.2.1 Context definition

To establish the parameters, initial conditions and restrictions for the model, it is important to collect information to know the context of the project. Therefore, a technological surveillance was made to have an overview in terms of energy, consulting specific data of the case study as historical data on energy consumption and existing energy demand.

The proposed strategy consists of a series of filters, where, according to different factors, it is considered whether an energy source is suitable for a possible implementation, discarding those that fail to comply. As shown in Figure 3-3, the starting point is ten energy sources, renewable and non-renewable, which passed an initial filter that considers whether the resource is available in the location of the case study. Once the existing resources have been defined, their potential is estimated by reviewing their maximum amount of exploitable energy or limit potential, which will be a factor to be considered in the final design. Finally, a review of the regulatory framework regarding the supply of energy and the implementation of renewable energies of the place was carried out to know any possible restriction on its implementation as well as various heuristics that could define if the resource is suitable to be put into operation.

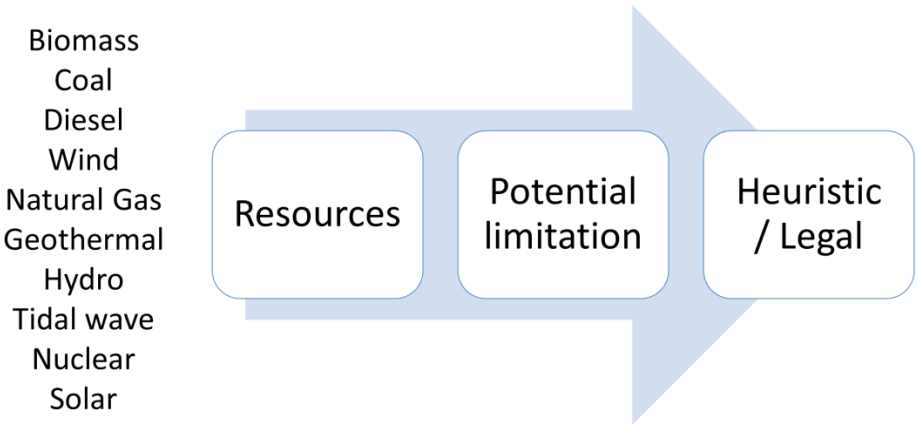

Figure 3-3. Schematic representation of the context definition step of the methodology.

3.2.2 Identification of sustainability indicators for energy planning

Once the context of the project has been defined, it is necessary to define the indicators that allow the decision maker to compare the alternatives in the different dimensions of sustainability. For this, an exhaustive search in the literature was carried out with the aim of obtain information about evaluation methodologies, as well as the indicators used. The information found was analyzed to build a database and start to set the evaluation criteria to be considered in the next phases.

A review of documents considering papers published from 2000-2020 on Scopus® and Web of Science databases along with a group of complementary documents provided by the research group was performed. The search was focused on energy planning studies resulting in a proposed energy mix or a ranking of energy production sources using indicators for different energy vectors considering various sustainability dimensions. Similarly, it was sought to include various methods of analysis to compare the way the decision was made for the same indicators. A search equation was defined according to the search strategy, as well as the type of documents and the period explored, an overview is shown in Table 3-1.

Table 3-1. Search methodology

Document search	Multicriteria decision AND energy AND plan* AND Sustainab*
Database	Scopus and Web Of Science
Period explored	1999-2020
Fields	Title, abstract, keywords
Type of documents	Articles, reviews and books.

Subsequently, the classification, selection, and analysis of the documents were made. An outline of three main filters was established with a focus on choosing the most relevant papers according to the objectives of the study. A general description can be seen in Figure 3-4, where, as a first filter, the articles appearing in both databases were removed so as not to be double counted. Then, an elimination was made from an abstract reading, and at the end, another filter was made by means of a quick reading stage. The articles that met the conditions were selected and analyzed in a much more detailed reading stage.

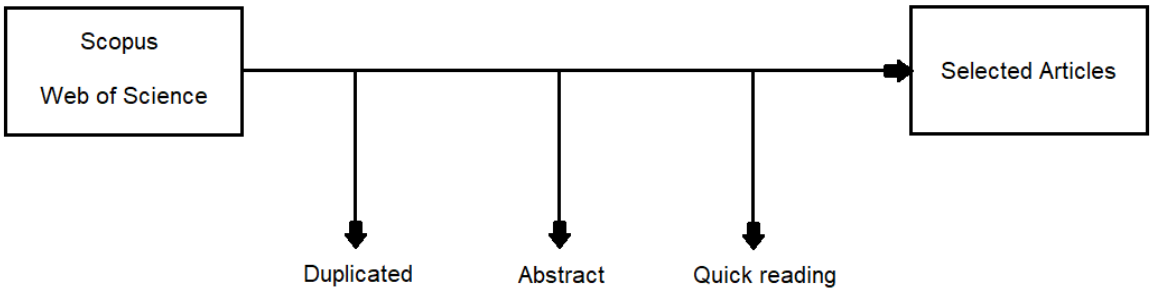

Figure 3-4. Outline of three filter system for article selection.

3.2.3 Identification and classification of stakeholders

An identification and classification of all possible actors involved in the design process of an energy supply system must be made in a general way and at the same time considering the case study in a process known as stakeholder analysis. A stakeholder can be defined as an individual or group of people who will have views of the strategic development of a project and who can affect or be affected by its performance [**95**]

In a project, various stakeholders need to be identified and they must be addressed for the stake that they hold. In practice, this comes down to providing stakeholders with the type of information about the operations in which they have an interest. Each stakeholder looks for and is interested in certain aspects of the company's operations. While the interests of stakeholders are intricately varied, and at times are even at odds with one another, it is important that an organization provides specific information and builds a strong reputation across exchanges with all these stakeholders. To do that, managers and communication practitioners typically start with identifying and analyzing the organization's stakeholders, their influence and interest in the organization. In this way, they have a clearer idea what the information needs of stakeholders are, what specific positions they have on an issue or in relation to a project activity, and what kind of communication strategy can be used to maintain support or counter opposition [**96**].

A basic approach of stakeholder identification analysis involves answering the following questions, which capture the essential information for effective stakeholder communication [**96**]:

- Who are the organization´s stakeholders?
- What are their interests?
- What opportunities and challenges are presented to the project in relation to its stakeholders?
- What responsibilities (economic, legal, ethical, and philanthropic) does the project have to all its stakeholders?

Another approach is to use a mapping model to identify and position stakeholders in terms of their influence on the project's operations or in terms of their stance on a particular issue related to the project. A mapping device enhances practitioners' knowledge of stakeholders and their influence and enables them to plan appropriate communication strategies. There are different ways in which stakeholder mapping can be used to gain an understanding of stakeholder influence. The stakeholder mapping identifies stakeholder expectations and power, it helps in understanding political priorities and underlines the importance of how interested each stakeholder is in impressing its expectations on the project's purposes and choice of strategies. [**96**,**97**].

Stakeholder mapping might help in understanding better some of the following issues [**97**]:

- In determining purpose and strategy, which stakeholder expectations need to be most considered?
- Discuss whether the actual levels of stakeholders' interest properly reflect the framework within which the project is organized.
- Who the key blockers and facilitators of a strategy are likely to be and how this could be responded to.
- Whether repositioning of certain stakeholders is desirable and/or feasible. This could be to lessen the influence of a key player or, in certain instances, to ensure that there are more key players who will champion the strategy.
- Maintaining the level of interest or power of some key stakeholders may be essential.

A general mapping device or tool that managers use for this task is the power-interest matrix developed by Mendelow in 1991. It is a framework to help analyze stakeholders' power and interest. The general objective is to categorize stakeholders on the basis of the

power that they possess and the extent to which they are likely to have or show an interest in the project's activities, all this, to formulate appropriate communication strategies on the basis of identifying and categorizing stakeholders. These mapping give an insight into whether stakeholders should only be kept informed about decisions or instead whether stakeholders should be actively listened to and communicated with on an ongoing basis. Johnson et al. suggested that this technique can be used in two situations [**95**,**97**]:

- To assess the impact of a particular strategic development on stakeholders.
- To keep track of changes in the potential influence of different stakeholder groups.

A general form for the power-interest matrix is shown in Figure 3-5 where the axes are the level of interest of stakeholders in supporting a particular strategy and the power of different stakeholders; that is, how much a stakeholder can affect the project [**98**].

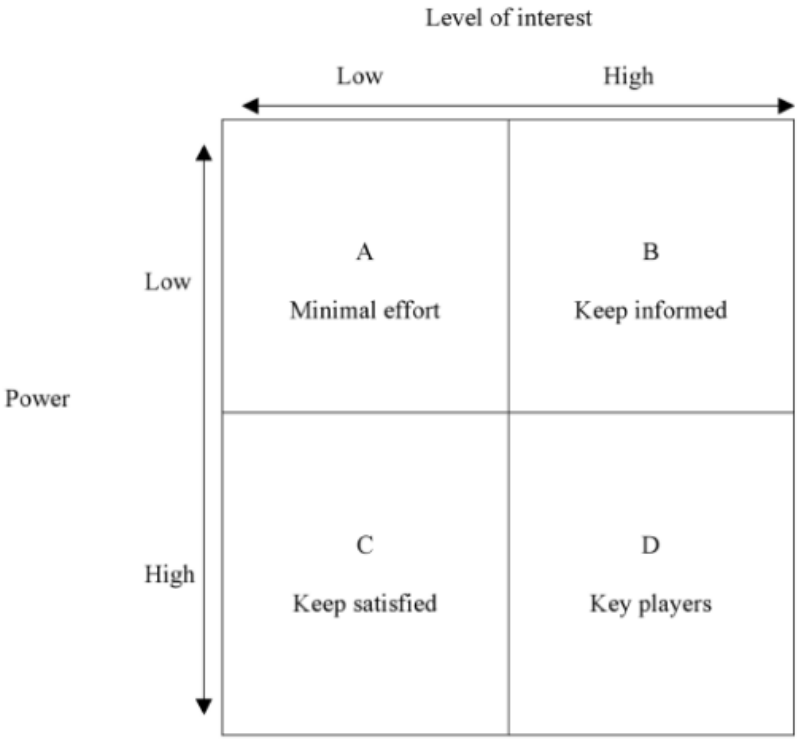

Figure 3-5. Power-interest Matrix [**98**].

The matrix identifies four areas that stakeholders may fall into: minimal effort, keep informed, keep satisfied, and key players. It should be noted that stakeholders can be

moved from one category to another. For example, a change in the levels of interest in an organization [**98**]. Johnson et al. suggest the following strategies to deal with each quadrant [**95**,**96**]:

- Box A – direction. Their lack of interest and power makes them malleable. They are more likely than others to accept what they are told and follow instructions.
- Box B – education/communication. These stakeholders can be crucially important 'allies' in influencing the attitudes of more powerful stakeholders. The positively disposed groups from this quadrant may lobby others to support the strategy. For the dissenters. If the strategy is presented as rational or inevitable including their opinion with a sort of consultation, this may stop them for joining forces with more powerful dissenters in C and D.
- Box C - intervention. Stakeholders here are the most challenging to maintain a relationship. Although these stakeholders might, in general, be relatively passive, a disastrous situation can arise when their level of interest is underrated, and they suddenly reposition to area D. The key is to keep them satisfied to avoid the adoption of a new strategy. Usually, this is done by reassuring them of the likely outcomes of the strategy well in advance.
- Box D – participation. These stakeholders can be major drivers of the change, but also the major opponents of the strategy. Their acceptability of strategies is of major importance, hence, there should be education/communication to assure them that the project is necessary, followed by discussion of how to implement it.

Once the stakeholders of the project were identified, the respective analysis and classification was carried out using the power-interest matrix. With this categorization, the least influential stakeholders, those located in the minimal effort quadrant (box A), were discarded; with the others, groups are formed according to the nature of their actions to build a map of actors with a view to using the Resources/Activities/Results (ReAR) methodology for needs analysis. The map of actors graphically reflects the connections between the various stakeholders, allowing for each of these connections to list the possible activities resulting from the interaction.

3.2.4 Need analysis as a tool for adapted indicator selection

With the information and work from the previous stages, several aspects were defined. Initially, on the context side, the energy sources with the highest viability were identified according to the estimated potential and the limitations at the demand or regulatory level as stated in legislative framework. In the same way, with all the information found after conducting the review in the literature related to energy supply system design problems, a list of all the usual sustainability indicators was obtained, which were grouped and synthesized through a series of assumptions. Intending to work with criteria adapted to the context, needs were identified through the ReAR methodology to select and use the indicators that allow the decision makers to evaluate the project considering all the dimensions of sustainability and the context. For this, the stakeholders' activities were defined, the minimum resources needed to carry them out were identified, when one of these resources becomes a limitation, a need is automatically conceived. Thus, the necessary requirements for a successful project implementation could be known with this analysis.

Need analysis is mainly related to the transformation of problems into a desired condition by means of resources or performance, showing that these elements have a strong dependence on the user or on the products. However, this approach could underestimate other types of needs, such as physiological or biological [**4**]. For that reason, Boly et al. [**99**] proposed a different methodology to identify needs based on observation of the context. In that methodology, an individual or group is considered as a unique system, and it is described through input, activities, and outputs.

Boly noticed that an innovation has better results if it is conceived considering the specific social and economic context. Consequently, attention has to be directed towards the identification of the main stakeholders, the activities of each stakeholder, and the ways they could interfere during the lifecycle of the product [**4**].

A diagram of ReAR could be seen in Figure 3-6. It is a model with a systematic approach that analyzes the resources that each stakeholder uses for the accomplishment of the activities with the aim of describing the whole environment through the interaction between all the involved stakeholders [**99**].

Figure 3-6. ReAR outlook for a stakeholder [**5**].

ReAR is a qualitative needs analysis tool in which a significant amount of observation and documentation work on the activities of the stakeholders is necessary. The actions of a stakeholder are a huge source of information. Each stakeholder could be considered as a process, and it is possible that the resources used by one stakeholder are the results of other or vice-versa. A limitation is that the reflections and internal emotions of the stakeholder could not be identified due to objective aspect of the model and its basis on the observation of appearances [**5**].

As a result of this process, apart from appreciating the activities in depth, the main output of ReAR model is an outlook of existing resources as well as the possible limitations or requirements to achieve an activity. These limitations could be translated into needs. To illustrate this, a small example of the analysis realized with this methodology is presented in Table 3-2.

Table 3-2. Example of the ReAR methodology.

Executor	Activity	Resource	Result	Involved	Limitation(s)
Local energy provider	Energy commercialization	Infrastructure	Earning profit	Customer	Selling price Production capacity Poor infrastructure

The main contribution of the ReAR approach is that it is a very convenient and meaningful way to formulate the needs of each stakeholder, particularly the implicit ones [**4**,**5**]. This approach is very different from the traditional approach, in which all the attention is focused on the product, generating only incremental innovations, while an observational approach such as ReAR is more advantageous, allowing to generate breakthrough innovations [**5**].

3.2.5 Selection of Indicators and Data collection

The ReAR methodology identified the limitations that could be translated in needs. A need could be associated to a principle, which are premises defined by the evaluator that must be fulfilled. For a principle, criteria and indicators should be selected; the first are measurable conditions that establish the level of application of the proposed principles and indicators, while the second are observable qualitative or quantitative values that allow the decision-maker to compare the performance of two or more alternatives in a specific criteria [**40**].

A comparison between the principles and criteria from needs analysis with the list of indicators used in energy design from literature was made with the purpose of selecting the most adapted with the context of the case study. With the selected indicators, a new literature review was carried out, this time focused on finding the reported values of each indicator for all the viable energy sources within the project context. These data were collected and statistically filtered discarding outliers using the Grubbs test.

Grubbs test, also called the maximum normed residual test, can be used to detect outliers in univariate datasets when normal distribution is assumed. Grubbs' test detects one outlier at a time; the outliers are expunged from the dataset, and the test is iterated until no further outliers are detected. However, multiple iterations change the probabilities of detection, and the test should not be used for sample sizes of six or less since it frequently tags most of the points as outliers. If the number of data (N) is higher than 25, then the result is just a coarse approximation [**100**,**101**].

Grubbs' test is defined for the hypothesis [**101**]:

H_0: There are no outliers in the data set

H_a: There is at least one outlier in the data set

The Grubbs' test statistic is defined as:

$$G = \frac{\max|Y_i - \bar{Y}|}{s}$$

Where $\bar{Y}$ is the sample mean and s is the standard deviation. The Grubbs test statistic is the largest absolute deviation from the sample mean in units of the sample standard deviation and the rejection of the null hypothesis of no outliers occurs at a significance level when:

$$G > \frac{(N-1)}{\sqrt{N}} \sqrt{\frac{t^2(\alpha/N,N-2)}{N-2+t^2(\alpha/N,N-2)}}$$

Where $t_{(\alpha/N,N-2)}$ is the critical value of the t-distribution with (N-2) degrees of freedom and a significance level of α/N.

3.2.6 Application of a multi-criteria decision analysis tool

Developing evaluation criteria and methods that reliably measure sustainability is a prerequisite for selecting the best alternative [**13**], with the information from the previous stages, a list of adequate energy sources regarding the case study is obtained; in the same way, criteria and indicators with their respective values were selected to compare. Afterwards, a Multi-criteria Decision Analysis (MCDA) was carried out in order to identify which technologies would be the most suitable for the case study, the selected methodology should be able to deal with the multi-dimensionality of the sustainability [**13**], in this case, the Analytic Hierarchy Process (AHP) was used.

Analytic Hierarchy Process (AHP) is one of the most used methods on the solution of problems involving MCDA. Thomas Saaty developed this technique in the 1970s, and it is a systematic decision-making approach capable of decomposing the problem into several sub-problems in terms of the hierarchical levels, which then represent a set of criteria or attributes relative to each sub-problem that are further subjectively evaluated. The subjective assessments are later converted into a numerical form and are arranged to determine the relative weights of the evaluation indicators, as well as to aggregate diverse opinions of decision makers to obtain the overall relative weights of the alternatives ranking each alternative on a numerical scale [**102**,**103**]

The principle of AHP is the pairwise comparison, here, a hierarchy is constructed through a series of comparisons, each attribute is compared against others using comparison matrices for which their consistency should be checked and maintained appropriately in

order to establish the preferences in a systematical approach, facilitating all decision makers to rationally select and prioritize the complicated decision problem [**10**,**102**].

This method has many advantages: simplicity, flexibility, intuitive appeal and, ability to handle both quantitative and qualitative criteria in the same framework. These advantages make AHP the most popular method for prioritizing alternatives, followed by PROMETHEE and ELECTRE [**9**,**10**]. In the same way, AHP considers stakeholders opinion and before using them the method evaluates the viability through the consistency index assuring decision makers that the judgments were consistent and consequently the final decision is made well [**9**,**12**]. The main disadvantage is that AHP is the high time consumption when the number of alternatives and/or criteria is large. Another is the possibility of overestimation of preference differences in the conversion from verbal to numerical judgments [**10**].

The key steps of AHP methodology are described as follows [**104**]:

Step 1: Development of the hierarchal structure of the decision-problem including objective, criteria, sub-criteria and alternatives for the target problem.

Step 2: Formulation of pairwise comparison matrix of the decision problem using Saaty's 1–9 point scale in Figure 3-7 for determining the degree of relative importance.

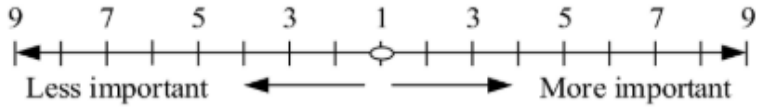

Figure 3-7. Pair-wise comparison matrix scale used in AHP [**104**].

Step 3: The criteria are compared to determine the relative importance via the principal eigenvalue and the corresponding normalized eigenvector of the comparison matrix. The elements of the normalized eigenvector are then named as weights with respect to criteria and sub-criteria.

Step 4: Calculating the consistency index (CI). In this step, CI can be used to measure the consistency of the pairwise comparison of the matrix. CI can be presented as:

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

Where λ_{max} are the eigenvalue and n is the number of main criteria

Step 5: Computing the consistency ratio (CR).

$$CR = \frac{CI}{RI}$$

Where RI is the random consistency index which depends on the quantity of criteria, its value is shown in Table 3-3.

Table 3-3. Values of Random consistency index (RI) [**104**].

N	1	2	3	4	5	6	7	8	9	10
RI	0,00	0,00	0,058	0,90	1,12	1,24	1,32	1,41	1,45	1,49

The consistency ratio (CR) must be within the limit of 0.1; if it is greater than 0.1, then the results could be inconsistent.

Step 6: Obtain the overall priorities of the candidate options. The best option is the one with the greatest value of the overall priority when taking all indicators into account.

3.2.7 Optimization approach

Based on information collected during context definition and once the criteria and indicators to be used were defined, an optimization model was developed to propose an optimal operating scheme that satisfies the energy demand of the municipality and the energy potential of the case study. A specific scheme showing the approach proposed in a graphical way for the Leticia campus of Universidad Nacional de Colombia is presented in Figure 3-8.

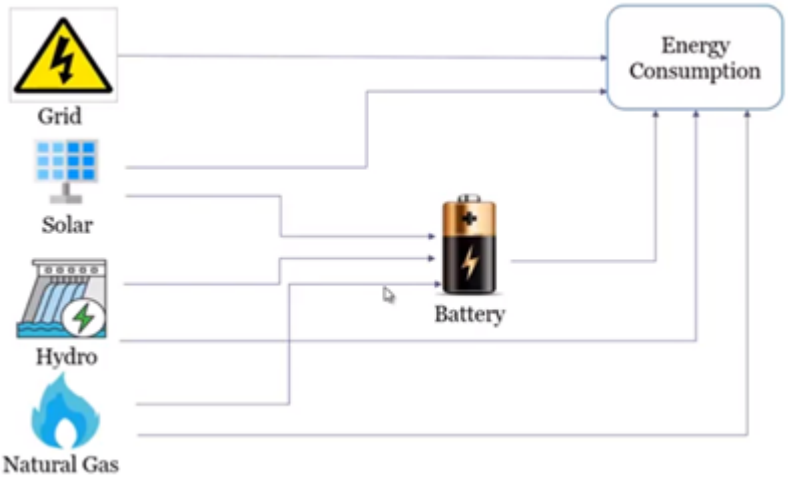

Figure 3-8. Scenario evaluated with the proposed optimization model.

The proposed optimization model is a multi-period method where 12 periods were considered equivalent to each of the months of the year; likewise, as objective function, the minimization of the total sum of the impacts in each of the dimensions was considered. For this, in each dimension a normalized variable was assigned together with a parameter that represents the weight with the aim of comparing indicators and dimensions of different nature.

Objective function

$$\min \left(\sum_{k=1}^{K} W_k N_k \right)$$

Where K is the total number of dimensions.

In addition, the initial conditions and restrictions were defined considering aspects such as the limitation of the potential. In other words, the resources will be used up to the highest possible capacity; in the same way, the energy supplied in each period must be equivalent to the demand in each month. Thus, through an energy balance, the demand D_j for a period j must be the sum of the energy produced by each of the sources (i) added to the net energy extracted by the battery as follows:

$$D_j = \sum_{i=1} P_{i,j} + B_j^{out} - B_j^{in}$$

The variable P represents the energy produced by an energy source (i), this value is calculated by the product of the amount of energy equivalent from a source (E), the efficiency (η) and the capacity factor (C), which is the ratio of the electrical energy produced during a time period to the energy that could have been produced at continuous full power operation during the same period [**105**].

$$E_{i,j} = \frac{P_{i,j} + P_{i,j}^B}{C_i \, \eta_i}$$

In the same way, the variables B^{in} and B^{out} were included to calculate whether it is necessary to store energy in a period to be used in the following one.

$$B_j^{in} = \sum_{i=1} P_{i,j}^B$$

$$B_j^{out} = B_j^{in} \, C^B \, \eta^B$$

The superscript B refers to the values of the variables for the battery.

An important assumption regarding storage is that in the first and last period it will be considered zero, it means that the battery will start with any charge and all the energy that is stored should be used throughout the period considered.

$$B_0^{out} = 0$$

$$B_{12}^{in} = 0$$

This model compares the different energy sources through the selected indicators and the information associated, obtaining the most appropriate energy arrangement according to the weight assigned to each of the dimensions of sustainability for the case study. However, this could not be possible without the normalization, which is the way to

compare values from indicators of different dimensions, adjusting them with respect to a common scale. In this case, this process was carried out depending on whether all the indicators within a dimension can be measured with the same units or not.

If the indicators ℓ on dimension k have the same units (i.e. economic with a monetary unit) a normalized value of dimension (N_k) is obtained by the use of max-min normalization method, which consist in rescaling a range of values from 0 to 1, being 0 for the minimum and 1 for the maximum.

$$N_k = \frac{Total_k - L_k}{H_k - L_k}$$

In this case, $Total_k$ represents the total impact generated in energy production for a dimension (k), H_k and L_k are the maximum and minimum values to obtain in the scenario with the greatest possible impact.

$$Total_k = \sum_{\ell=1}\sum_{j=1}\sum_{i=1} I_{k,\ell,i}\,(P_{i,j} + P^B_{i,j}) \; + \sum_{\ell=1}\sum_{j=1} {I^B}_{k,\ell}\, P^B_{i,j}$$

$$H_k = \left(\sum_{j=1} \frac{D_j}{C^B\,\eta^B} \sum_{\ell=1} \mathrm{Max}(I_{k,\ell,i})\right) + \left(\sum_{j=1} D_j \sum_{\ell=1} {I^B}_{k,\ell}\right)$$

$$L_k = \left(\sum_{j=1} D_j \sum_{\ell=1} \mathrm{Min}(I_{k,\ell,i})\right)$$

Max indicates the function that returns the largest numeric value in the set of values (I) collected for an indicator, while Min is the function where the output is the smallest value. For dimensions whose indicators have different unit of measure, the normalization process is like the previously described with an additional function which allows the indicators to be comparable.

$$N_k = \frac{\sum_{\ell=1} N_{k,\ell}}{t_k}$$

Where t_k is the number of indicators present within a dimension k.

$$N_{k,\ell} = \frac{Total_{k,\ell} - L_{k,\ell}}{H_{k,\ell} - L_{k,\ell}}$$

$$Total_{k,\ell} = \sum_{j=1} \sum_{i=1} I_{k,\ell,i} P_{i,j} + \sum_{j=1} {I^B}_{k,\ell} P^B_{i,j}$$

$$H_{k,\ell} = \left(\sum_{j=1} \frac{D_j}{C^B \eta^B} \ \mathrm{Max}(I_{k,\ell,i}) \right) + \left(\sum_{j=1} D_j \ {I^B}_{k,\ell} \right)$$

$$L_{k,\ell} = \left(\sum_{j=1} D_j \ \mathrm{Min}(I_{k,\ell,i}) \right)$$

Finally, some restrictions must be considered: the value of the energy generated for a source cannot be negative and it cannot exceed the amount of available energy calculated from the resources of the territory (A).

$$E_{i,j} \leq A_{i,j}$$

$$0 \leq P_{i,j}$$

$$0 \leq {P^B}_{i,j}$$

4 Case Study

As mentioned previously, the proposed methodology was applied to a specific case study, which was the Amazonas Campus of the Universidad Nacional de Colombia located in the city of Leticia on the Amazonia region of Colombia. This site has been chosen because it is in an area not covered by the national distribution network (ZNI). In addition, it has the necessary elements in infrastructure to represent the behavior of the city on a smaller scale, such as laboratories as well as residential units, besides, the inclusion of the possibility of accessing the facilities and the data associated with it. Consequently, in this chapter some information related to the city of Leticia and the Campus will be provided, specifically describing part of context as well as the problem at the energy level that the proposed model aims to face.

4.1 Municipality of Leticia

The Amazonia region of Colombia comprises 42% of the national territory and it is the least populated area of the country [**106**]. Within this region there are seven departments, including the Amazonas, whose capital is Leticia. The exact location could be seen in Figure 4-1.

Figure 4-1. Location of Leticia in Colombia. Source: D-Maps [**107**].

4.1.1 Geography and climate

Leticia is located in the borders between Brazil and Colombia and between Peru and Colombia, in a region called *Tres fronteras* (Three Borders). Leticia is bordered to the north by the municipality of Tarapacá (Colombia), to the east by the Republic of Brazil (Tabatinga), to the south by the Republic of Peru (Santa Rosa de Yavarí) and to the west by Puerto Nariño (Colombia) [**106**]. Leticia has an area of 5,980 km^2, which is equivalent to 5.44% of the Department of Amazonas, whose total extension is 109,665 km^2 [**108**].

Leticia is located 1100 kilometers from Bogotá (the capital city of Colombia), and access is complicated by its isolation from the rest of the country due to impenetrable jungles. By air, only two commercial routes connect Leticia and the Three Borders Zone to the world. On the Colombian side, the daily Bogotá-Leticia service, and on the Brazilian side, the Manaus-Tabatinga connection. By land, Leticia is connected to the city of Tabatinga by a road known as the Avenida Internacional (International Avenue), where taxis, minibuses, and motorcycles circulate throughout the two cities.

In the same way, the city can be accessed by the Amazon River; by the river the closest point Santa Rosa de Yavarí (Peru), ten minutes away. Commercially, two routes are enabled by the Amazon River, the route to Iquitos (Peru) with a duration of twelve hours and from Manaus (Brazil) with a time of around thirty-six hours [**106**].

The municipality is located between 0 and 80 m above the level of the sea [**106**], has a tropical rainforest climate and the temperature does not vary much during the year. Leticia has notably more rainy and dry months, being March the rainiest and July the driest. The weather chart throughout the year is shown in Table 4-1, the data obtained are the average values from 1981 to 2010.

Table 4-1. Climate data for Leticia – Average for the period 1981-2010 [**109**]

Measurement	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average High Temperature (°C)	30,7	30,7	30,8	30,5	30,1	29,5	30,0	31,1	31,6	31,6	31,3	30,8
Daily Mean Temperature (°C)	26,0	26,0	26,1	26,0	25,7	25,1	25,1	25,7	26,1	26,3	26,3	26,0
Average Low Temperature (°C)	23,0	22,9	23,0	23,0	22,7	21,8	21,2	21,5	22,0	22,6	22,9	22,9
Average Relative Humidity (%)	88	88	88	88	88	88	86	85	85	86	87	88

Leticia is the main Colombian port on the Amazon River. The municipality has abundant permanent and stationary water bodies, which form a hydrographic network of great importance for the region because many are employed for consumption by the native communities and rural population. In addition, this network serves as a habitat for many wild aquatic species. The largest water resource is represented by the macrobasin of the Amazon River, which is the most important river in the department and the means by which economic, tourist, and environmental development of the region is possible.

4.1.2 Economic

The Colombian economy in 2021 grew 10,7% compared to the previous year, reaching a GDP of 330.5 billion dollars at constant prices of 2015, this value represents a growth of 2,9% compared to 2019 [**110**,**111**]. In the same year, the Amazonas department contributed with $769 billion COP at current prices to the country's economy, equivalent

to a share of 0.1%. Regarding Leticia, the municipality contributed to the 75% of the of the department's GDP with $576 billion COP [**112**].

By branches of economic activities defined by the International Standard Industrial Classification of All Economic Activities (ISIC), the greatest participation in the Amazonas department was registered by the groups of Public administration and defense; Compulsory social security + Education + Human health and social work activities with 33.6%, followed by Wholesale and retail trade; repair of motor vehicles + Transportation and storage + Accommodation and food service activities with 31.3% and Agriculture, finally, forestry and fishing with 16.9%. These three groups cover around 82% of the department's GDP [**112**]. In the case of Leticia, the municipality registered the distribution showed on Table 4-2 for the same year. The largest contribution comes from tertiary activities such as commerce and public administration because in recent years Leticia has become an important national and international tourist destination due to the beautiful landscapes and diversity of fauna and flora.

Table 4-2. Distribution of GDP in Leticia according to major branches of activity for 2019 (in billions of COP) [**112**]

Municipality	Primary activities	Secondary activities	Tertiary activities	Total added value
Leticia	76	41	459	576

4.1.3 Social

4.1.3.1 Population and employment

For 2018, Leticia had 42,844 inhabitants, 51.5% men and 48.5% women. Additionally, the population is divided on rural (36.7%) and urban (63.3%). Similarly, the town has 18,212 people belonging to some native community, a percentage of 42.5%, the main communities present are Uitotos, Ingas, Tucanos, Ticunas and Nukak [**113**].

Respecting the employment situation of the municipality, the labor market statistics in 2019 registered a population of 26,948 people, corresponding to the urban fraction. Of these, 20,615 were of working age, 12,968 are economically active, which meant a global

participation rate (GPR) of 62.9%, on the other hand, the unemployment rate reached a 6,7% for the same year [**114**]. The branches of economic activity that presented the greatest demand for employment were communal, social, and personal services (34.0%), and commerce, hotels and restaurants (32.8%). In contrast, the branches of activity with the least participation were financial intermediation (1.8%) and gas, water, and electricity supply (0.7%) [**114**]. Even though the low unemployment rate, the job offer is scarce presenting a 60.1% of workers are self-employed [**108**] while 16.6% are private employee, and 12.4% are government employee [**114**].

Moreover, for the 7,647 persons belonging to the inactive population by 2019 in Leticia, they were mainly engaged in studying (50.6%), in household labors (35.5%), and in other activities (pensioners, retired persons, persons permanently unable to work, renters, and persons not attracted by work) (13.9%) [**114**].

4.1.3.2 Housing

Leticia has 11,611 dwellings, 80% are in the urban area and 20% in the rural area, Table 4-3 exposes the distribution by housing type.

Table 4-3. Distribution of housing in Leticia for 2018 [**113**].

Housing type	Share (%)
House	80.53
Apartment	11.21
Room Type	7.07
Traditional Native Housing	0.78
Traditional Ethnic Housing (Afro-Colombian, islander, Roma)	0.05
Other (container, tent, boat, wagon, cave, natural refuge, etc.)	0.35

The number of people per house ranges from the uninhabited to 18 people, presenting a majority in the range of 3-5, as shown in Figure 4-2.

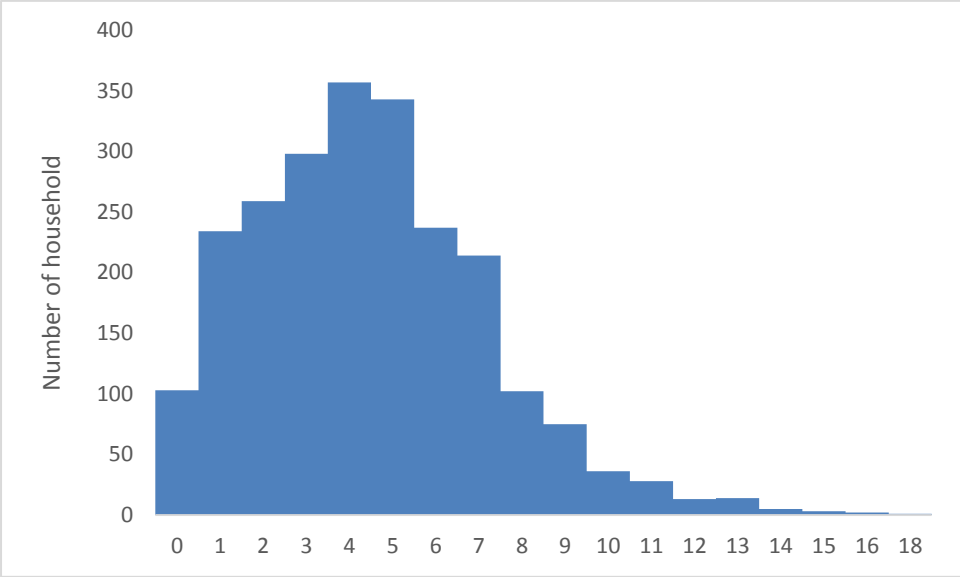

Figure 4-2. Distribution number of people per household in Leticia for 2018 [**113**].

In addition, a classification by socioeconomic stratum of the house is shown in Figure 4-3, the majority are of stratum 1 and 2, which shelter the users with lower revenue. It should be noted that the percentage of stratum 5 and 6, which are those that contribute to the local budget by means of payment of surcharges over the value of the public services, is almost zero.

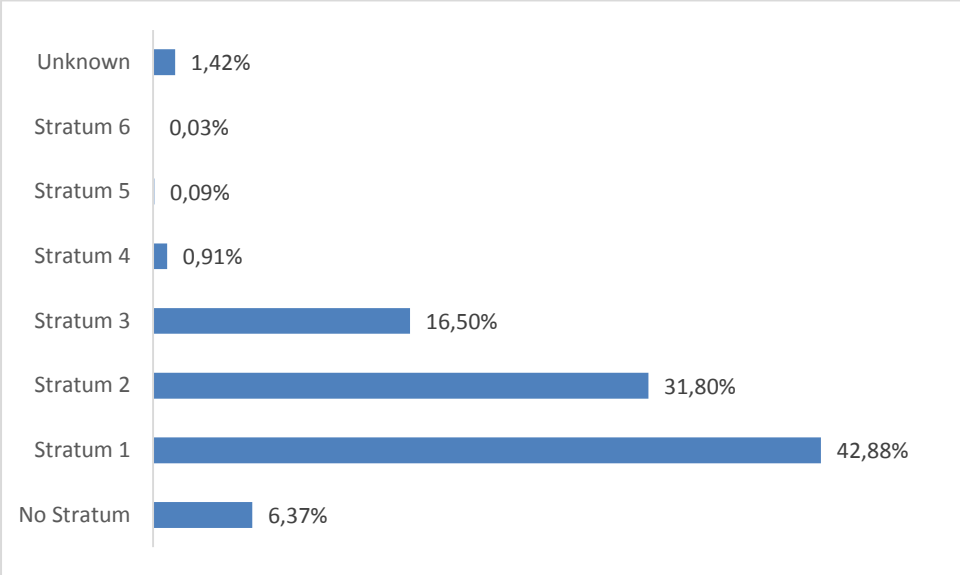

Figure 4-3. Housing classification by socioeconomic stratum in Leticia for 2018 [**113**].

4.1.3.3 Poverty

In Colombia, the multidimensional poverty and unsatisfied basic needs are the indices used to measure the development of a place based on its deficiencies, resulting in a characterization of the level of poverty. The following is a brief explanation of the calculation of each of the indices along with the information related to Leticia.

In the case of multidimensional poverty index, the estimation in Colombia at municipal level has five dimensions (educational conditions of the household, conditions of children and youth, health, work, access to public services and dwelling conditions) and 15 indicators. Each dimension has a weight of 20% and the indicators have the same weight within their respective dimension. In this case, households that are deprived in at least 33.3% of the indicators are considered poor [**115**]

The results of the calculation of multidimensional poverty for the municipality of Leticia are presented in Table 4-4.

Table 4-4. Multidimensional poverty index for Leticia in 2018 [**115**].

Multidimensional poverty index	**Share of Leticia population (%)**
Total	48,4
Urban areas	41,9
Rural areas	67,8

According to the index, 48,4% of total population are considered poor with a value for rural areas of 67,8% very high compared to urban areas, in order to find the difference a disaggregated table showing all indicators is presented in Table 4-5.

Table 4-5. Disaggregated estimation of Multidimensional Poverty Index for Leticia in 2018 [**115**].

Indicators	Share of Leticia population (%)		
	Total	**Urban**	**Rural**
Illiteracy	9,0	6,7	18,1
Low educational attainment	45,1	38,4	71,2
Barriers to accessing early childhood care services	4,0	3,4	6,5
Barriers to access to health services	5,8	5,5	6,8
Economic dependency ratio	39,2	34,1	59,0
Critical overcrowding	24,0	23,1	27,7
Inadequate excreta disposal	41,7	46,1	24,7
School absence	5,8	5,2	8,3
Inadequate exterior walls	24,0	29,7	1,8
Inadequate floors	3,5	2,8	6,0
Education gap	25,5	22,4	37,4
No access to improved water source	47,8	44,1	62,2
No health insurance	26,6	25,5	30,7
Child labor	1,4	1,2	1,8
Informal employment	85,3	83,6	91,9

Overall, there is a high degree of informal employment, at the same time, a low access to improved water and poor waste disposal. Comparing the rural and urban areas, at rural level there are more serious problems at the educational level and high economic dependency, on the contrary, they have a better excreta disposal and better infrastructure in exterior walls than the urban area.

With respect to the Unsatisfied Basic Needs (UBN) index, it is the best known and most used method in Latin America to identify critical deficiencies in a population and characterize poverty. It was introduced by the Economic Commission for Latin America and the Caribbean (ECLAC) in the early 1980s to take advantage of the information obtained by demographic and housing census using indicators directly related to four areas of basic needs of people (housing, health services, basic education and minimum income) [**116**].

The indicators for calculating the UBN index are [**117**]:

- Inadequate housing
- Critically overcrowded housing

- Housing with inadequate services
- Housing with high economic dependence
- Homes with school-age children who do not attend school.

In Table 4-6, the estimation of Unsatisfied Basic Needs Index for Colombia, Amazonas department and the municipality of Leticia is presented.

Table 4-6. Unsatisfied Basic Needs Index for Colombia, Amazonas and Leticia, percentage of people for 2018 [**117**].

	Colombia		**Amazonas**		**Leticia**	
%	**Urban**	**Rural**	**Urban**	**Rural**	**Urban**	**Rural**
People in UBN	9,42	30,22	25,62	45,60	25,01	32,90
Proportion of People in Misery	1,76	10,51	5,94	16,41	5,75	7,82
Housing component	2,88	13,63	3,76	7,97	3,88	5,47
Services Component	2,06	8,78	10,90	28,45	9,50	9,99
Overcrowding Component	2,49	9,42	12,75	19,70	13,23	17,53
Non-attendance component	1,56	3,11	2,72	4,75	2,61	3,58
Economic dependency component	2,62	10,33	3,06	9,41	3,00	6,97

Comparing Colombia with the Amazonas department, at the urban scale the percentage of people with UBN and living in misery is higher than the Colombian average, showing a development delay of the region justified by the scarce coverage on public services and high overcrowding rate. At departmental level, the values in urban scale are similar, but, at the rural scale are lower. These facts confirm that Leticia is the most developed town of the region.

4.1.3.4 Access to Services

Regarding the access to public services, the Figure 4-4 shows the coverage for each of the basic services in Leticia. Globally, the municipality has scarce access to internet and

natural gas. The urban area has a global better access compared to the rural, especially in those related to water supply, sewerage, and waste collection.

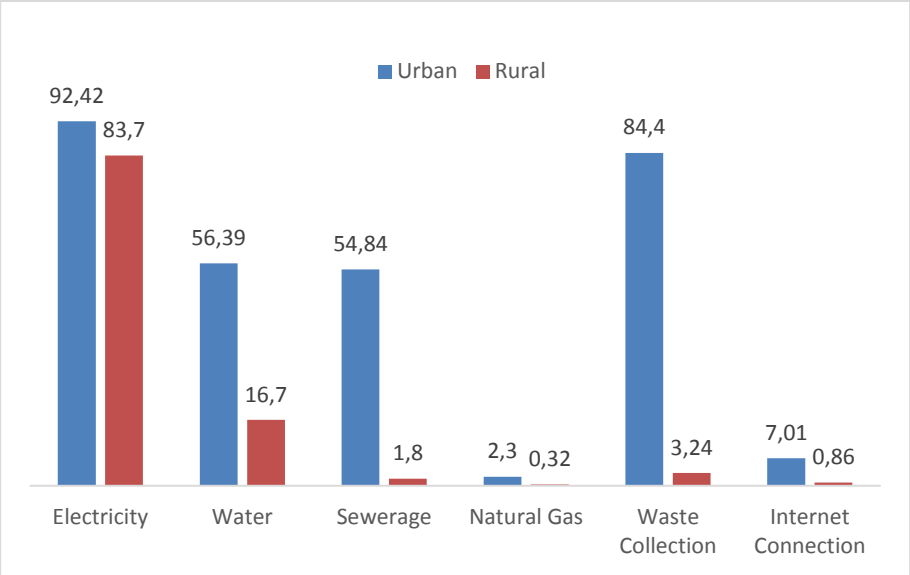

Figure 4-4. Coverage percentage of public services in Leticia for 2018 [**113**].

With respect to access to electricity, Amazonas is one of the departments with the least coverage at Colombian level because it is a ZNI and has no contact with the SIN distribution network, so electricity must be generated *in situ*. Nowadays, intending to meet the demand in Leticia, the municipality has made use of liquid fuels of fossil origin through eight plants that use diesel with a total capacity of 23,300 kW [**118**]. In addition to the already known environmental impact on the ecosystem caused by burning this type of fuel, another consequence of this method of obtaining energy is the high cost to the end consumer compared to other areas of the country connected to the grid. For example, while the price for the residential area in a place covered by the network such as Bogotá is 541.49 COP/ kWh [**119**], in Leticia it reaches 1,553.63 COP/kWh [**120**]. This high price, combined with the economic condition of the population, makes necessary the intervention of the state helping with subsidies so that the inhabitants can pay the service to the supplier company.

In the same way, there is a problem associated with dependence on this fuel, which means that access to energy is limited by its availability. There is only one access point for the delivery of fuel through river transport from the surrounding cities, which can become complex depending on weather conditions and affect the operation of important

equipment for the city, such as the water extraction and purification plant. On the other hand, other problems are not associated with the method of energy production but are specific to the region, especially linked to the infrastructure. Among these, the existing network usually has problems due to the fall of trees on the electrical wiring or transformers destabilization, and damage is presented due to the unwanted presence of wildlife; at the same time, some interruptions in service take place due to breakdowns caused by vandalism in the city.

These problems along with the constant growth of the municipality in recent years, especially due to an increase in tourist demand, have promoted the search for new energy solutions that can support the current energy supply and at the same time be able to supply future demand in a technologically and economically viable, environmentally sustainable and with a social sense.

4.2 Leticia Campus of Universidad Nacional de Colombia

Universidad Nacional de Colombia established the Leticia Science Station in 1989 as a research site in the Amazon region. In 1994 it raised its status, constituting the fifth University Campus in the country. In Leticia, the university has been committing for the production, systematization, and projection of knowledge from and to the Amazonia region, facing current and future responsibilities related to its geostrategic and environmental importance in order to contribute to Colombia development promoting border integration processes and projecting the region internationally. The Amazonia Campus currently offers undergraduate and graduate programs at the master and doctoral levels as an effort to provide young people with high quality education in a region whose departments of influence have very low coverage rates in higher education, managing to admit 1,813 students since its creation, whose socioeconomic composition is mainly of low stratum, including native communities, victims of the conflict and, in general, vulnerable population [**121**].

4.2.1 Campus and Local Historical Data

The campus is located on the periphery of Leticia, in front of the runway of the Alfredo Vasquez Cobo International Airport, more precisely, on kilometer 2 of the road to

Tarapacá, precisely in the latitude -4.193741° and longitude -69.940746°. The campus has a total area of 160,000 m^2, it has the infrastructure to carry out courses, such as classrooms, laboratories and a library, as well as space for administrative offices. A peculiarity of this campus is that it also has recreation areas for the accommodation of people associated with the university, there is an ecological path as well as a resting place with rooms, swimming pool, maloca, gym, playroom, music room, grand hall, etc. A detailed map of the campus can be seen in Figure 4-5.

Figure 4-5. Leticia Campus Map [**121**].

In recent years, the number of people attending the campus has increased, from 115 people in 2009 to a total of 241 people by 2019, including students, professors and administrative staff, as can be seen in Figure 4-6. The number of professors and administrative staff is a minority and has remained almost constant, while the number of students has increased with a high influence on the number of the population. This growth is justified by the university's attempt to increase coverage and try to provide access to higher education to a greater number of people.

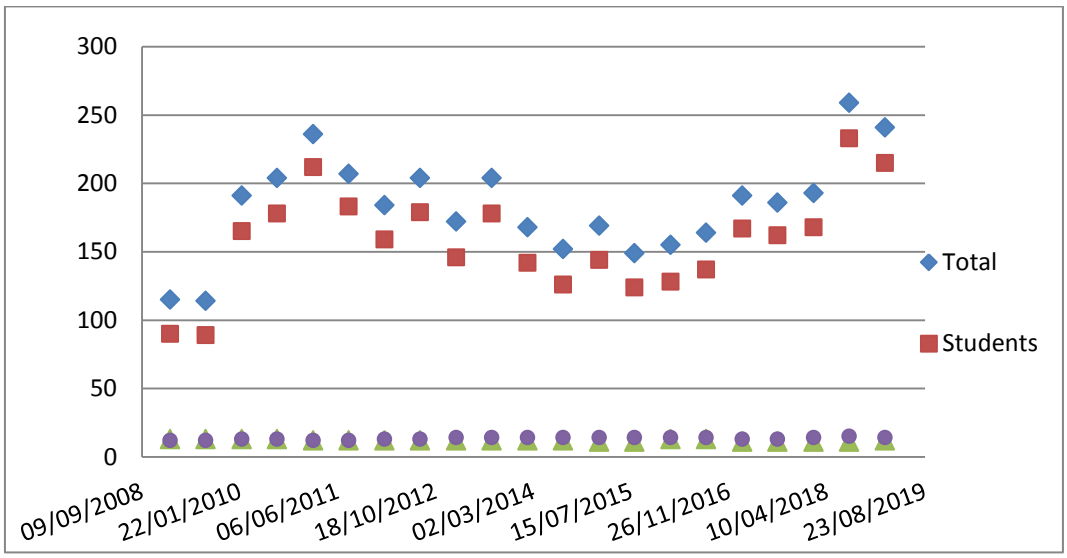

Figure 4-6. Number of people occupying the Leticia Campus from 2008 to 2019 [**122**].

Regarding the electricity consumption inside the campus, data from 2016 to 2018 was obtained and is presented in Figure 4-7. As a result, the consumption is relatively constant throughout the year, except for the half and end of year periods. This is because of scholar holidays. In Colombian educational system, the school calendar has two big periods of Mid-year and Christmas holidays.

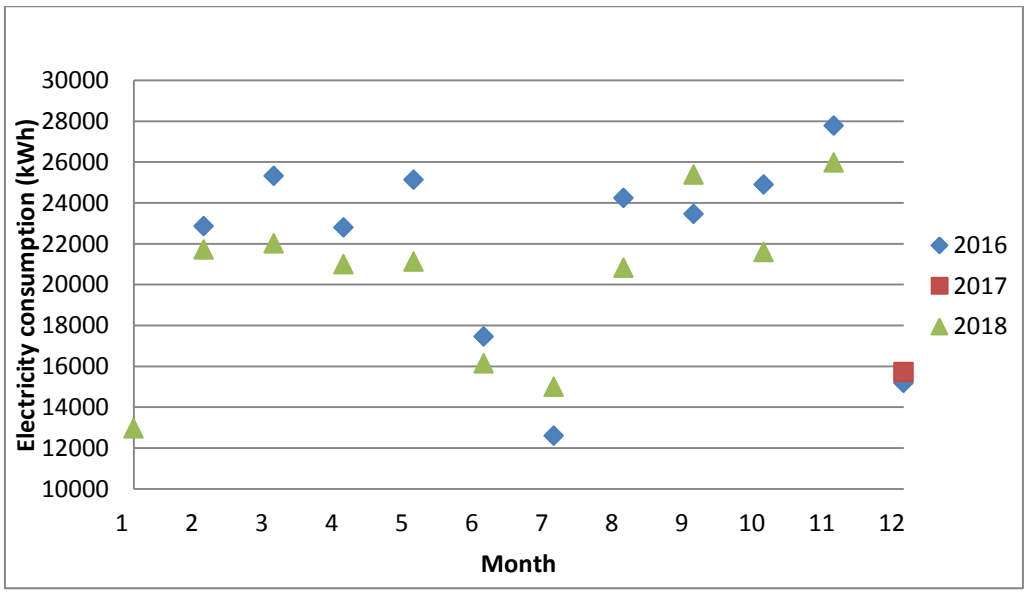

Figure 4-7. Amount of electricity consumed in kWh in Leticia Campus throughout the year (Month 1: January and Month 12: December).

5 Application of proposed methodology to case study

5.1 Context definition

5.1.1 Renewable energy potential estimation

5.1.1.1 Solar radiation

In order to estimate the solar energy potential, Solcast database was used to obtain the Global Horizontal Irradiance (GHI) values for the campus during each hour for the period between 2017 and 2019. With these data, a consolidation was made in order to organize the average radiation on a monthly basis, which is presented in Table 5-1.

Table 5-1. Estimation of solar energy in Leticia from 2017 to 2019 [**123**].

Month	**Radiation (kWh / m^2)**
January	134.0
February	122.4
March	150.8
April	137.3
May	139.8
June	137.7
July	155.8
August	165.5
September	162.9
October	158.0
November	146.6
December	137.2

5.1.1.2 Wind speed

In parallel, POWER Data Access Viewer from NASA database was used to measure the wind capacity by means of the wind speed at 10m height, the data was synthetized in a frequency chart due to the large amount of data as seen in Figure 5-1.

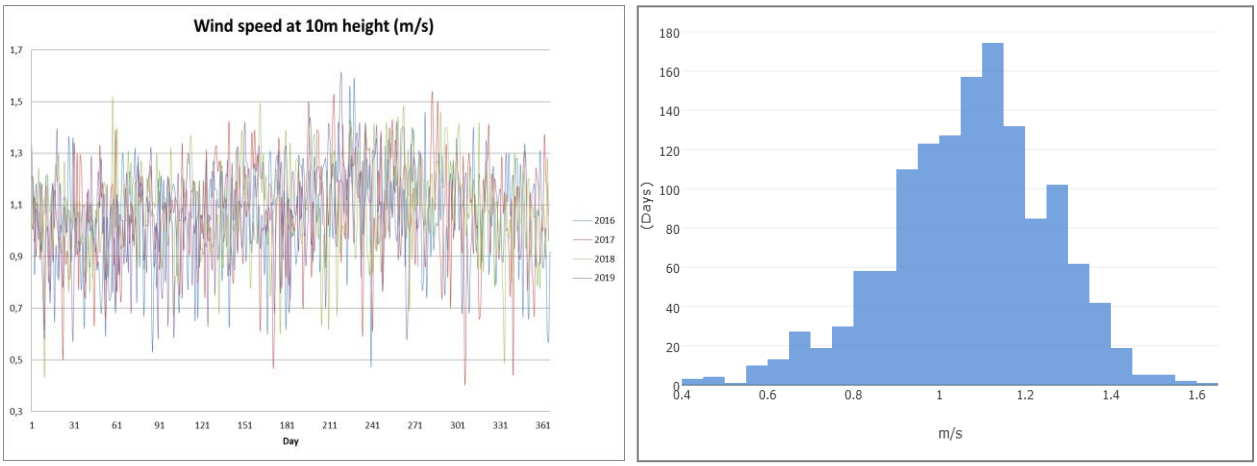

Figure 5-1. Wind data in Leticia Campus from 2016 to 2019 [**124**] a) Wind speed at 10m height b) Frequency chart.

5.1.1.3 Hydro

Leticia is a city located next to the Amazon River. The river does not cross the city but becomes a natural border surrounding the west side of the urban place with its course as shown in Figure 5-2.

Figure 5-2. Panoramic view of Leticia [**125**].

Even though a sector of the city is connected with the river, it is dedicated to transport and commercial activities especially due to the presence of the river port, where there is a substantial flow of cargo that allows the arrival of products and trade with neighboring cities as well as the circulation of tourists desiring to visit surrounding areas. In the same way, it should be noted the existence of the floating cottages that serve as housing or as place of accommodation for visitors.

IDEAM (Spanish acronym for Institute of Hydrology, Meteorology and Environmental Studies) carried out a study to identify the flood zones and levels from which the first damages would appear in the urban area of Leticia caused by the Amazon River [**126**]. Twenty-three sections of the river were analyzed in variables such as flow, width, area and speed. Among these options, some sections located upstream from the Leticia dock were selected with an average velocity of 1.045 m/s. However, despite obtaining this information, the authors also point out that there is a climatic phenomenon in the region, which is a unimodal rainfall regime, meaning that there is a very marked dry season and similarly a marked rainy season, which affects the level of the river and therefore the flow. The months where the river level is higher are between April and May, while the lowest level is observed in September and October; according to this information, a recalculation of the velocity was made on a monthly basis where the variation of level was included as a differential factor, the result can be seen in Figure 5-3.

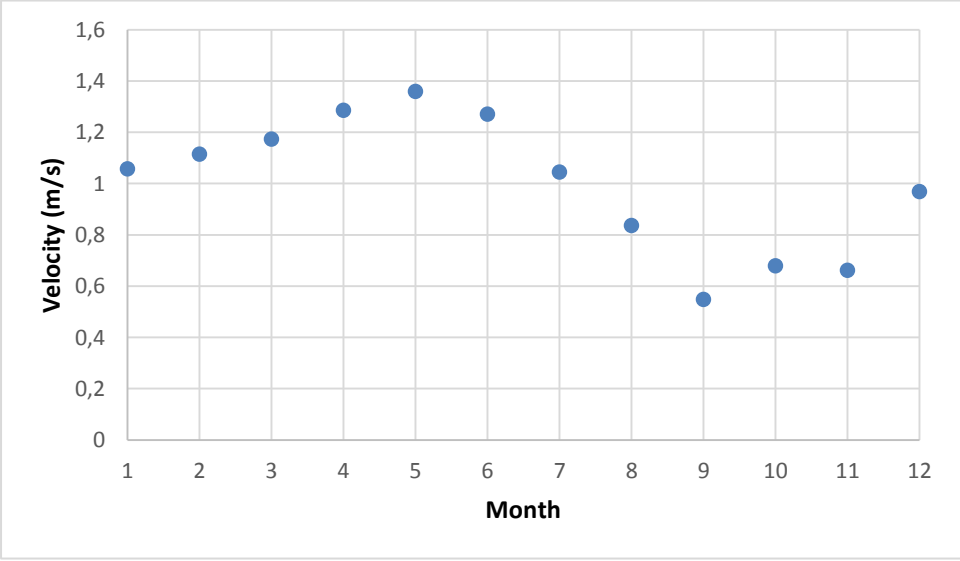

Figure 5-3. River velocity in m/s throughout the year considering level change (Month 1: January – Month 12: December).

The energy potential could be estimated using the previously obtained velocity data and the selection of the appropriate turbine for the location. Leticia is a city that does not have large height differences in the water currents located near the campus. For this reason, it is necessary to find a technology different from the conventional, which instead of taking advantage of the difference in height, makes use of the flow rate. This is the case with the emerging technology called “run-of-river”, whose main characteristic is the use of the natural movement of water currents, specifically their kinetic energy. The potential can be estimated by the following equation [**127**]:

$$P = \frac{1}{2}\,\rho A V^3$$

Where

P = power possessed by flowing water

ρ = water mass density

A = the area swept by turbine blades, equal to πr2

v = water velocity

For the sweeping area of the turbine, it was decided to install two turbines with a radius of 1.5m one next to the other, occupying a cross-sectional area of 3m, having in mind that that the river section where the installation is projected is 200m, the blades would be occupying a 1.5% of the total width causing minimal impact on the natural course of the river.

5.1.1.4 Biomass

To determine the potential of this resource, a calculation was made using the municipality of Leticia as a reference due to the lack of specific data within the campus. The Atlas of the Energy Potential of Residual Biomass in Colombia [**128**] was used for this, which evaluates the amount of energy contained in biomass from some representative species of agriculture, livestock, and organic solid waste. The estimation of energy potential is made using data reported by the institutions in charge of these sectors and the physicochemical composition obtained from the collection of field samples. It should be noted that, as the data is shown by department, those from Amazonas were used.

Initially, for the agricultural sector, the data reported in the atlas corresponds to the by-products generated during the harvesting and transformation processes of the crops. Eight representative crops were chosen by the authors: two transitory (rice and corn) and six permanent (banana, coffee, sugar cane, panela cane, oil palm, and plantain). The values reported are presented in Table 5-2.

Table 5-2. Energy potential of residual biomass from agriculture in the Amazonas department [**128**]

Crop	Sown area (ha)	Production (ton/year)	Amount of waste (ton/year)	Energy potential (TJ/year)
Rice	28	38	97	0.43
Corn	179	204	289	3.10
Plantain	670	2,008	12,350	7.05

From the crops selected in the atlas, only three are present in the department of Amazonas. It is essential to mention that the potential could be higher due to the presence of other crops in the region, such as cassava and some exotic fruit trees.

Regarding the livestock sector, in the atlas, the bovine, pig, and poultry subsectors were selected. The manure generated by their respective productive chains was considered residual biomass. In the department of Amazonas, pig and poultry farming are not very significant while the bovine sector is the most prominent within its economy. The estimated potential for this sector can be seen in Table 5-3.

Table 5-3. Energy potential of the residual biomass of the bovine sector in the Amazonas department [**128**]

Population (head/year)	Amount of manure (ton/year)	Energy potential (TJ/year)
7,148	28,383	26.19

In the case of urban organic solid waste, the Atlas considered waste from supply centers, market squares, and pruning of urban green areas in some Colombian cities where the data was available. A relationship between the volume of waste generated and the population reported was used to estimate the potential for the department of Amazonas, as shown in the Table 5-4.

Table 5-4. Energy potential of the residual biomass from urban organic solid waste in the Amazonas department [**128**]

Waste source	Total population reported	Amount of waste (ton/year)	Energy potential (TJ/year)	Energy potential per inhabitant (TJ/ year-person)
Supply centers and market squares	20,179,354	120,210	91.72	4.55×10^{-6}
Pruning of urban green areas	19,351,669	44,811	318.13	1.64×10^{-5}

Summing up, there is an energy potential of 10.58 TJ/year of agricultural waste, 26.19 TJ/year from the bovine sector, and 2.10×10^{-5} TJ/year-person of urban organic solid waste. Keeping in mind that these data have been reported to the Amazonas department, the energy potential of Leticia will be estimated using the percentage of economic contribution to the GDP assuming a proportional contribution to waste generation, thus, using a 75% of GDP contribution [**112**], the energy potential for Leticia will be 7.94 TJ/year for agricultural residue and 19.64 TJ/year for bovine. For urban organic waste, the factor found is multiplied by the reported population of Leticia (42,844 inhabitants [**113**]), reaching a potential of 0.9 TJ/year. Finally, grouping all the different sources, a final potential of 28.48 TJ/year is obtained.

5.1.1.5 Diesel and Natural Gas

In the case of diesel, it is the source used nowadays by the energy supply company and therefore it is considered that the amount available is sufficient to always meet the demand given that it is the scenario that currently occurs on the campus.

With regard to natural gas, storage in a stationary tank within the campus was assumed. The capacity was defined using the information contained in the resolution 2045 of 2016 of the Colombian Ministry of Mines and Energy, by which the technical regulations for cylinders and stationary tanks are issued. In this regulation, two important characteristics are emphasized, the first is that the maximum pressure must be 240 psi and the maximum filling capacity must be 42%. Reviewing the capacity of commercial stationary tanks offered in the Colombian market, the largest commercial capacity found is 5000 gal; it means that an effective volume of maximum 2000 gallons of gas will be stored at the

environmental conditions of Leticia and at the pressure mentioned in the standard considering what is stated in regulation.

5.1.2 Feasibility analysis

Considering all the possible energy sources, the proposed methodology for context evaluation was used to determine the feasibility of the sources for the place of study; the result is presented in Figure 5-4.

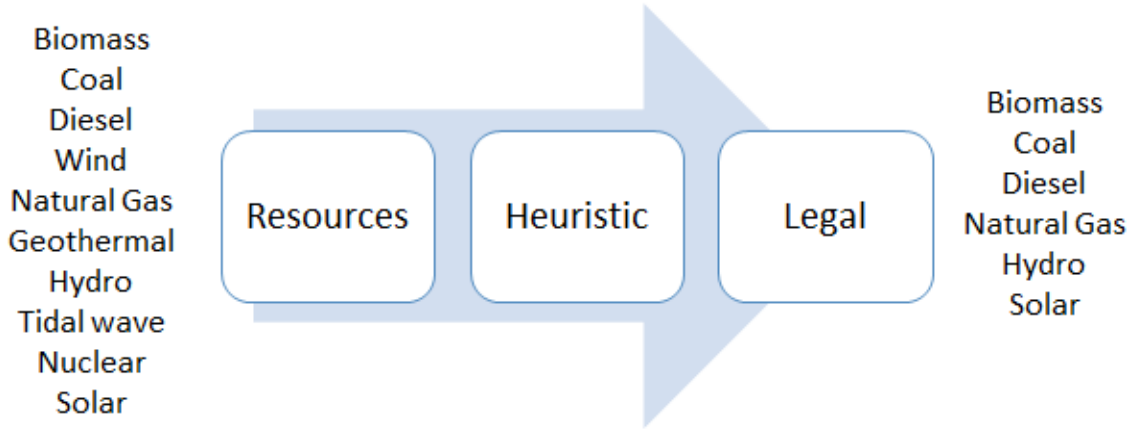

Figure 5-4. Resulting feasibility analysis for the Leticia campus

From the ten energy sources initially considered, after applying the respective filters, six feasible energy sources are obtained. First, in terms of resources, geothermal, tidal wave and nuclear were ruled out because they do not exist in the study area. Next, the wind resource had to be discarded because its potential is not enough to be exploited, according to a heuristic given by the UPME, which claims that wind speed should be higher than 3 m/s at a height of 10 meters to be viable [**128**]. From the legal point of view, no option was discarded since Colombian Legislation does not impose any restrictions on the installation of small-scale energy systems, as established by Decree 1076 of 2015, resulting available the implementation for facilities such as the campus.

5.1.3 Identification of sustainability indicators

5.1.3.1 Identification and classification of stakeholders

A list of the possible stakeholders involved was made to determine which of them could stand out for the implementation of the project using the stakeholders mapping. This process begins by identifying the parties involved, making a list of them, and classifying them on different scales. These scales were defined by the different environments where the stakeholders can be located and have influence over the project, starting from the smallest, such as a building, to the largest, which is the world. The result of this classification by scale can be seen in Table 5-5.

Table 5-5. Potential stakeholders of the project

Scale	Stakeholders
Building	Users (Students, teachers, administrative staff and guests)
Campus	Campus direction Maintenance workers Trade union Planning and Infrastructure Unit
Municipality (Leticia)	Contractors Energy provider Municipal Hall Habitants
Department (Amazonas)	Corpoamazonia(Environmental authority) Departmental Comptroller of Amazonas (fiscal control)
Country (Colombia)	Universidad Nacional general direction Ministry of Mines and Energy Ministry of Environment and Sustainable Development Ministry of Science, Technology and Innovation ANLA (National Environmental Licensing Authority) UPME (Mining and Energy Planning Unit) IPSE (Institute for Planning and Promotion of Energy Solutions for ZNI) CREG (Energy and Gas Regulation Commission) XM (Company of energy systems management) Superintendence of Industry and Commerce (Consumer protection) Superintendence of Home Public Services (Control for basic service providers) Consulting firms Colombian Association of Renewable Energies (Private Association) Environmental NGOs Financing entities
Continent (South America)	Environmental NGOs Financing entities Private Associations Latin American Energy Organization (OLADE)

World	Private Associations Environmental NGOs United Nations (UN) Organisation for Economic Co-operation and Development (OECD) International Energy Agency (IEA) International Renewable Energy Agency (IRENA) International Atomic Energy Agency (IAEA)

As can be seen, the country scale is the scale with the largest quantity of stakeholders, highlighting the existence of multiple actors in the Colombian energy sector, which could have a direct impact on the implementation of an energy supply system for the Leticia campus. To verify the direct impact on the project, the power-interest matrix was applied to the entire set of stakeholders, placing each one in a quadrant depending on how interested and influent they could be in the project´s implementation; this decision was based on the functions and scope defined in the organizational structure of each stakeholder. The result is presented in Figure 5-5.

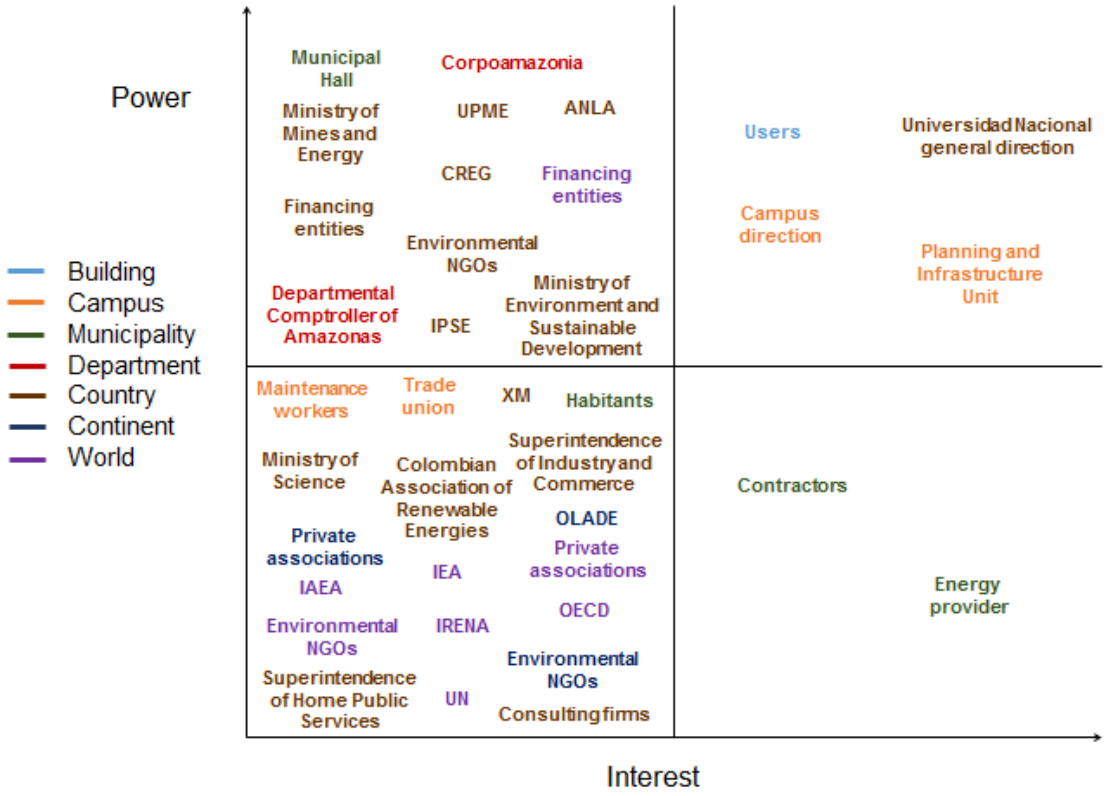

Figure 5-5. Power-interest matrix applied to the case study.

According to the power-interest matrix in Figure 5-5, it can be observed that most of the stakeholders are in the low interest quadrant. This is explained by the size of the project, since it is relatively small and located in a specific environment such as the campus, whose jurisdiction and management depend mostly on the Universidad Nacional de Colombia. However, for the power side, in the upper zone there are mainly the entities that define the project together with the control, financing, and regulatory bodies; most of these are from the Colombian context, seeing that they could interfere more directly in the projects than the entities at the global or continental level. On the other hand, there are some entities in the lower zone, the area of little power and interest. Even though they could participate and have some kind of interaction, their role is not so relevant in the implementation of the campus power supply system.

In order to better understand the interactions of the stakeholders, an additional study was conducted, taking into account the stakeholders located in the ranks of high power and high interest. Due to the large number and considering that many of them were similar in nature, it was decided to group them as shown in Table 5-6.

Table 5-6. Categorization of the stakeholders for the case study

Group	Stakeholders
Users	Users (Students, teachers, administrative staff and guests)
Direction	Campus direction Planning and Infrastructure Unit Universidad Nacional general direction
Contractors	Contractors
Local providers	Energy provider (Leticia)
Control entities	Corpoamazonia(Environmental authority) Departmental Comptroller of Amazonas (fiscal control) CREG (Energy and Gas Regulation Commission) ANLA (National Environmental Licensing Authority)
Legislators	Municipal Hall Ministry of Mines and Energy Ministry of Environment and Sustainable Development
Promoters	UPME (Mining and Energy Planning Unit) IPSE (Institute for Planning and Promotion of Energy Solutions for ZNI)
Activists	Environmental NGOs (Country, continent and world level)
Funders	Financing entities (Country, continent and world level)

Once the stakeholders were grouped, an analysis of the possible interactions between the different groups was carried out with the aim of identifying which of these were the most influential for the development of a project of this type, resulting in the scheme presented in Figure 5-6.

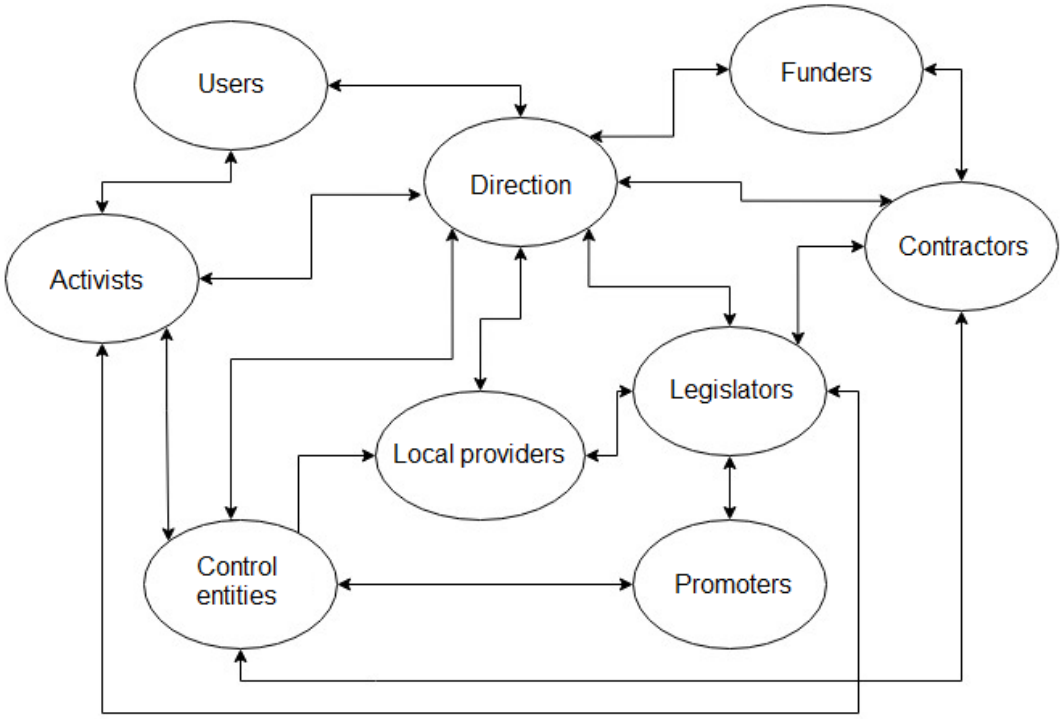

Figure 5-6. Stakeholders mapping

In the map in Figure 5-6, it can be observed that the direction group has a relationship to most of the others, concluding that it is the most important stakeholder, which is logical because it is the main group involved in the decisions, and in the case of implementing the project, it will be the most affected in several aspects. For example, in the economic aspect, this group would have to be in charge of a large percentage of the costs being supported by the funders. In the same way, at the infrastructure level, the project would affect the campus due to the installation works in a process where the users and activists could be involved; at last, the direction would also be in charge of interacting with the different control entities and contractors and carrying out the project within the legal terms defined by the legislators.

In addition, in a second degree of importance are the control entities and legislators, who define the regulatory framework for the implementation of energy supply projects; without their approval; it would not even be possible to imagine them. Finally, in a third degree, there are contractors and activists; the former play a very important role because they are in charge of construction, installation, and even the acquisition of technologies, while the latter can have a high degree of influence, being able to promote or block the project.

5.1.3.2 Need analysis as a tool for adapted indicator selection

From the stakeholder mapping, the main groups were found, as well as their possible relationships. With this information, it was possible to apply the ReAR methodology to identify possible needs. For this, it was necessary to analyze each of the connections, listing what activities are carried out by each of the actors. For each of these activities, there will be another stakeholder(s) involved who will be directly affected; similarly, the resources needed to carry out the activity and its respective result must be identified. As a result of the ReAR methodology, Table 5-7 presents the identified limitations resulting from its application. The complete development of this methodology for this project can be seen in Appendix I.

Table 5-7. List of identified limitations

Limitation	Explanation
Installed capacity	Without a good installed capacity, it is not possible to produce the amount of energy demanded. Installed capacity also influences the reliability of the network because it ensures a continuous supply of electricity.
Energy source availability	If the energy source is not available, the amount of energy that can be produced may be limited. If the resource exists, it should be consumed as little as possible to ensure its future availability.
Financial solvency	Without financial solvency, the different investments required to carry out the project could not be made.
Agreement	There must be an agreement between different groups to implement projects.
People / Initiatives	If people are not involved or if there are no initiatives, the project could lose a certain degree of acceptance, generating a rejection.
Knowledge	Without knowledge, new ideas and proposals cannot be generated.

Supply / Demand Balance	The price of energy depends on the balance between energy supply and demand.
Targeting of public resources	There should be financial support from public institutions for projects involving renewable energies.
Area	The extension of the new infrastructure to be installed is limited by the available area.
Level of generated interest	If users are not attracted to the programs proposed by the project managers, acceptability will be low.
Infrastructure	The network will not properly work or will fail if there is no good infrastructure.
Climatic factors	There may be natural events that prevent the operation of the network or otherwise condition the availability of the source.
Diagnosis time	The project evaluation time must be short to be able to make decisions quickly.
Estimated execution time	The project must be completed in the shortest possible time to avoid inconveniences and possible cost overruns.
Spare parts	The necessary spare parts should be easily obtained and with a low cost.
Trained staff	In the absence of specialized personnel, problems will take longer to be solved, and as a consequence, cost overruns will occur.
Number of equipment	The system must be as simple as possible and use the fewest number of units possible, as this will affect the cost and, due to the difficult access location, possible long delivery times.
Installation time	The project must be completed in the shortest possible time to avoid inconveniences and possible cost overruns.
Price	Energy must be produced at a competitive price compared to the existing supplier.
Production capacity	Depending on the production capacity, the purchase price from the local energy provider could vary.
Stakeholder transparency	If any of the parties involved are not transparent, the project may have a longer execution time or possible cost overruns.
Weak legal framework	Without a supporting legal framework, the project may be at a higher risk of larceny due to factors such as poor budget control.
Compatibility with existing network	If the new network is compatible with the existing one, it is possible to expand the capacity and increase the reliability of distribution.
Treatment capacity	Low treatment capacity leads to poor waste management.
Amount of waste	The generation of large amounts of waste should be avoided because the environmental impact is greater and greater treatment capacity would be required.

Appropriate studies	Without adequate studies, the new infrastructure will not perform well, resulting in malfunctions, cost overruns, or safety risks for users.
Land-use planning	It must be clear which areas are modifiable and suitable for the construction of the new network.
Probability of accidents	It is necessary to have a low probability of accidents to ensure user safety and avoid possible insurance cost overruns.
Insurance coverage level	If the level of coverage is low, the damages caused by the events could not be covered.

5.1.4 List of selected indicators

A list of the sustainability indicators and MCDA methods involved in studies related to the implementation of renewable energies was obtained from the literature review. This information may help potential users of MCDA identify and set a group of indicators in terms of sustainability.

In the bibliographic review, after carrying out the three-filter system described in Figure 3-4, a total of 499 articles were obtained: 400 were found with the proposed search equation and 99 from the research group database. Although the search was focused on the selection of energy sources, results from other related applications appeared, such as land use planning, buildings (construction), mining, brownfield land, urbanism (urban land), water treatment, municipal landfills, electric vehicles, transportation, forestry (plantations, wood production), sidewalks, and another not related or unusual like e-government. With the use of the three-filter system, a total of 153 articles were selected, which were published mainly by European countries, where Italy, Spain, Greece, and Turkey stand out. This trend has been documented in several reviews [**12**,**129**] and can be interpreted as a sample of the global effort to transition to renewable energy sources. For example, in countries such as Italy and Greece, which have small, isolated islands, these studies seek a better way to extend the coverage of electricity.

Likewise, it is observed that publications of MCDA on energy planning have been increasing over time. This fact can be explained because this methodology appears as an appropriate response to support the decision-making process, making the decisions more clear and justifiable due to the variety of methods and adaptability of uncertainties

associated with these problems. MCDA applications in energy planning cover mainly two aspects. First, the compilation of methods used in MCDA on energy planning, and second, the collection of sets of indicators included in the evaluation methods. In this case, it should be noted that not only MCDA is comprised, the indicators can be used in other methodologies such as life cycle analysis (LCA), optimization methods, own proposed, among others.

Some reviews have been made with the purpose of knowing the most commonly used indicators currently on MCDA for energy planning. Wang et al. [**13**] made a classification of indicators employed on energy supply systems, classifying them in four aspects: technical, economic, environmental, and social criteria. In parallel, Dorning et al. [**130**] reviewed 179 papers that described or used energy indicators to compare different primary energy sources, showing the specific measurement units applied to quantify each indicator. Another approach was identified, where an indicator review is made in order to select and use some in a specific case study. Santoyo-Castelazo and Azapagic [**131**] recapitulated many studies and listed some indicators to assess the sustainability of various electricity scenarios for Mexico in the year 2050. Shaaban and Scheffran [**132**] presented a collection of indicators from the literature with the intention of selecting those of high importance and relevance based on interviews with energy experts and then applying them in a case study in Egypt. Lastly, Kuleli Pak et al. [**69**] reviewed and selected with experts some environmental indicators to evaluate in a sustainable way the impact of renewable energy sources in Turkey.

With the purpose of including sustainability indicators in this study, the first step was to list the indicators that have been involved in studies related to the implementation of renewable energies. For this, the 153 selected articles were used as the basis for this study; however, given the amount of information to be extracted, much of it was repeated. Thus, a final selection of 29 articles was made, of which 12 were review articles that previously worked on the search for indicators and the other 17 were studies of the design of energy supply systems using MCDA. These were selected using two criteria: the first was the total number of citations, and the second was the number of citations per year, taking into account the validity of the study over time. The list is presented in Appendix II.

As a result of the strategy previously described, a total of 690 indicators were collected; at first glance, it seems like a large amount, but it is necessary to refine them in order to make a proper selection. Consequently, the indicators were grouped by name and reduced to a total of 448, considering a literal match. Then, the indicators were grouped into the dimensions reported by the authors. It was observed that, in addition to the four dimensions usually reported (technical, economic, environmental, and social), some authors considered other different dimensions such as energy [**133**], politic [**129**,**134**], risk [**135**], quality of life [**133**,**136**]. In the same way, the traditional dimensions were considered but grouped under names such as socio-political or technical-economic; besides, some dimensions, despite covering the same field, have a different name. It is the case of the technical dimension sometimes named technological, or as in the case of economic dimension sometimes named financial [**15**]. It should be noted that the classification depends on the researcher's point of view, and many indicators are placed in different dimensions; for example, visual impact is found in social and environmental dimensions. On the contrary, it was also found that many authors used the indicators directly in the MCDA method without the need to classify them [**18**,**129**,**137**], so a dimension was assigned according to the way they were put into use.

After reviewing the definitions proposed by the authors for each indicator in the list collected, it was found that some had the same definition despite the different name, leading to a reduction from 448 to 215 indicators. It is worth mentioning that the meaning of the indicator could change depending on the author; sometimes the same indicator is found in the literature with different definitions; this is important for the selection process because an indicator could evaluate the problem in a completely different way depending on its meaning. By way of example, security/safety indicator can refer to the reliability (presence of supply interruptions) or also to the probability of any damage, injury, or accident. Otherwise, some indicators express the same despite having a different name, which is the case of continuity and network stability.

Despite a considerable reduction in the number of indicators, there is still a large number, so a more specific filter was considered to continue with the selection of indicators. For this, it was decided to divide the indicators into qualitative and quantitative categories, with quantitative indicators being chosen in this case, this choice was made thinking

about the next phase, the optimization model, which requires a modeling based on numerical values. As a result, a total of 80 indicators were obtained, of which 20 were technical, 20 economic, 31 environmental, 5 social, and 4 political, and are listed in Appendix III.

This result shows that although all dimensions of sustainability began to be included, it is difficult to find indicators of the social and political sphere, whose appearance in studies is relatively new. In addition, they tend to be mostly qualitative indicators, as opposed to technical, economic, and environmental indicators. This fact confirms a new trend in studies where social factor is included in various published articles [**18**], but the inclusion of environment or social indicators makes the treatment much more uncertain because there are few historical data or patterns to take into account.

For the final selection of indicators, various factors were considered. Initially, a contextualization must be made in order to make an appropriate choice according to the framework of the study; a first selection was made using the needs analysis done previously, associating the limitations found to a principle, then to a criteria, and finally to indicators. As a result, 29 quantitative indicators were found to meet the needs of the project; this association is shown in Table 5-8. However, in some of these, it was not possible to find a previously existing indicator in the studies that could cover the limitation, either due to the fact that the evaluation is made in a qualitative manner or simply because it does not exist.

Table 5-8. Indicators associated to needs of case study.

Limitation	Principle	Criteria	Possible indicators
Installed capacity	Ensure infrastructure that meets demand with a continuous supply of energy	Promote technologies that work most of the time using few resources	Capacity factor Availability Efficiency
Energy source availability	Sufficient availability of resources to be used for energy production	Ensure the amount of resources needed for the project	Resource Availability. Water consumption

Financial solvency	Get the financial resources to carry out the project	Control of expenses and investments	Capital Costs Annualized Costs Fuel Cost Net Present Value Investment Cost Operation and Maintenance Cost
Agreement	Participation and inclusion of entities with different interests to reach a common agreement.	Reliance on participative decision-making processes	N/A
People / Initiatives	Support of stakeholders to the project	Choose an alternative with high acceptance	N/A
Knowledge	Encourage generation and sharing of knowledge	Improve transfer of skills, technology, as well as knowledge between organizations.	N/A
Supply / Demand Balance	Define a price that is in line with the context of the project.	Profitability generated through energy production	Levelized Cost of Electricity
Targeting of public resources	Increase resources from public entities for energy supply projects.	Decrease in project expenses	Subsides Feed-In-Tariffs
Area	Make efficient use of space	Use of as little space as possible	Land Use Distance
Level of generated interest	Change perception of risk and benefits distribution in neighboring communities	Promotion of user awareness.	N/A
Infrastructure	Ensure the use of high quality materials and good manufacturing practices with high productivity	Reduction of technical failures	Capacity factor
Climatic factors	Reduction of pollution caused by fossil fuels	Inclusion of renewable energy	Renewable Fraction
Diagnosis time	Identifying potential problems as quickly as possible	Quick solution to problems encountered	Implementation Period Realization time Lifespan Payback Period
Estimated execution time	Project time management	Decrease in project execution time	Implementation Period Realization time Lifespan Payback Period
Spare parts	High accessibility to materials, tools and working personnel	Expand the purchasing power to respond to the demands of the project	Operation and Maintenance Cost

Trained staff	Involvement of specialized personnel for problem solving during the execution of the project	High expertise and performance of selected workforce	N/A
Number of equipment	Select easy-to-use and easy-to-acquire technologies	Increase of technical feasibility	Efficiency Investment Cost Fuel Cost
Installation time	Guarantee a development of the project according to the estimated times	Rapid project execution	Implementation Period Realization time Lifespan Payback Period
Price	Produce energy at a competitive price in the local market	Reduced production cost	Levelized Cost of Electricity
Production capacity	Generate energy to meet the demand	Increased access to energy	Capacity factor Availability
Stakeholder transparency	Perform controls to ensure processes in accordance with regulations	Availability of detailed information on the performance of each stage of the process.	N/A
Weak legal framework	Follow existing regulations related to the development of the project.	Compatibility with political, legislative and administrative framework	N/A
Compatibility with existing network	Integration of the energy generated to the existing distribution network	Simplicity of connection between the new and the existing network	Availability
Treatment capacity	Ensure adequate waste and emissions treatment	Growth of the waste and emissions treatment capacity	CO_2 reduction Energy Saving
Amount of waste	Minimization of environmental impact	Reduction of amount of waste generated	CO_2 reduction Carbon Tax Energy Saving
Appropriate studies	Obtain the necessary information to find the best way to produce energy	Strategic technology roadmap according to technical requirements	N/A
Land-use planning	Respect the territory destined for a possible construction of an energy production system	Reduction of area used	Land Use Distance from residential areas
Probability of accidents	Risk prevention	Increase the level of process safety	Accident fatalities Distance from residential areas CO_2 emissions Human Health Impact Particles emissions

Insurance coverage level	Support project integrity in the face of an unexpected adverse event	Reception of compensation for damages	External Costs Human Health Impact

Consulting the literature, it is stated that as the number of criteria and indicators increases, the evaluation will be more rigorous and objective from the point of view of sustainability; nevertheless, an excessive number of them proportionally increases the complexity of the solving process. According to the literature, the typical number of indicators used in the MCDA studies is between 6 and 10 [**12**]. Taking this into account, it was decided to further reduce the number of indicators to be used in the study.

A revision of the definition of the indicators was made, and it was found that it was possible to group them despite the slight differences. For example, in the case of capital cost and investment cost, implementation period and realization time. In the same way, it was verified that there was no redundancy in the indicators, which means that they do not evaluate similar things or that they are linked somehow. For example, in the case of CO_2 reduction and CO_2 emissions, although by definition they are different, they evaluate practically the same; the same occurs with carbon tax and CO_2 emissions, where both indicators are linked since carbon tax depends on the amount of CO_2 emitted. In parallel, the applicability of the indicators was taken into consideration, as in the case of the renewable fraction, an indicator that could be useful but not at this stage because the initial purpose is to compare the different energy sources by means of the MCDA, so it is not possible to report a value; the same happens with indicators such as net present value and payback period, whose value is known once the project is defined.

After this analysis, 13 final indicators were selected, and their proposed definition based on the information found in the literature is presented in Table 5-9.

Table 5-9. Definition of sustainability indicators selected for the project.

Dimension	Indicator	Definition
Technical / Technological	Efficiency	The ratio of the output energy to the input energy, referring to how much useful energy can be obtained from an energy source [**13**,**26**,**138**,**139**,**140**].

	Capacity factor	Ratio of the electrical energy produced during a time period to the energy that could have been produced at continuous full power operation during the same period [**15**,**26**,**105**,**140**].
	Realization time	Time required to set up and put into operation the power plant designed, including installation, testing, and commissioning time [**105**,**136**].
	Lifespan	The expected lifetime, or the acceptable period of use in service [**13**].
Economic	Operation & Maintenance Cost	Operation and maintenance costs (O&M) consist of two parts. One is the operation cost, which includes wages and the funds spent for the energy, products, and services for the energy system operation. Another is the maintenance cost, which includes spent to extend the life of the energy system and avoid failures that could cause its operation to be suspended [**13**,**26**,**105**,**139**,**141**].
	Capital Cost	Total cost of establishing a power plant included the cost of land, equipment, labor, installation, infrastructure, and commissioning [**26**,**105**,**131**].
	Fuel Cost	Funds spent for the provision of raw materials necessary for power plant operation [**13**,**26**]
Environmental	Land Use	Land required by a power plant [**13**,**105**,**136**,**139**].
	CO_2 emission	Estimated GHG emissions expressed in carbon dioxide equivalent of an energy system [**130**,**136**,**138**,**139**,**142**].
	Water consumption	Volume of freshwater used and then evaporated during the production of energy [**143**,**144**].
	Particle emission	Particulate matter emissions released by power plant operation, depend mainly on the technology used and on the fuel quality [**136**].

Social	External costs	Cost generated over the entire lifecycle of an electricity generation plant for the restoration of the bad side effects of its operation on human health and the ecosystem [**26**,**140**].
	Accident fatalities	Number of fatalities of workers and public due to normal operation or severe accidents [**69**,**136**,**142**,**145**]

5.1.5 Application of a multi-criteria decision analysis tool for ranking of desirable technologies

With the defined indicators, the feasible energy sources obtained from the 3-filter system explained previously in the section of context definition were ranked using the AHP method. This method was chosen because of its simplicity and the fact that it presents an ordered list of options according to the different preferences of the stakeholders as a result. To apply it, it was necessary to find reported values of the indicators for each of the six energy sources. For this, an exhaustive search was made in the literature for each of the selected indicators, and after consultation, several values are reported, which can be seen in Appendix IV. A statistical treatment of the data collected was performed using the Grubbs test described previously in order to obtain a unique value for each source. The values are shown in Table 5-10.

Table 5-10. Indicators values for selected energy sources

Indicator	**Energy source**					
	Biomass	Coal	Diesel	Natural Gas	Hydro	Solar
Capacity factor (%)	77.7	63.7	64.5	65.9	39.8	21.9
Realization time (Months)	17.6	44	12	24	24	16.4
Lifespan (years)	19.3	35.8	16.7	19.6	32.3	23.2
Efficiency (%)	29.4	39.7	38.8	45.8	84.3	16.6
Operation and Maintenance Cost ($US/MWh)	8.61	6.75	13.19	1.63	6.57	5.36
Fuel Cost ($US/kWh)	0.0204	0.0124	0.08	0.0473	0	0
Capital Cost ($US/kW)	2,291	1,701	573	765	2,039	3,656

Land Use (m^2/kW)	1607.4	1003	148.3	2.2	473.78	42.49
Water consumption (m^3/MWh)	7.054	15	2.766	14.704	0.033	1.379
Particles emissions (mg/kWh)	498.0	157.7	102.6	8.8	1.7	33.7
CO_2 emissions (g/kWh)	41.4	996.2	379.5	465.8	27.1	65.1
External Cost ($US/kWh)	0.0236	0.0654	0.0446	0.0142	0.0046	0.0030
Accident fatalities (Deaths/TWh)	0.0009	0.0289	0.0439	0.0097	0.0356	0.0002

With the values in Table 5-10, the next step to apply the method is to define the weights for each of the dimensions considered. A weight is assigned to a dimension, criteria, or indicator to point out its relative importance. This process should be made regardless of the number of factors used, and it determines their impact within the sustainable energy decision making problem. This assignment could be made employing mathematical methods or based on the preferences of multiple actors, such as experts, people from a targeted community, government organizations, NGOs, etc. In the case of subjective assignation, more experts are needed to modify the subjective weights to get a high concordance, and, for the objective weights, combination methods are applied to determine the integrated weights [**18**]. Neither approach is perfect because errors are unavoidable to some extent. However, the objective ones are relatively weak compared to the subjective [**13**]. One of the advantages of the AHP method is that it allows, through the comparison matrix, the decision-maker to obtain a calculation of the weights, transforming a subjective assessment into something numerical, as long as the required consistency is met.

In this application, it was decided to perform a sensitivity analysis in order to observe the behavior of the result using different weights. The sensitivity analysis was made by adjusting the weights of the indicator; this is a highly useful option for analysis because it allows the user to appreciate the effects of different assumptions on the outcome, showing which is expected for stakeholders representing different interests [**15**]. This option was possible since a final decision should not be made yet and the AHP methodology is only one more filter to select the most suitable options to be included in the next phase, the optimization model.

TOTAL DECISION® software was employed to apply this method to this problem, the software; it allows the users to automatically perform the AHP with a simultaneous sensitivity analysis. An initial scenario where all four dimensions have the same weight (25% each) was established; an important assumption for using this method was that the weight of a dimension is divided equally for each of the indicators within the dimension.

The sensitivity analysis was performed for each dimension, which means that a sweep was made varying the value of weight for a specific dimension and distributing the remaining percentage in the others; for example, assuming 40% importance assignment for one dimension and knowing that the weight of a dimension can vary from 0 to 100%, the remaining three dimensions will be distributed with an equal weight of 20%. This process was done for each of the four dimensions, and the results can be seen from Figure 5-7 to Figure 5-10.

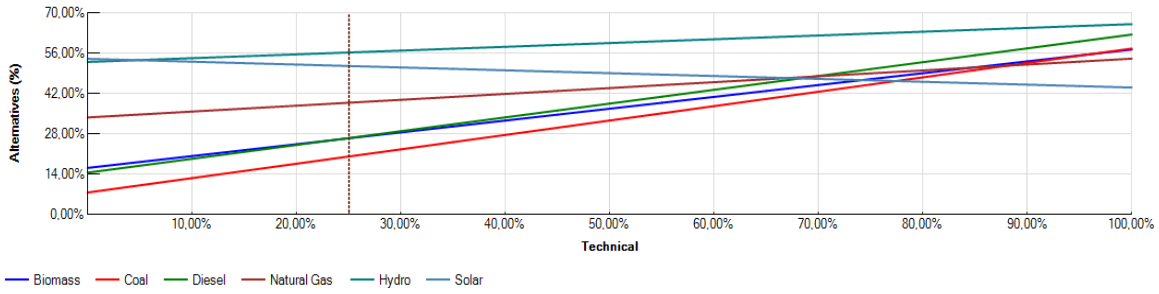

Figure 5-7. AHP Sensitivity analysis of technical dimension.

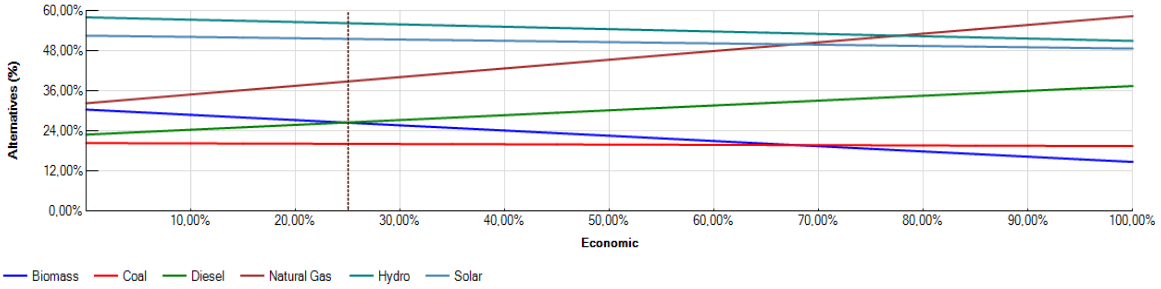

Figure 5-8. AHP Sensitivity analysis of economic dimension.

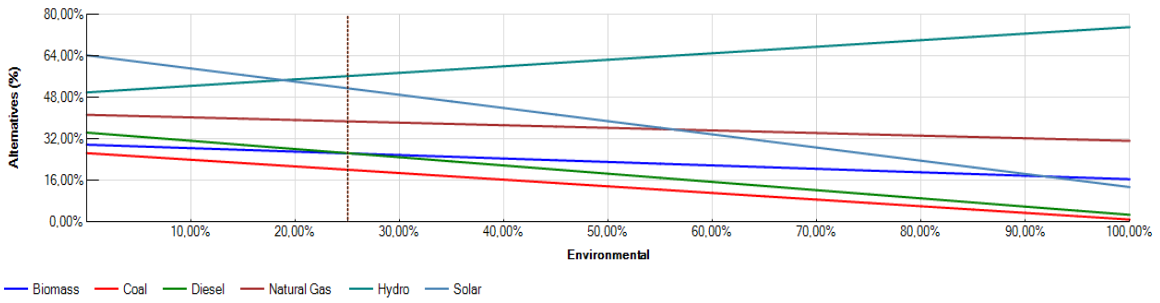

Figure 5-9. AHP Sensitivity analysis of environmental dimension.

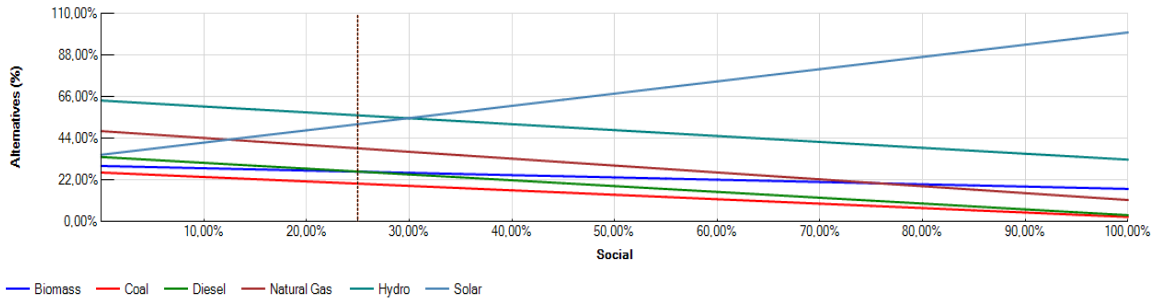

Figure 5-10. AHP Sensitivity analysis of social dimension.

As a result of the analysis, the figures show a series of lines that reflect the variation in percentage of preference or inclination towards one alternative, each with a different color; the higher the percentage, the more suitable an alternative is. Observing the sensitivity analysis in each of the four dimensions, it is clear that for the initial scenario, represented by the vertical dotted line, there is a slight advantage of these three sources of energy: hydro, solar, and natural gas. Reviewing the complete scan by varying the weights of each dimension in the spectrum from 0 to 100%, it is noted that, in general, the three sources above are the most suitable in the vast majority of the weights' distributions. However, when the weight of the dimension is increased, the inclusion of one or two extra sources can be seen. For example, this effect can be observed in the technical dimension, where diesel and coal appear with a weight of around 80%, and in the same way in the social dimension, where biomass appears as an alternative when the weight is about 75%.

Finally, through this analysis, it is concluded that four of the six alternatives will be used in the optimization model. Three of them will be those that, according to the multi-criteria method, could be the most suitable to implement (hydro, solar, and natural gas), while the

fourth to include is diesel, which, although the model shows that there is not much preference, is the source that is currently used at the project site, so it is necessary to include it because it is the existing scenario and the starting point to consider in the model.

5.1.6 Multi-period optimization model

With the selection of the four energy sources, it is possible to implement the optimization model, whose approach and development were explained in Section 3.2.7. The objective of this model is to propose how the different energy sources should be distributed according to the priorities of the decision maker(s), satisfying the demand at the study site.

As observed in Figure 3-8, a battery was included in order to analyze whether it is worth storing energy so that it can be used in the future; this addition led to a collection of data corresponding to each of the indicators for this element, which can be seen in Table 5-11. The values reported are the result of a process completely analogous to the carried out for the different energy sources, and in the same way, the source values can be consulted in Appendix IV.

Table 5-11. Indicators values for battery.

Indicator	Value
Capacity factor (%)	96.67
Efficiency (%)	80.76
Operation and Maintenance Cost ($US/MWh)	3.93
Fuel Cost ($US/kWh)	0
Capital Cost ($US/kW)	933
Land Use (m^2/kW)	220.56
Water consumption (m^3/MWh)	0.173
Particles emissions (mg/kWh)	284.8
CO_2 emissions (g/kWh)	110.33
External Cost ($US/kWh)	0.01
Accident fatalities (Deaths/TWh)	0.2396

Observing the indicators presented in Table 5-11, it is important to highlight that some of the indicators used during the application of the multi-criteria methodology for the

selection of the energy source, i.e. lifespan and realization time, do not appear in the case of the battery. This is because they will not be used in the optimization model, given that values are not normalized to the amount of energy, and consequently they have no influence on the final model estimation. Similarly, it should be noted that technical indicators must always be included since the performance of an energy source is governed by them, so stakeholders' preferences will change according to the distribution of weights between the economic, environmental, and social components.

The optimization model explained in Chapter 3 was applied for the Leticia campus of Universidad Nacional de Colombia, considering the availability of each source and the demand. To show more clearly and concisely the result obtained from the model, it was decided to make a sort of ternary diagram, presented in Figure 5-11, in which each axe represents one dimension.

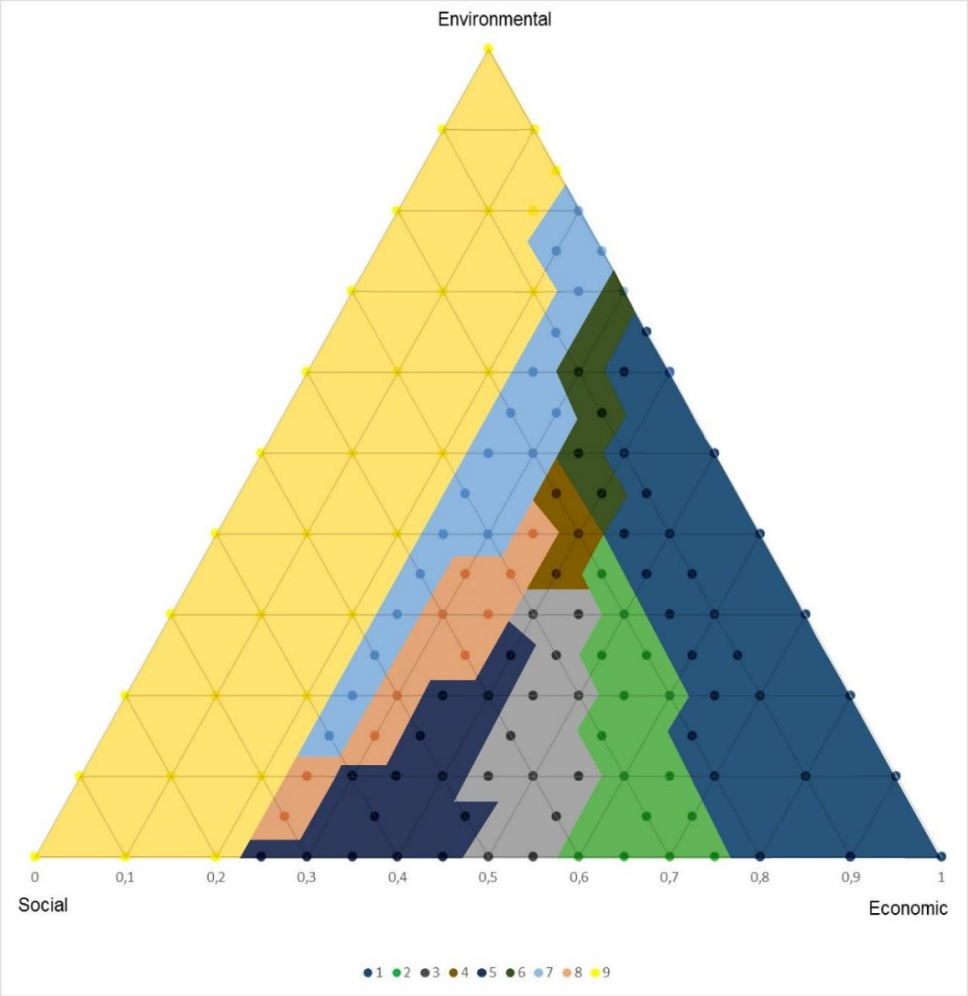

Figure 5-11. Final result of the optimization model for the case study

As a result of optimization, each combination of weights is associated with a single point in the ternary diagram, as can be seen in Figure 5-11. Strictly speaking of the case study, the Leticia campus of Universidad Nacional de Colombia, 134 combinations were modeled, and from this, 9 zones were found where the numerical result from the model in each one was the same. These zones represent different scenarios where there is a unique combination of energy sources; at the same time, an approximate delimitation of them was made by shading using the points found as a base.

It is worth mentioning that this model was able to generate various scenarios, each suggesting a different proposal that meets the demand depending on the preferences of the stakeholders in multiple dimensions, showing that there is no single optimal solution for this case study. This approach makes this study different; although some studies obtained various scenarios with the prioritization of certain dimensions, such as that of Stein [**15**], the main particularity and advantage of the proposed approach is that a sweep was made calculating all combinations so that all possible scenarios could be found. This fact is very important because, as has been pointed out in many studies, an unique optimal solution could be found by only considering a single criterion, but in most real-life decision situations, basing a decision on a single criterion is insufficient [**10**].

Before presenting the entire set of scenarios found for the case study, an explanation of how to use the ternary diagram obtained as a result of the optimization will be provided. Each of the edges of the triangle represents a weight of 100% for the assigned dimension; this percentage is distributed depending on the location within the diagram. For example, considering an equal weight for all dimensions (approximately 33.33% each), the proposed scenario would be Scenario 8. In the same way, each proposed scenario has a bar chart that indicates how the total energy demand for each month should be distributed for each of the sources, which are represented by different colors: yellow for solar, gray for hydro, orange for gas, blue for the grid, and finally green for the energy stored in the battery. With this information, a detailed explanation of the scenarios is presented below.

Scenarios 1 and 9 are observed in Figure 5-12. These scenarios could be said to be analogous since the entire demand could be met using a single energy source. In the

case of scenario 1, it is by means of energy from the grid, which is the existing situation on the campus with the use of diesel as basic source and a predominance of economic preferences. On the other hand, in scenario 9, the energy is provided only by the solar source; it should be noted that this scenario results when a weight of 100% is considered in the social component or the environmental component. It can also be seen that these scenarios can be generated through a large number of combinations of weights, covering a large area within the diagram.

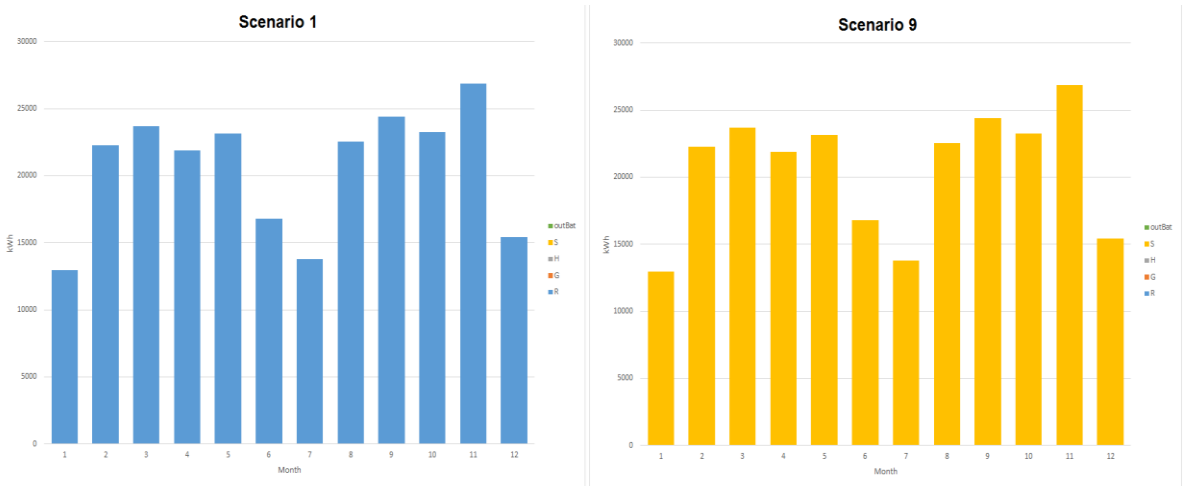

Figure 5-12. Scenarios 1 and 9 generated by the model.

As can be seen in Figure 5-13, scenarios 3 and 4 are very similar; the case of scenario 4 is highly particular because it is the scenario least likely to occur. Both scenarios use three energy sources (gas, hydro, and diesel); the only difference is that in scenario 4, there is a slightly higher participation of hydro in the energy matrix, contributing more in months 1, 6, 7, and 12. This behavior can be explained by the way in which the weights were distributed.

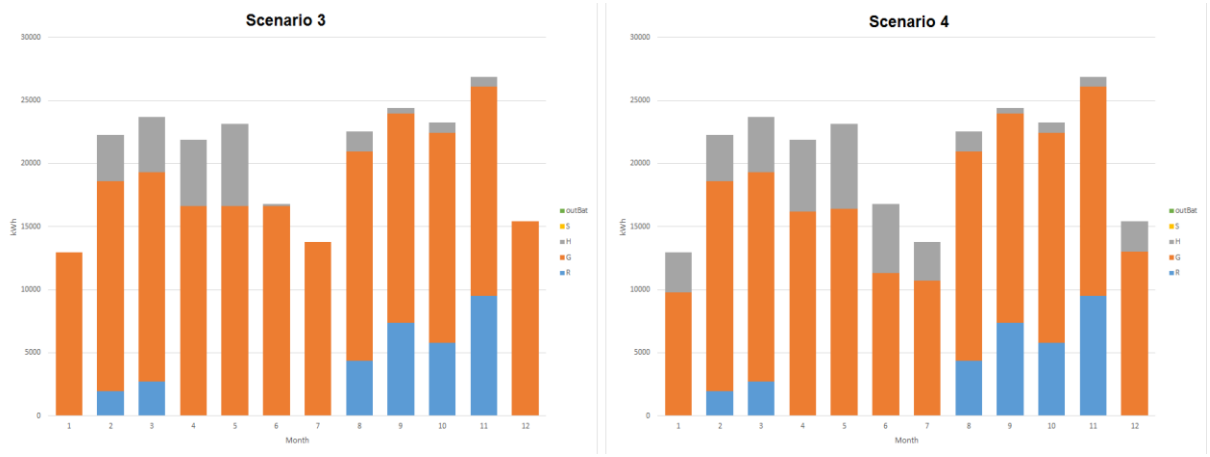

Figure 5-13. Scenarios 3 and 4 generated by the model

As shown in the previous case, scenarios 5 and 8 are also analogous, but in this case the demand is met by means of gas, solar, and hydro sources as seen in Figure 5-14. The difference between the two scenarios is the same as in the case described above, where in certain months of the year there is a greater use of hydro resource. This phenomenon is explained by the fact that months 1, 6, 7, and 12 have lower energy demand throughout the year, so the source choice can be more flexible since those months require a minor amount of energy. In addition, the inclusion of hydro source in scenarios 4 and 8 could be explained by the distribution of weights, specifically in the environmental dimension, where an increase prioritized the hydro resource over gas, changing the scenario initially proposed by the model. This effect is due to the values of the indicators; according to the reported quantities, gas indicators have a higher value than hydro ones, which translates into a greater impact.

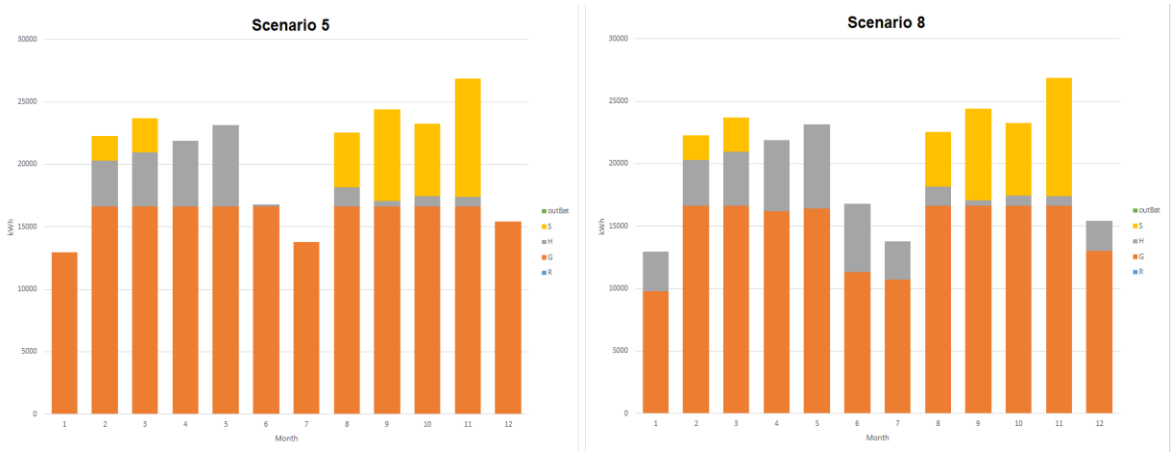

Figure 5-14. Scenarios 5 and 8 generated by the model.

The last three scenarios are 2, 6, and 7, presented in Figure 5-15. The particular feature of those scenarios is that the demand can be met by two different energy sources. However, the combination obtained will depend on the way the preferences have been established. In scenario 2, the proposed combination is between gas and the traditional grid; scenario 6, similar to scenario 1, where the traditional diesel-based grid predominates, the difference here is that a small fraction is covered with energy generated by hydro; and finally, in scenario 7, the same behavior takes place, where the scenario totally covered by solar is complemented by hydro source.

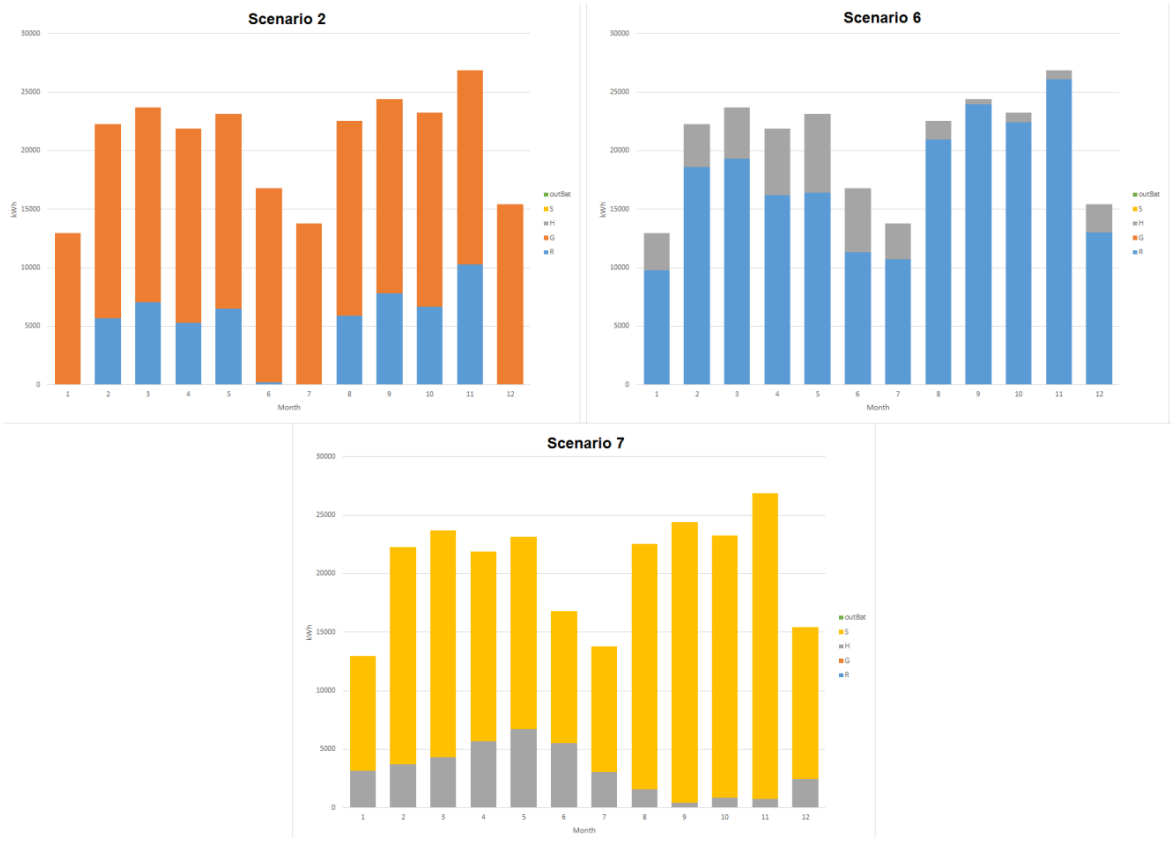

Figure 5-15. Scenarios 2, 6 and 7 generated by the model

Finally, after viewing the configuration of each scenario, the numerical value obtained for each of the selected indicators is presented in Table 5-12. This information is beneficial to learn more about the differences that could exist economically, socially, and environmentally during a year of operation for each scenario and to be able to give a more quantitative point of view to stakeholders so they can make better-informed decisions.

Table 5-12. Numerical values obtained for each of the scenarios found by the model for the case study

Indicator	Scenario								
	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9
Operation and Maintenance Cost ($US)	0.0	312.4	468.1	540.1	638.1	251.5	1,370.7	710.2	1324.3
Fuel Cost ($US)	0.0	29,996	29,996	27,712	29,996	0,0	0,0	27,712	0,0
Capital Cost($US)	86,812	223,109	281,876	307,695	431,851	181,774	1,168,642	457,670	1,254,617
Land use (ha)	5.1	1.2	2.3	3.2	1.8	6.8	3.8	2.8	1.5
Water consumption (m^3)	683.4	2,971.4	2,906.7	2,692.6	2,862.7	578.8	289.2	2,648.6	340.7
Particles emissions (Kg)	25.4	7.4	5.0	4,9	2.8	21.5	7.1	2.7	8.3
CO_2 emissions (ton)	93.8	110.3	102.0	95.6	92.0	80.3	14.6	85.6	16.1
External cost ($US)	11,019.8	5,193.4	4,245.7	4,105.7	2,925.7	9,488.5	802.5	2,785.6	741.24
Accident fatalities (Deaths)	1.08E-5	4.29E-6	4.10E-6	4.47E-6	2.71E-6	1.05E-5	1.40E-6	3.09E-6	4.94E-8

Observing the model and the results obtained, apart from mentioning the fact that it was possible to generate multiple scenarios, it should be highlighted that the final number of configurations was relatively small considering the endless possible combinations of the weights of the three dimensions. This effect can be associated with having normalized values; thus, even if the results of the final objective function were numerically different, the resulting scenarios proposed could be grouped because of the equivalent output.

Another remarkable result was the non-inclusion of the battery; although it was comprised in the mathematical formulation of the model, it was never considered as an alternative in the proposed scenarios. There are two possible reasons that explain this result. The first is the availability of the resource; in all the scenarios found, it can be said that the contemplated resources were sufficient to meet the demand. In addition, the study case of the campus is on a relatively small scale, a fact that could be verified by comparing the

value of the demand with respect to the city; the campus has an annual demand of around 250,000 kWh while the entire city consumes 3,700,000 kWh according to IPSE [**146**], representing a 6,75%. The second reason is the possible negative impact, especially in social and environmental aspects, that would be generated by the addition of a storage system. Therefore, for the amount required, trying to include a storage system would have a greater impact than producing the energy immediately. It would be interesting to observe if the battery would become more important in the face of a decrease in the availability of resources.

Although there are no studies clearly related to the campus, Fuso et al. carried out a MCDA applying the simple weighting methodology to explore rural electrification options in the Brazilian Amazon; although it is not Leticia, it contemplates a nearby region [**147**]. In this study, 16 indicators were used qualitatively and aggregated into five dimensions whose weights were very similar (technical 22%, economic 22%, environmental 20%, social 17%, institutional 19%). As a result, biomass and photovoltaic systems have the highest scores in the final index, followed by micro-hydro and hybrid plants, and finally, diesel generator systems have the lowest index value. Comparing this study to the MCDA conducted, it is similar in that this type of analysis is more inclined towards renewable energy sources, even though a different method was used, in addition to the fact that in this study the evaluation was made in a quantitative manner.

Similarly, Fonseca et al. [**148**] studied the design of an optimal energy system for the municipality of Leticia with the objective of supplying electricity and methane, considering as approach four single-objective optimization problems associating one indicator to each dimension, using as a base an optimization model developed by them in a previous study [**74**] that simplifies the calculation. Even if the scenarios obtained were slightly different from this study due to the different objectives and the use of other indicators as well as other technologies such as hydrogen and CO_2 capture, in addition to not considering the existing network, it is noteworthy that of the four scenarios established for each of the dimensions, the social and environmental scenarios result in the same structure, choosing the use of the same technologies, being similar to this study where the same scenario is produced in the cases when social and environmental are priority respectively (Scenario 9).

Finally, it should be mentioned that the result of this study is purely conceptual. However, it tries to be a first step to better link the specific planning and design studies with effects at the operative stage, need identified in [**12**]. It is important to remember that the main objective of this study is to propose a methodology to help stakeholders in the design of energy supply systems, and that the case of campus Leticia of the Universidad Nacional de Colombia is a singular application. The proposed methodology has the advantage of being flexible and can be applied in any location. In the event of replication, a summary of the stages to be followed is presented in Figure 5-16.

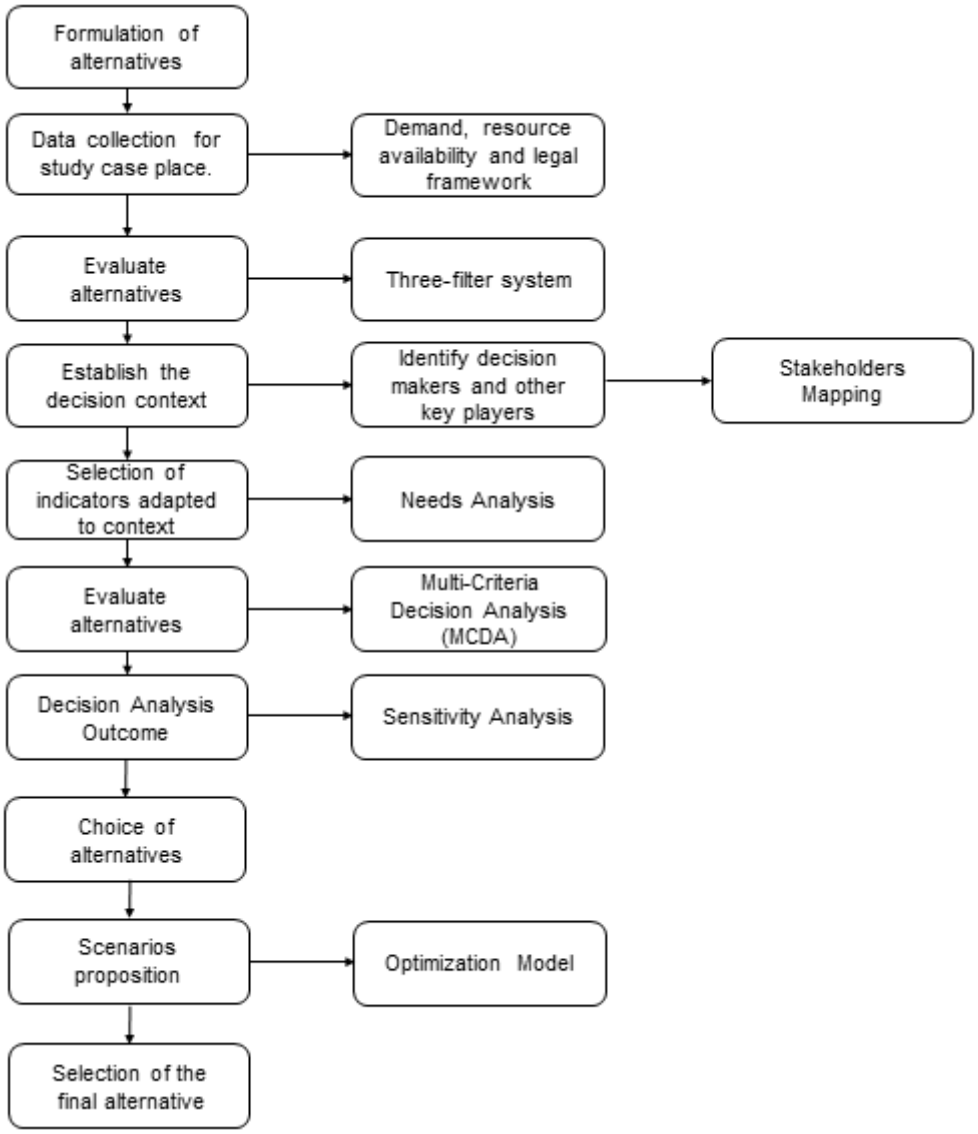

Figure 5-16. Outline of the proposed methodology

Ideally, based on the results of this methodology, at the stage of formulation of alternatives, besides including all energy sources, it would have been interesting to include specific technologies associated with them; similarly, a more detailed optimization model could be developed with the addition of other equipment closer to reality, for example, converters and transformers that change the energy so that it can be compatible with the network and be used directly; however, it is likely that model could become complex, making optimization difficult. Despite the lack of this information, the methodology was able to answer the question of which energy sources are most appropriate for the case study and how they should be linked; nevertheless, for the choice of only one of all the scenarios generated, the result must be complemented with the consideration of society represented by a broad set of relevant stakeholders. This future socialization stage will attempt to seek a social consensus by organizing a broad collective debate of reflection on the future so that, based on the analysis of the scenarios and the prospects developed, the process of formulating the final strategy and the actions to carry it out can begin.

6 Conclusions and perspectives

A methodology was proposed to help stakeholders define the best energy arrangement considering the context and dimensions established by the sustainability triple bottom line. Some information was collected through a literature review to select the way that evaluation should be made, calling attention to MCDA methods, a novel and growing global trend that is turning into a powerful tool for decision-making about sustainable energy systems. This approach has become popular due to its simplicity and flexibility and the huge applicability of finding objectively the better solutions to problems with multiple scenarios, stakeholders, and conflicting criteria. This review also revealed an increase in the inclusion of environmental and social factors in an effort to shift the energy transition toward renewable energies.

In the same way, a context assessment for the study case was used to define the energy potential for different energy sources as well as the initial conditions and restrictions. This assessment was followed by a systematic review to collect the main indicators used in energy design systems; a total of 690 indicators were found and finally reduced to 13 using an innovative methodology based on needs analysis called ReAR. The selected indicators were used in a multi-objective optimization model with a multi-period approach to include demand and variation in source availability throughout the period considered. These indicators were classified into technical, economic, environmental, and social dimensions, which have been associated with an objective in an optimization model. A weighting process was necessary to contemplate how the final decision could change depending on stakeholders' preferences. Following the application of the model for the case study at the Amazonas campus of the Universidad Nacional de Colombia located in Leticia, nine scenarios were obtained, each with a different energy arrangement.

The proposed methodology provides a first perspective on how the energy matrix should be configured, taking into account the available resources and the energy needs of the community. However, it should be noted that most of the values of the indicators used were calculated for specific cases worldwide. Therefore, the next study could focus on obtaining indicators for the selected energy sources in a Colombian context. Likewise, further work could be done on the selection of technologies for each of the sources, which would mean the inclusion of another step evaluating the possible procedures to obtain energy from a single source.

Different scenarios were proposed by this model for the specific study case; however, for the choice of a particular scenario, a meeting could be scheduled. In this meeting, representatives from each of the identified stakeholder groups could discuss certain ideas and present their points of view to help select one of the scenarios. According to the selected scenario, a next stage of engineering with the basic designs and equipment dimensioning could be carried out since the amount of energy to be produced by each energy source is known as a result of the model.

A. Appendix I: ReAR methodology application

Executor	Activity	Resource	Result	Involved	Limitation(s)
•Direction •Local Providers	•Ensure energy supply	•Appropriate infrastructure •Trained staff	•Produce sufficient amount of energy •Increased electricity coverage •Customer satisfaction	•Users	•Installed capacity •Energy source availability
•Direction	•Expansion of energy network	•Policies •New internal infrastructure	•Definition of an energy transformation path •Change in energy matrix •Energy independence •Introduction of renewable energies •Ensure electricity in long term •Adaptation of the existing grid •Capacity reassessment	•Users •Funders	•Installed capacity •Financial solvency •Agreement
•Users •Promoters •Activists •Contractors	•Proposing new ideas	•Residents •Government initiatives •Trained staff	•Definition of energy transformation roadmap •Selection of an alternative	•Direction	•People / Initiatives •Knowledge •Financial solvency

•Legislators •Control entities	•Setting prices	•Discussions •Agreements •Laws	•Regulated prices •Energy pricing	•Direction •Local providers	•Agreement •Supply / Demand Balance •Energy source availability
•Legislators •Promoters	•Initiatives for the implementation of renewable energy projects	•Laws	•Tax incentives. •Reduction of production costs. •Responsible use of natural resources for energy production. •Preservation of natural resources/biodiversity •Impulse to energy transformation •Other stakeholders involved •Subsidies •Reduction of environmental impact	•Contractors •Direction	•Targeting of public resources
•Legislators	•Establishing sustainable development policies	•Trained staff •Laws	•New laws, decrees. •Integration of sustainable development principles into existing policies. •Coupling of external/international policies.	•Direction •Promoters •Contractors	•Agreement
•Direction	•Commitment to energy transformation	•Integral energy management program	•Implementation of the sustainable approach. •New policies •Creation of alliances	•Users •Contractors	•Agreement

•Direction	•Renewable resources inclusion	•Advertising campaign •Management initiative •Policies •Integrated energy management program	•Image improvement •Use of renewable resources •Diversification of sources •Development of an energy culture •Willingness to change •Reduction of environmental impact. •Limitation of fossil fuel sources •Community impact	•Activists •Users •Local providers	•Agreement •Financial solvency •Area
•Direction	•Increased service reliability/service quality	•Adequate infrastructure •System controls	•Stability of supply •More satisfied users •Sense of belonging •Low probability of dissatisfaction/protest. •Handling disagreement	•Users •Activists	•Installed capacity •Energy source availability
•Direction	•Involve users in the process of energy transformation.	•People •Area •Programs •Advertising	•Creation of discussion spaces •Feedback for future modifications •Preparing people for changes •Knowing in advance the interest •Acceptance by society •Mediation	•Users •Activists	•Level of generated interest
•Direction	•Management program (consumer culture)	•Media •Advertising •Environmental awareness campaigns	•Responsible consumption of resources	•Users	•Financial solvency •Level of generated interest
•Funders •Promoters	•Financing for energy transition projects	•Money •Goods and services	•Purchasing capacity •Resources secured for the project	•Direction •Control entities	•Financial solvency

•Contractors	•Network start-up	•New energy network •Trained staff	•Employment generation •Energy supply	•Direction •Funders	•Infrastructure •Climatic factors
•Contractors	•Technical evaluation of the project	•Trained staff •Tools •Technical standards	•Feasibility studies. •Diagnosis of the existing network. •Estimation of construction time and costs. •Risk analysis •Design of the new energy supply system •Selection of alternatives and technologies	•Direction •Funders	•Financial solvency •Diagnosis time •Estimated execution time
•Direction •Control entities	•Impact reduction assessment	•Environmental regulations •Impact studies •Trained staff •Tools	•Infrastructure and operation according to environmental legislation	•Contractors	•Financial solvency
•Contractors	•Network maintenance	•Tools •Trained staff •Technology •Spare parts	•Guarantee the proper condition of the installations •Increase useful life time	•Direction •Users	•Spare parts •Trained staff •Financial solvency
•Contractors	•Network installation	•Tools •Trained staff •Manufacturers •Technical standards •Technology	•Expansion of the energy matrix •Improved connectivity •New energy network. •Modification of existing infrastructure. •Use of new technologies	•Direction •Users	•Financial solvency •Number of equipment •Installation time •Area
•Local providers	•Energy trading	•Infrastructure	•Earnings	•Direction	•Price •Production capacity •Infrastructure

•Direction •Control entities	•Monitoring project implementation	•Trained staff •Protocols •Tools •Laws	•Avoid cost overruns •Completion of the work within the agreed terms. •Budget control •Fines or penalties. •Accompaniment •Control of healthy competition	•Contractors	•Trained staff •Stakeholder transparency •Weak legal framework
•Contractors	•Request permissions	•Impact studies •Policies	•Environmental license •Construction permissions	•Direction	•Weak legal framework
•Contractors	•Connection to the existing network	•Equipment •Technology •Trained staff	•Mixed connection system •Increased capacity and reliability •Testing of new infrastructure	•Direction	•Trained staff •Number of equipment •Compatibility with existing network
•Direction	•Integrated waste management	•Programs •Protocols	•Reduced environmental impact •Balance with the environment •Possible waste valorization	•Users •Contractors	•Treatment capacity •Amount of waste
•Contractors	•Recruitment and training of trained staff	•Recruitment protocol • Trained staff •Training sessions •Dissemination of information	•Hiring of qualified staff •Successful project development •Employment generation	•Direction •Funders •Users	•Financial solvency •Trained staff
•Direction •Contractors •Control entities	•Ensuring user safety	•Adequate equipment •Safety protocols •Technical standards	•Guaranteed health. •Increase in the useful life time. •Generate a sense of security •Compliance with technical standards •Accident prevention	•Users •Activists	•Number of equipment •Appropriate studies

•Contractors	•Land preparation for construction	•Equipment •Tools •Trained staff	•Area prepared for construction	•Direction •Control entities	•Number of equipment •Area •Financial solvency •Land-use planning
•Users •Activists	•Maintain the cultural and physical identity of the environment	•Programs •Partnerships with associations	•Possible opposition. •Respect for the environment. •Movement in favor of renewable energies •Sensitization of users. •Creation of associations. •Actions in favor of the environment	•Direction •Control entities •Contractors	•Level of generated interest
•Direction	•Entering into contracts	• Contract • Lawyers • Participants • Legislation	•Selection of project executors (Companies and individuals)	•Contractors •Control entities •Activists	•Agreement •Weak legal framework
•Direction •Contractors	•Domestic energy production	•New energy network •Natural resources	•Energy generation •Obtaining profits from sales •Energy independence •Energy storage	•Local providers	•Installed capacity •Energy source availability
•Direction	•Equipment acquisition	•Money •Technical studies	•Improved energy efficiency. •Efficient transformation •New infrastructure •Use of more sustainable materials	•Contractors	•Financial solvency
•Direction	•Validation/Approval	•Review •Meetings	•Approved decisions and budgets •Consensus	•Contractors	•Agreement •Financial solvency

•Funders	•Emergency support	•Emergency fund •Insurance and Policies	•Support for any eventuality	•Direction •Contractors	•Financial solvency •Probability of accidents •Insurance coverage level

B. Appendix II: Selected articles for indicators collection.

Author(s)	Title	Year	Reference
Wang et al.	Review on multicriteria decision analysis aid in sustainable energy decision-making	2009	[**13**]
Pohekar and Ramachandran	Application of multicriteria decision making to sustainable energy planning - A review	2004	[**9**]
Kumar et al.	A review of multi criteria decision making (MCDM) towards sustainable renewable energy development	2017	[**18**]
Strantzali and Aravossis.	Decision making in renewable energy investments: A review	2016	[**20**]
Liu.	Development of a general sustainability indicator for renewable energy systems: A review	2014	[**138**]
Mardani et al.	Sustainable and renewable Energy: An overview of the application of multiple criteria decision making techniques and approaches	2015	[**137**]
Ibanez-Forés et al.	A holistic review of applied methodologies for assessing and selecting the optimal technological alternative from a sustainability perspective	2014	[**149**]
Onat and Bayar	The sustainability indicators of power production systems	2010	[**143**]
Ilbahar et al.	A state-of-the-art review on multi-attribute renewable energy decision making	2019	[**129**]
Sheikh et al.	Social and political impacts of renewable energy: Literature review	2016	[**150**]
Theodorou et al.	The use of multiple criteria decision making methodologies for the promotion of RES through funding schemes in Cyprus, A review	2010	[**151**]

Cajot et al.	Multicriteria Decisions in Urban Energy System Planning: A Review	2017	[**12**]
Dorning et al.	Review of indicators for comparing environmental effects across energy sources	2019	[**130**]
Kaya and Kahraman.	Multicriteria renewable energy planning using an integrated fuzzy VIKOR & AHP methodology: The case of Istanbul	2010	[**139**]
San Cristóbal.	Multi-criteria decision-making in the selection of a renewable energy project in spain: The Vikor method	2011	[**152**]
Beccali et al.	Decision-making in energy planning. Application of the Electre method at regional level for the diffusion of renewable energy technology	2003	[**153**]
Afgan and Carvalho.	Multi-criteria assessment of new and renewable energy power plants	2002	[**25**]
Haralambopoulos and Polatidis	Renewable energy projects: structuring a multi-criteria group decision-making framework	2003	[**154**]
Santoyo-Castelazo and Azapagic	Sustainability assessment of energy systems: integrating environmental, economic and social aspects	2014	[**131**]
Amer and Daim.	Selection of renewable energy technologies for a developing county: A case of Pakistan	2011	[**105**]
Chatzimouratidis and Pilavachi.	Technological, economic and sustainability evaluation of power plants using the Analytic Hierarchy Process	2009	[**26**]
Cavallaro and Ciraolo.	A multicriteria approach to evaluate wind energy plants on an Italian island	2005	[**141**]
Terrados et al.	Regional energy planning through SWOT analysis and strategic planning tools. Impact on renewables development	2007	[**155**]
Chatzimouratidis and Pilavachi.	Multicriteria evaluation of power plants impact on the living standard using the analytic hierarchy process	2008	[**136**]
Gallego and Mack.	Sustainability assessment of energy technologies via social indicators: Results of a survey among European energy experts	2010	[**145**]
Streimikiene et al.	Prioritizing sustainable electricity production technologies: MCDM approach	2012	[**142**]
Stein.	A comprehensive multi-criteria model to rank electric energy production technologies	2013	[**15**]
Vafaeipour et al.	Assessment of regions priority for implementation of solar projects in Iran: New application of a hybrid multi-criteria decision making approach	2014	[**135**]
Maxim.	Sustainability assessment of electricity generation technologies using weighted multi-criteria decision analysis	2014	[**140**]

C. Appendix III: List of indicators obtained after filters

Dimension	Indicator	Other name(s)	Reported in
Technical/Technological	Availability	Continuity, Network stability, Average availability (load) factor	[**15**,**20**,**26**,**142**]
	Capacity	Fuel import vulnerability, Installed capacity, Nominal Power, Power, Power generated, Power generation	[**15**,**18**,**20**,**129**,**137**,**152**]
	Capacity factor		[**15**,**26**,**105**,**137**,**140**]
	Demand for electricity	Load demand	[**18**,**20**,**135**]
	Efficiency	Energy Yield, Performance, Energy efficiency	[**13**,**15**,**18**,**20**,**25**,**26**,**105**,**129**,**137**,**138**] [**139**,**140**,**143**,**149**,**150**,**151**]
	Energy Consumption		[**149**]
	Energy loss		[**18**,**137**]
	Energy production capacity	Electricity production, Amount of energy produced	[**20**,**137**,**139**,**141**]

	Energy saving	Conventional energy saved, Fuel saved, Saving of energy	[**137**,**141**,**149**,**153**,**154**]
	Energy use per capita		[**137**]
	Exergy Efficiency		[**13**,**139**]
	Implementation Period		[**137**,**152**]
	Lifespan	Lifetime, Useful life, Service life	[**13**,**20**,**137**,**139**,**149**,**152**]
	Operating hours		[**137**,**152**]
	Peak load coverage	Peak traffic contribution	[**15**,**145**]
	Plant complexity		[**137**]
	Primary energy ratio	Renewable Energy integration, Renewable energy supply	[**13**,**15**,**20**,**137**,**139**]
	Realization time	Deployment time, Duration	[**105**,**139**,**141**]
	Resource availability	Availability of resource, Fuel reserve years, Need of reserve capacity, Supply capability	[**15**,**18**,**20**,**105**,**135**,**137**,**143**,**145**]
	Slope		[**129**]
Economic	Benefits	Income, National economic benefits, Economic benefits	[**18**,**105**,**137**,**149**]
	Black-out cost		[**15**]
	Capital Cost		[**15**,**18**,**26**,**105**,**129**,**131**,**138**,**149**]
	Conventional fuel savings		[**15**]
	Cost of saved primary energy		[**153**]
	Eco-efficiency	Ratio cost-benefit	[**149**]

	Equivalent annual cost	Total annualized costs	[**13**,**20**,**131**,**139**,**149**]
	External costs		[**18**,**26**,**140**]
	Fossil fuel import cost		[**18**]
	Fuel cost		[**13**,**15**,**18**,**26**,**137**,**139**]
	Internal Rate of Return (IRR)		[**15**,**18**,**20**]
	Investment cost		[**13**,**15**,**20**,**25**,**135**,**137**,**139**,**141**,**149**,**151**]
	Investment Ratio		[**137**,**152**]
	Levelized cost of electricity (LCOE)	Electrical generation cost, Cost of energy, Cost of electricity, Electric cost, Electricity cost, Energy Cost, Private costs, Unit energy cost	[**13**,**15**,**20**,**25**,**105**,**129**,**131**,**137**,**138**,**139**] [**140**,**142**,**143**]
	Net import % of energy		[**15**]
	Net present cost (NPC)	Life Cycle Cost (LCC)	[**15**,**20**,**138**]
	Net present value (NPV)		[**13**,**15**,**18**,**20**,**135**,**139**,**149**]
	Operation and Maintenance (O&M) Cost		[**13**,**15**,**18**,**20**,**26**,**105**,**129**,**135**,**137**,**138**] [**139**,**141**,**149**,**152**]
	Payback period	Economic viability, Payback time	[**13**,**18**,**20**,**105**,**135**,**137**,**138**,**139**,**149**]
	Return on investment		[**137**,**138**,**149**,**154**]
Environmental	Abiotic depletion potential (ADP)		[**131**]

	Acidification potential		[**130**,**131**]
	Aquatic toxicity		[**130**,**131**]
	CO emission		[**13**,**139**]
	CO_2 avoided	CO_2 reduction, Carbon emission reduction, GHG emissions reduction, Reduction in greenhouse gases, Resource requirements	[**15**,**130**,**137**,**141**,**152**,**153**]
	CO_2 emissions	Carbon dioxide equivalent (CO2-eq), GHG emissions, Risk of climate change	[**13**,**15**,**18**,**20**,**25**,**130**,**136**,**137**,**138**,**139**] [**142**,**143**]
	Distance between plants	Distance to electricity substations	[**137**]
	Distance from network	Distance to power lines	[**129**,**137**]
	Distance from residential areas	Distance to town or villages	[**129**]
	Distance from roads	Distance to main roads	[**129**,**137**]
	Emissions avoided	Emission reduction	[**129**,**137**]
	Environmental external costs		[**15**,**140**,**142**]
	Eutrophication potential		[**130**,**131**]
	Global warming potential (GWP)		[**131**]
	Human toxicity (HTP)		[**129**,**137**]
	Land Use	Area requirement, Land area, Land requirement	[**13**,**15**,**18**,**20**,**25**,**105**,**129**,**130**,**136**,**137**] [**139**,**140**,**143**,**145**,**149**]
	Loss of life expectancy		[**15**]

	Noise	Acoustic emissions, Acoustic noise	[**13**,**15**,**18**,**20**,**129**,**130**,**139**,**141**,**149**, **153**]
	Non-methane volatile organic compounds (NMVOCs)		[**13**,**136**,**139**]
	NOx emission		[**13**,**15**,**18**,**20**,**130**,**136**,**138**,**139**]
	Ozone depletion potential (ODP)		[**130**,**131**]
	Particles emission	Particulate matter	[**13**,**20**,**130**,**136**,**139**]
	Photochemical ozone creation (POCP) or summer smog,		[**130**,**131**]
	Radioactivity		[**130**,**136**]
	Health external cost	Radionuclide costs	[**15**,**142**]
	Waste recycle		[**149**]
	Renewable fraction		[**138**]
	Risk of climate change		[**18**]
	SO_2 emission		[**13**,**15**,**18**,**20**,**136**,**138**,**139**]
	Terrestrial ecotoxicity (TETP)	Terrestrial toxicity	[**130**,**131**]
	Water consumption	Fresh water consumption, General water, Water quantity	[**130**,**137**,**143**]
Social	Accident fatalities	Accidental risk	[**15**,**18**,**136**,**137**,**142**,**145**]
	Compensation rates		[**136**]

	Human health impact		[**15**,**20**,**131**,**142**,**145**,**149**]
	Job Creation	Creation of job, Employment, Employment generation potential, Employment growth, Labor impact, Contribution to employment, Local employment generation, Number of jobs created, job opportunities	[**13**,**15**,**18**,**20**,**105**,**129**,**136**,**137**,**138**, **139**] [**140**,**142**,**145**,**149**,**150**,**153**,**154**]
	Fuel Import dependency		[**131**]
Politic	Carbon tax	Cap and trade	[**150**]
	FIT (Feed-In Tariffs)	Net metering	[**150**]
	Fossil fuel lobbies		[**150**]
	Subsidies	Incentives	[**150**]

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D. Appendix IV: Indicator values obtained from literature

CAPACITY FACTOR				
Energy source	**Characteristics**	**Value**	**Units**	**Source**
Biomass	Biomass (landfill)	70	%	[**156**]
	Biomass (incinerator)	75	%	[**156**]
	Biomass	83	%	[**105**]
	Biomass	70	%	[**140**]
	Biomass boiler (heat)	13-29	%	[**157**]
	Direct combustion	85	%	[**157**]
	CHP	63-74	%	[**157**]
	Gasification	80	%	[**157**]
	Biomass plant - energy crops	50-85	%	[**158**]
	Biomass	83	%	[**159**]
	Biomass-Waste	83	%	[**160**]
	Biomass	54	%	[**161**]

	Slow pyrolysis	86	%	[**162**]
	Gasification to electricity	75	%	[**162**]
	Combustion to electricity	75	%	[**162**]
	Decentralized combined heat and power (CHP)	25	%	[**162**]
	Biogas	80	%	[**163**]
	Biomass Gasifier	80	%	[**163**]
	Biomass	83	%	[**164**]
	Biomass	70	%	[**26**]
	Biomass	76,8	%	[**132**]
Coal	Conventional coal power plant	30	%	[**156**]
	Advanced supercritical coal	40	%	[**156**]
	IGCC	40	%	[**156**]
	Coal	85	%	[**140**]
	Coal-fired power plant	25-85	%	[**158**]
	Coal	85	%	[**164**]
	Coal	85	%	[**165**]
	Coal/Lignite	70,8	%	[**26**]
	Coal	70	%	[**166**]
	Coal	84,4	%	[**132**]
Diesel	Diesel generator	70	%	[**156**]
	Oil-fired power plant	20-85	%	[**158**]
	Oil	85	%	[**160**]

	Diesel Power	80	%	[**163**]
	Oil	85	%	[**164**]
	Oil	26,2	%	[**26**]
Natural Gas	Conventional gas turbine	60	%	[**156**]
	Advanced gas turbine	60	%	[**156**]
	Gas engine	90	%	[**156**]
	Natural Gas	85	%	[**140**]
	Natural Gas-fired plant	15-85	%	[**158**]
	Natural Gas	87	%	[**160**]
	Gas	85	%	[**164**]
	Natural Gas	85	%	[**165**]
	Natural Gas turbine	16,6	%	[**26**]
	Natural Gas Combined Cycle	38,2	%	[**26**]
	Natural Gas	84,4	%	[**132**]
Hydro	Small hydropower	35	%	[**156**]
	Large hydropower	18	%	[**156**]
	Hydro (small)	50	%	[**140**]
	Hydro (large)	54	%	[**140**]
	Small hydropower	30	%	[**167**]
	Large-scale power plants	17-59	%	[**157**]
	Small hydro	34-50	%	[**157**]
	Mini-hydroelectric plant - conventional dam	23-47	%	[**158**]

	Hydro	50	%	[**159**]
	Hydro	25	%	[**161**]
	PicoHydro System	30	%	[**163**]
	Micro Hydropower	40	%	[**163**]
	Hydro	50	%	[**164**]
	Hydro (dam)	54	%	[**165**]
	Hydro (r-o-r)	54	%	[**165**]
	Hydro	29,6	%	[**26**]
	Hydro	47	%	[**166**]
Solar	Solar thermal	38	%	[**156**]
	Solar photovoltaic	18	%	[**156**]
	Solar photovoltaic (DG)	17	%	[**156**]
	Solar thermal	18	%	[**105**]
	Solar photovoltaic	25	%	[**105**]
	Solar thermal	45	%	[**140**]
	Solar PV	20	%	[**140**]
	Photovoltaic solar energy	20	%	[**167**]
	Solar PV - Building level	12-20	%	[**157**]
	Solar PV - Centralized plant	15-21	%	[**157**]
	CSP - Parabolic trough	25-28	%	[**157**]
	CSP - Linear Fresnel	22-24	%	[**157**]
	CSP - Power tower	55	%	[**157**]

	Solar thermal- Flat plate collector	4,1-13	%	[**157**]
	Photovoltaic solar plant - different panels	10-35	%	[**158**]
	Solar thermal - Parabolic trough	18-37	%	[**158**]
	Solar	25	%	[**159**]
	Solar PV	20	%	[**160**]
	Solar CSP	25	%	[**160**]
	Solar PV	15	%	[**161**]
	Solar Home System	20	%	[**163**]
	Solar PV	20	%	[**163**]
	Solar CSP	25	%	[**160**]
	Solar PV	20	%	[**160**]
	Solar	20	%	[**164**]
	Solar PV	18	%	[**165**]
	Photovoltaic	22,4	%	[**26**]
	Solar	17,5	%	[**166**]
	CSP	35,6	%	[**132**]
	PV	20,4	%	[**132**]
Battery	100	100	%	[**168**]
	92	92	%	[**168**]
	79	79	%	[**168**]
	53	53	%	[**168**]

WATER CONSUMPTION				
Energy source	**Characteristics**	**Value**	**Units**	**Source**
Biomass	Biomass-Waste	235	gal/MWh	[**160**]
	Biomass	2271	m^3/GWh	[**164**]
	Biomass	18,5-100-250	kg/kWh	[**132**]
Coal	Coal	2405	m^3/GWh	[**164**]
	Coal	15-78	kg/kWh	[**132**]
	Coal	15-30	kg/kWh	[**143**]
Diesel	Oil	826	gal/MWh	[**160**]
	Oil	2405	m^3/GWh	[**164**]
Natural Gas	Natural Gas	240	gal/MWh	[**160**]
	Gas	1480	m3/GWh	[**164**]
	Natural Gas	0,94-39,6	m3/MWh	[**169**]
	Natural Gas	15-78	kg/kWh	[**132**]
	Natural Gas	15-30	kg/kWh	[**143**]
Hydro	Hydro	0	m3/GWh	[**164**]
	New SHP	0	m3/MWh	[**169**]
	Hydro	0,1-1	kg/kWh	[**143**]
Solar	Solar PV	26	gal/MWh	[**160**]
	Solar CSP	865	gal/MWh	[**160**]
	Solar	0	m3/GWh	[**164**]

	Solar PV	1-10	kg/kWh	[**132**]
	CSP	3,4	kg/kWh	[**132**]
	Photovoltaic	0,5	kg/kWh	[**143**]
Battery	Lead-acid battery	0,144	g/Wh	[**170**]
	Lead-acid battery	0,151	g/Wh	[**170**]
	Lead-acid battery	0,161	g/Wh	[**170**]
	Lead-acid battery	0,168	g/Wh	[**170**]
	Lead-acid battery	0,173	g/Wh	[**170**]
	Lead-acid battery	0,177	g/Wh	[**170**]
	Lead-acid battery	0,181	g/Wh	[**170**]
	Lead-acid battery	0,186	g/Wh	[**170**]
	Lead-acid battery	0,192	g/Wh	[**170**]

FUEL COST				
Energy source	**Characteristics**	**Value**	**Units**	**Source**
Biomass	Biomass	2,05	€cent/kWh	[**26**]
	Biomass - 1	857	$cent/Gcal	[**171**]
	Biomass - 2	1714	$cent/Gcal	[**171**]
	Biomass	5,73	$/GJ	[**131**]
	Biogas	1,10-1,33-1,59	UScent$/kWh	[**163**]

	Biomass gasifier	2,66-3,21-3,85	UScent$/kWh	[**163**]
Coal	Coal/lignite	1,31	€cent/kWh	[**26**]
	Coal	1553	$cent/Gcal	[**171**]
	Coal	1,52	$/kWh	[**166**]
	Coal	16,87	$/GJ	[**131**]
	Coal	2,79-2,97	€/GJ	[**172**]
Diesel	Oil	302	€/tn	[**173**]
	Oil	1,84	€cent/kWh	[**26**]
	Diesel Engine - 1	6187	$cent/Gcal	[**171**]
	Diesel Engine - 2	8858	$cent/Gcal	[**171**]
	Diesel Engine - 3	6508	$cent/Gcal	[**171**]
	Diesel Engine - 4	6508	$cent/Gcal	[**171**]
	Diesel Engine - 5	6508	$cent/Gcal	[**171**]
	Diesel Engine - 6	6187	$cent/Gcal	[**171**]
	Diesel Engine - 7	6508	$cent/Gcal	[**171**]
	Oil	25,21	$/GJ	[**131**]
	Diesel gen set	14,04-16,84-18,48	UScent$/kWh	[**163**]
Natural Gas	Natural Gas	287	€/tn	[**173**]
	Natural Gas	0,08	€/kWh	[**174**]
	Natural Gas turbine	2,34	€cent/kWh	[**26**]
	Natural Gas combined cycle	2,34	€cent/kWh	[**26**]
	Gas Turbine - 1	8858	$cent/Gcal	[**171**]

	Gas Turbine - 2	6187	$cent/Gcal	[**171**]
	Gas	27,11	$/GJ	[**131**]
	Gas OC	6,38-8,69	€/GJ	[**172**]
	Gas CC	6,38-8,69	€/GJ	[**172**]
Hydro	Hydro	0	€cent/kWh	[**26**]
	Hydro	0	$/kWh	[**166**]
	Pico Hydro	0	UScent$/kWh	[**163**]
	Micro Hydro	0	UScent$/kWh	[**163**]
Solar	Photovoltaic	0	€cent/kWh	[**26**]
	Solar	0	$/kWh	[**166**]
	Solar PV	0	UScent$/kWh	[**163**]

CAPITAL COST				
Energy source	**Characteristics**	**Value**	**Units**	**Source**
Biomass	Biomass (landfill)	3300	$/kW	[**156**]
	Biomass (incinerator)	6400	$/kW	[**156**]
	Biomass	3370	US$/kW	[**161**]
	Biomass boiler (heat)	310-1200	US$/kW	[**157**]
	Direct combustion	1880-4260	US$/kW	[**157**]
	CHP	3550-6820	US$/kW	[**157**]
	Gasification	2140-5700	US$/kW	[**157**]

	Biomass	55,3	$/MWh	[**105**]
	Biomass-Biogas	2800	€/kW	[**175**]
	Biomass	1667	€/kW	[**26**]
	Biomass	2661	$/kW	[**131**]
	Biogas	2490-2330-2280	US$/kW	[**163**]
	Biomass Gasifier	2880-2560-2430	US$/kW	[**163**]
	Biomass	2240-3300	US$/kW	[**176**]
	Biomass (energetic cultivations) P<5MW	1803	€/kW	[**152**]
	Biomass (forest and agricultural wastes) P<5MW	1803	€/kW	[**152**]
	Biomass (farming industrial wastes) P<5MW	1803	€/kW	[**152**]
	Biomass (forest industrial wastes) P<5MW	1803	€/kW	[**152**]
	Biomass (co-combustion in conventional central) P>50 MW	856	€/kW	[**152**]
	Wood Energy Biomass	1886	US$/kW	[**93**]
	Co-combustion/ Biomass	1886	US$/Kw	[**93**]
Coal	Conventional coal power plant	1600	$/kW	[**156**]
	Advanced supercritical coal	2200	$/kW	[**156**]
	IGCC	5500	$/kW	[**156**]

	Lignite	1400	€/kW	[**175**]
	Coal/Lignite	975	€/kW	[**26**]
	Coal	1133	$/kW	[**166**]
	Coal (USC)	1234	$/kW	[**131**]
	Coal (IGCC)	1516	$/kW	[**131**]
	Coal CCS (USC)	1957	$/kW	[**131**]
	Coal CCS (IGCC)	1889	$/kW	[**131**]
	Coal	2130	€/kW	[**172**]
	Coal	1300-2400	US$/kW	[**176**]
Diesel	Diesel generator	550	$/kW	[**156**]
	Oil	483	€/kW	[**26**]
	Heavy fuel oil	1817	$/kW	[**131**]
	Diesel gen set	640-595-590	$/kW	[**163**]
Natural Gas	Conventional gas turbine	550	$/kW	[**156**]
	Advanced gas turbine	780	$/kW	[**156**]
	Gas engine	770	$/kW	[**156**]
	Natural Gas	400-800	US$/kW	[**169**]
	Natural Gas	1077-1500	€/kW	[**173**]
	CCGT	800	€/kW	[**175**]
	Natural Gas Turbine	612	€/kW	[**26**]
	Natural Gas Combined Cycle	587	€/kW	[**26**]
	Gas	551	$/kW	[**131**]

	Gas CCS	772	$/kW	[**131**]
	Gas OC	675	€/kW	[**172**]
	Gas CC	900	€/kW	[**172**]
	Natural Gas	450-1060	US$/kW	[**176**]
Hydro	Small hydropower	2000	$/kW	[**156**]
	Large hydropower	1200	$/kW	[**156**]
	Hydro	2040	US$/kW	[**161**]
	Large-scale power plants	1400-3680	US$/kW	[**157**]
	Small hydro	1590-4150	US$/kW	[**157**]
	New SHP	880	US$/kW	[**169**]
	Hydro	2000	€/kW	[**175**]
	Small hydro	2300	€/kW	[**175**]
	Hydro	2417	€/kW	[**26**]
	Hydro	2810	$/kW	[**166**]
	Hydro	2130	$/kW	[**131**]
	Pico Hydro	1560-1485-1470	US$/kW	[**163**]
	Micro Hydro	2600-2470-2450	US$/kW	[**163**]
	Hydroelectric P<10 MW	1500	€/kW	[**152**]
	Hydroelectric 10<P<25 MW	700	€/kW	[**152**]
	Hydroelectric 25<P<50 MW	601	€/kW	[**152**]
Solar	Solar thermal	4300-2750	$/kW	[**156**]
	Solar photovoltaic	1200-790-630	$/kW	[**156**]

	Solar photovoltaic (DG)	1500-1000	$/kW	[**156**]
	Solar PV	4550	US$/kW	[**161**]
	Solar PV - Building level	3700-6800	US$/kW	[**157**]
	Solar PV - Centralised plant	2700-5200	US$/kW	[**157**]
	CSP - Parabolic trough	6066	US$/kW	[**157**]
	CSP - Linear Fresnel	3745	US$/kW	[**157**]
	CSP - Power tower	4169	US$/kW	[**157**]
	Solar thermal- Flat plate collector	1421	US$/kW	[**157**]
	Solar thermal- Tube collector	1677	US$/kW	[**157**]
	Solar PV	194,6	$/MWh	[**105**]
	Solar thermal	259,4	$/MWh	[**105**]
	PV	2100	€/kW	[**175**]
	Photovoltaic	4167	€/kW	[**26**]
	Solar	4845	$/kW	[**166**]
	Solar CSP	4761	$/kW	[**131**]
	Solar PV	1190	$/kW	[**131**]
	Solar PV	7510-6590-5860	US$/kW	[**163**]
	PV	2500-1000	€/kW	[**172**]
	CSP	6090-3400	€/kW	[**172**]
	CSP	4260-5850	US$/kW	[**176**]
	PV	2080-5000	US$/kW	[**176**]
	Solar Thermo-electric P>10 MW	5000	€/kW	[**152**]

	Solar Thermal Energy	3082	US$/kW	[**93**]
	Photovoltaic Solar Energy	3823	US$/kW	[**93**]
Battery	Battery	600	$/kW	[**177**]
	Lead-acid batteries	640	$/kW	[**178**]
	Lithium Ion	916	$/kW	[**179**]
	Lithium Ion	1554	$/kW	[**179**]
	Lithium Ion	1902	$/kW	[**179**]
	Lithium titanate	703	$/kW	[**180**]
	Lead-acid battery	50-400	$/kW	[**181**]
	Nickel-cadmium battery	400-2400	$/kW	[**181**]
	Sodium-sulfur battery	254-500	$/kW	[**181**]
	Lithium ion battery	600-2500	$/kW	[**181**]
	Vanadium redox battery	150-1000	$/kW	[**181**]
	Zinc bromine battery	150-1000	$/kW	[**181**]
	Pb-A	300-600-200-300-400	$/kW	[**182**]
	Li-ion	1200-4000-900-1300-1590	$/kW	[**182**]
	Na-S	1000-3000-350-3000	$/kW	[**182**]
	Ni-Cd	500-1500	$/kW	[**182**]
	Vanadium redox battery	600-1500	$/kW	[**182**]
	Zn-Br	700-2500-400-200	$/kW	[**182**]

OPERATION & MAINTENANCE (O&M) COST				
Energy source	**Characteristics**	**Value**	**Units**	**Source**
Biomass	Biomass (landfill)	2	$/kW	[**156**]
	Biomass (incinerator)	640	$/kW	[**156**]
	Biomass	99,4	$US/kW-year	[**161**]
	Biomass boiler (heat)	13-43	$US/kW-year	[**157**]
	Direct combustion	84	$US/kW-year	[**157**]
	CHP	54-86	$US/kW-year	[**157**]
	Gasification	65-71	$US/kW-year	[**157**]
	Biomass	13,7	$/MWh	[**105**]
	Biomass-biogas	62,5	€/kW-year	[**175**]
	Biomass	60,83	€/kW-year	[**26**]
	Biomass - 1	2,75	$/kW-month	[**171**]
	Biomass - 2	2,75	$/kW-month	[**171**]
	Biomass	66,9	$/kW	[**131**]
	Biogas	1,88-1,63-1,44	UScent$/kWh	[**163**]
	Biomass gasifier	1,91-1,39-0,75	UScent$/kWh	[**163**]
	Biomass	90,08	US$/kW	[**176**]
	"Biomass (energetic cultivations) P<5MW"	0,007106	€/kWh	[**152**]
	Biomass (forest and agricultural wastes)	0,005425	€/kWh	[**152**]

	P<5MW			
	Biomass (farming industrial wastes) P<5MW	0,005425	€/kWh	[**152**]
	Biomass (forest industrial wastes) P<5MW	0,002813	€/kWh	[**152**]
	Biomass (co-combustion in conventional central) P>50 MW	0,00456	€/kWh	[**152**]
Coal	Conventional coal power plant	64	$/kW	[**156**]
	Advanced supercritical coal	88	$/kW	[**156**]
	IGCC	92	$/kW	[**156**]
	Lignite	37	€/kW-year	[**175**]
	Coal/Lignite	19	€/kW-year	[**26**]
	Coal	5,02	$/kW-month	[**171**]
	Coal	22	$/kW-year	[**166**]
	Coal (USC)	56,57	$/kW	[**131**]
	Coal (IGCC)	73,06	$/kW	[**131**]
	Coal CCS (USC)	86,96	$/kW	[**131**]
	Coal CCS (IGCC)	89,6	$/kW	[**131**]
	Coal	22,8	€/kW	[**172**]
	Coal	44,6	US$/kW	[**176**]
Diesel	Diesel generator	3,8	$/kW	[**156**]
	Oil	18,4	€/kW	[**173**]

	Oil	6,25	€/kW-year	[**26**]
	Diesel engine - 1	9,21	$/kW-month	[**171**]
	Diesel engine - 2	0,21	$/kW-month	[**171**]
	Diesel engine - 3	2,08	$/kW-month	[**171**]
	Diesel engine - 4	1,33	$/kW-month	[**171**]
	Diesel engine - 5	6,02	$/kW-month	[**171**]
	Diesel engine - 6	4,56	$/kW-month	[**171**]
	Diesel engine - 7	1,12	$/kW-month	[**171**]
	Heavy fuel oil	12,12	$/kW	[**131**]
	Diesel gen set	5-4,75-4,8	UScent$/kWh	[**163**]
Natural Gas	Conventional gas turbine	4,5	$/kW	[**156**]
	Advanced gas turbine	24	$/kW	[**156**]
	Gas engine	8	$/kW	[**156**]
	Natural Gas	12,6	€/kW	[**173**]
	CCGT	20	€/kW-year	[**175**]
	Natural Gas turbine	10,83	€/kW-year	[**26**]
	Natural Gas combined cycle	10	€/kW-year	[**26**]
	Gas turbine - 1	3,56	$/kW-month	[**171**]
	Gas turbine - 2	10,05	$/kW-month	[**171**]
	Gas	9,93	$/kW	[**131**]
	Gas CCS	19,85	$/kW	[**131**]
	Gas OC	8,2	€/kW	[**172**]

	Gas CC	9,7	€/kW	[**172**]
	Natural Gas	23,14	US$/kW	[**176**]
Hydro	Small hydropower	14	$/kW	[**156**]
	Large hydropower	10,8	$/kW	[**156**]
	Hydro	14,85	$US/kW-year	[**161**]
	Large-scale power plants	25-75	$US/kW-year	[**157**]
	Small hydro	25-75	$US/kW-year	[**157**]
	Hydro	22,4	€/kW-year	[**175**]
	Small hydro	22,4	€/kW-year	[**175**]
	Hydro	72,5	€/kW-year	[**26**]
	Hydro	84,3	$/kW-year	[**166**]
	Hydro	14,15	$/kW	[**131**]
	Pico Hydro	0,9-1,66-0,88	UScent$/kWh	[**163**]
	Micro Hydro	1,49-1,65,1,51	UScent$/kWh	[**163**]
	Hydroelectric P<10 MW	0,00145	€/kWh	[**152**]
	Hydroelectric 10<P<25 MW	0,0007	€/kWh	[**152**]
	Hydroelectric 25<P<50 MW	0,0006	€/kWh	[**152**]
Solar	Solar thermal	64	$/kW	[**156**]
	Solar photovoltaic	24	$/kW	[**156**]
	Solar photovoltaic (DG)	37	$/kW	[**156**]
	Solar PV	30	$US/kW-year	[**161**]
	Solar PV - Building level	19-110	$US/kW-year	[**157**]

	Solar PV - Centralised plant	14-69	$US/kW-year	[**157**]
	CSP - Parabolic trough	66	$US/kW-year	[**157**]
	CSP - Linear Fresnel	55	$US/kW-year	[**157**]
	CSP - Power tower	55	$US/kW-year	[**157**]
	Solar thermal- Flat plate collector	28-50	$US/kW-year	[**157**]
	Solar PV	12,1	$/MWh	[**105**]
	Solar thermal	46,8	$/MWh	[**105**]
	PV	29	€/kW-year	[**175**]
	Photovoltaic	16,67	€/kW-year	[**26**]
	Solar	19,38	$/kW-year	[**166**]
	Solar CSP	58,94	$/kW	[**131**]
	Solar PV	12,12	$/kW	[**131**]
	Solar PV	8,05-7,63-5,80	UScent$/kWh	[**163**]
	PV	20	€/kW	[**172**]
	CSP	53,8	€/kW	[**172**]
	CSP	94,21	US$/kW	[**176**]
	PV	35,54	US$/kW	[**176**]
	Solar Thermo-electric P>10 MW	0,0042	€/kWh	[**152**]
Battery	Battery	10	$/kW-yr	[**177**]
	Lead-acid batteries	5	$/kW	[**178**]
	Lithium Ion	23,5	$/kW-yr	[**179**]
	Lithium Ion	31,1	$/kW-yr	[**179**]

	Lithium Ion	42,6	$/kW-yr	[**179**]
	Lithium titanate	12,3	$/kW-yr	[**180**]
	Pb-A	50	$/kW-yr	[**182**]
	Na-S	80	$/kW-yr	[**182**]
	Ni-Cd	20	$/kW-yr	[**182**]
	Vanadium redox battery	70	$/kW-yr	[**182**]

LAND USE				
Energy source	**Characteristics**	**Value**	**Units**	**Source**
Biomass	Biomass	222	m2/kW	[**161**]
	Biomass	5000	km2/1000 MW	[**159**]
	Biomass	5000	km2/1000 MW	[**105**]
	Biomass	12,65	m2/MWh	[**140**]
	Biomass - Waste	2	km2 /500MW	[**160**]
	Biomass	11,3-13,9	m2/MWh	[**164**]
	Biomass	5000000	m2/MW	[**171**]
	Biogas	144	m2/kW	[**163**]
	Biomass gasifier	112	m2/kW	[**163**]
	Wood Energy Biomass	0,0045	Ha/KW	[**93**]
	Co-combustion/ Biomass	0,0039	Ha/KW	[**93**]

	Biomass	5000	km2/1000 MW	[**136**]
Coal	Coal	0,39	m2/MWh	[**140**]
	Coal	360-440	m2/MWh	[**164**]
	Coal Steam	2500	m2/MW	[**171**]
	Coal	2,2	km2/1000 MW	[**166**]
	Coal/Lignite	2,5	km2/1000 MW	[**183**]
	Coal/Lignite	2,5	km2/1000 MW	[**136**]
Diesel	Oil	1	m2/500MW	[**160**]
	Oil	36-44	m2/MWh	[**164**]
	Diesel GT	2500	m2/MW	[**171**]
	Diesel Gen Set	182	m2/kW	[**163**]
	Oil	2,5	km2/1000 MW	[**136**]
Natural Gas	Natural Gas	0,31	m2/MWh	[**140**]
	Natural Gas	1	km2 /500MW	[**160**]
	Gas	36-44	m2/MWh	[**164**]
	Natural Gas	0,222	m2/kW	[**169**]
	LNG CCY	2500	m2/MW	[**171**]

	Natural Gas	2,5	km2/1000 MW	[**183**]
	Natural Gas	1–4	km2/GW	[**143**]
	Natural Gas turbine	2,5	km2/1000 MW	[**136**]
	Natural Gas combined cycle	2,5	km2/1000 MW	[**136**]
Hydro	Hydro	500	m2/kW	[**161**]
	Hydro	750	km2/1000 MW	[**159**]
	Hydro (large)	4,1	m2/MWh	[**140**]
	Hydro (small)	0,02	m2/MWh	[**140**]
	Hydro	101-156	m2/MWh	[**164**]
	New SHP	100	m2/kW	[**169**]
	Hydro	750000	m2/MW	[**171**]
	Small Hydro	18000	m2/MW	[**171**]
	Hydro	750	km2/1000 MW	[**166**]
	Hydro	750	km2/1000 MW	[**183**]
	Pico Hydro	50	m2/kW	[**163**]
	Micro Hydro	50	m2/kW	[**163**]

	Hydro	75–750	km2/GW	[**143**]
	Hydro	750	km2/1000 MW	[**136**]
Solar	Solar PV	150	m2/kW	[**161**]
	Solar	35	km2/1000 MW	[**159**]
	Solar PV	35	km2/1000 MW	[**105**]
	Solar thermal	40	km2/1000 MW	[**105**]
	Solar thermal	0,46	m2/MWh	[**140**]
	Solar PV	0,33	m2/MWh	[**140**]
	Solar PV	42	km2 /500MW	[**160**]
	Solar CSP	47	km2 /500MW	[**160**]
	Solar	110-130	m2/MWh	[**164**]
	Solar	100000	m2/MW	[**171**]
	Solar	35	km2/1000 MW	[**166**]
	Solar PV	48,5	m2/kW	[**163**]
	Photovoltaic	28–64	km2/GW	[**143**]
	Solar Thermal Energy	0,00219	Ha/KW	[**93**]
	Photovoltaic Solar Energy	0,001	Ha/KW	[**93**]

	Photovoltaic	35	km2/1000	[**136**]
Battery	Lithium Ion	2,17/200	acres/MWh	[**179**]
	Lithium Ion	3,3/400	acres/MWh	[**179**]
	Lithium Ion	5/600	acres/MWh	[**179**]
	Sodium-sulfur battery	14000/350	m2/MWh	[**184**]
	Utility-scale battery	400/9,6	m2/GWh	[**185**]
	Battery storage	0,017	acre/MW	[**186**]

REALIZATION TIME				
Energy source	**Characteristics**	**Value**	**Units**	**Source**
Biomass	Biomass (landfill)	2	years	[**156**]
	Biomass (incinerator)	3	years	[**156**]
	Biomass	24-26	months	[**187**]
	Biomass (energetic cultivations) P<5MW	1	years	[**152**]
	Biomass (forest and agricultural wastes) P<5MW	1	years	[**152**]
	Biomass (farming industrial wastes) P<5MW	1	years	[**152**]
	Biomass (forest industrial wastes) P<5MW	1	years	[**152**]

	Biomass (co-combustion in conventional central) P>50 MW	1	years	[**152**]
	Wood Energy Biomass	1	years	[**93**]
	Co-combustion/ Biomass	1	years	[**93**]
Coal	Conventional coal power plant	3	years	[**156**]
	Advanced supercritical coal	4	years	[**156**]
	IGCC	4	years	[**156**]
Diesel	Diesel generator	1	years	[**156**]
Natural Gas	Conventional gas turbine	2	years	[**156**]
	Advanced gas turbine	3	years	[**156**]
	Gas engine	1	years	[**156**]
	Natural Gas	2	years	[**169**]
Hydro	Small hydropower	4	years	[**156**]
	Large hydropower	7	years	[**156**]
	New SHP	2	years	[**169**]
	Hydroelectric P<10 MW	1,5	years	[**152**]
	Hydroelectric 10<P<25 MW	2	years	[**152**]
	Hydroelectric 25<P<50 MW	2,5	years	[**152**]
Solar	Solar thermal	2	years	[**156**]
	Solar photovoltaic	1	years	[**156**]
	Solar photovoltaic (DG)	1	years	[**156**]
	Solar	12-16-18	months	[**187**]

	Solar Thermo-electric P>10 MW	2	years	[**152**]
	Solar Thermal Energy	2	years	[**93**]
	Photovoltaic Solar Energy	0,5	years	[**93**]

LIFESPAN				
Energy source	**Characteristics**	**Value**	**Units**	**Source**
Biomass	Biomass (landfill)	20	years	[**156**]
	Biomass (incinerator)	25	years	[**156**]
	Biomass boiler (heat)	20-30	years	[**157**]
	Direct combustion	20	years	[**157**]
	CHP	25	years	[**157**]
	Gasification	20-25	years	[**157**]
	Biomass plant - energy crops	20-25	years	[**158**]
	Biomass	40	years	[**159**]
	Slow pyrolysis	10	years	[**162**]
	Gasification to electricity	20	years	[**162**]
	Combustion to electricity	20	years	[**162**]
	Decentralized combined heat and power (CHP)	10	years	[**162**]
	Biogas	20	years	[**163**]
	Biomass Gasifier	20	years	[**163**]
	Biomass-biogas	35	years	[**175**]

	Biomass (energetic cultivations) P<5MW	15	years	[**152**]
	Biomass (forest and agricultural wastes) P<5MW	15	years	[**152**]
	Biomass (farming industrial wastes) P<5MW	15	years	[**152**]
	Biomass (forest industrial wastes) P<5MW	15	years	[**152**]
	Biomass (co-combustion in conventional central) P>50 MW	20	years	[**152**]
	Wood Energy Biomass	15	years	[**93**]
	Co-combustion/ Biomass	20	years	[**93**]
Coal	Conventional coal power plant	30	years	[**156**]
	Advanced supercritical coal	40	years	[**156**]
	IGCC	40	years	[**156**]
	Coal-fired power plant	25-40	years	[**158**]
	Lignite	40	years	[**175**]
Diesel	Diesel generator	10	years	[**156**]
	Oil-fired power plant	20-40	years	[**158**]
	Diesel power	20	years	[**163**]
	Conventional gas turbine	12	years	[**156**]
	Advanced gas turbine	15	years	[**156**]

Natural gas	Gas engine	10	years	[**156**]
	Natural Gas-fired plant	20-30	years	[**158**]
	Natural Gas	30	years	[**175**]
	Gas- fired power plant	20	years	[**188**]
Hydro	Small hydropower	40	years	[**156**]
	Large hydropower	50	years	[**156**]
	Large-scale power plants	35	years	[**157**]
	Mini-hydroelectric plant - conventional dam	20-50	years	[**158**]
	Hydro	100	years	[**159**]
	PicoHydro System	5	years	[**163**]
	Micro Hydropower	30	years	[**163**]
	Hydro (Large/Small)	50	years	[**175**]
	Hydroelectric P<10 MW	25	years	[**152**]
	Hydroelectric 10<P<25 MW	25	years	[**152**]
	Hydroelectric 25<P<50 MW	25	years	[**152**]
Solar	Solar thermal	30	years	[**156**]
	Solar photovoltaic	20	years	[**156**]
	Solar photovoltaic (DG)	20	years	[**156**]
	Solar PV	20	years	[**157**]
	CSP	25	years	[**157**]
	Solar thermal	10-15	years	[**157**]

	Photovoltaic solar plant - different panels	20-25	years	[**158**]
	Solar thermal - Parabolic trough	25-30	years	[**158**]
	Solar	25	years	[**159**]
	Solar Home System	20	years	[**163**]
	Solar PV	20	years	[**163**]
	PV	25	years	[**175**]
	Solar Thermo-electric P>10 MW	25	years	[**152**]
	Solar Thermal Energy	25	years	[**93**]
	Photovoltaic Solar Energy	25	years	[**93**]
Battery	Lead-acid battery	10	years	[**188**]
	Lithium polymer battery	8,2	years	[**188**]
	Battery	5	years	[**189**]
	Lithium titanate	15	years	[**180**]
	Lead-acid battery	5-20	years	[**181**]
	Nickel-cadmium battery	10-20	years	[**181**]
	Sodium-sulfur battery	5-15	years	[**181**]
	Lithium ion battery	5-15	years	[**181**]
	Vanadium redox battery	5-30	years	[**181**]
	Zinc bromine battery	5-10	years	[**181**]
	Pb-A	5-15-13	years	[**182**]
	Li-ion	5-15-14-16	years	[**182**]

	Na-S	10-15-15-12-20	years	[**182**]
	Ni-Cd	10-20-3-20-15-20	years	[**182**]
	Vanadium redox battery	5-10-20	years	[**182**]
	Zn-Br	5-10-10-8-10	years	[**182**]

EFFICIENCY				
Energy source	**Characteristics**	**Value**	**Units**	**Source**
Biomass	Biomass (landfill)	30	%	[**156**]
	Biomass (incinerator)	22	%	[**156**]
	Biomass	25,3	%	[**161**]
	Biomass plant - energy crops	22-30	%	[**158**]
	Biomass	33	%	[**159**]
	Biogas	33	%	[**163**]
	Biomass Gasifier	32	%	[**163**]
	Biomass	35	%	[**140**]
	Biomass - Waste	22-28	%	[**160**]
	Biomass-biogas	40	%	[**175**]
	Biomass	28	%	[**26**]
	Biomass	30,6	%	[**176**]
Coal	Conventional coal power plant	35	%	[**156**]
	Advanced supercritical coal	46	%	[**156**]

	IGCC	45	%	[**156**]
	Coal-fired power plant	30-42	%	[**158**]
	Coal	48	%	[**140**]
	Coal	38	%	[**165**]
	Lignite	37	%	[**175**]
	Coal/Lignite	39,4	%	[**26**]
	Coal	39	%	[**166**]
	Coal	40	%	[**172**]
	Coal	40,8	%	[**176**]
	Coal	30-45	%	[**143**]
Diesel	Diesel generator	31	%	[**156**]
	Oil-fired power plant	32-46	%	[**158**]
	Diesel power	40	%	[**163**]
	Oil	38-44	%	[**160**]
	Oil	42	%	[**173**]
	Oil	37,5	%	[**26**]
Natural gas	Conventional gas turbine	34	%	[**156**]
	Advanced gas turbine	40	%	[**156**]
	Gas engine	40	%	[**156**]
	Natural Gas-fired plant	32-56	%	[**158**]
	Natural Gas	59	%	[**140**]
	Natural Gas	39	%	[**160**]

	Natural Gas	52	%	[**165**]
	Natural Gas	45	%	[**169**]
	Natural Gas	45	%	[**173**]
	Natural Gas	54	%	[**175**]
	Natural Gas turbine	39	%	[**26**]
	Natural Gas combined cycle	54,8	%	[**26**]
	Gas OC	35	%	[**172**]
	Gas CC	53	%	[**172**]
	Natural Gas	47,4	%	[**176**]
	Natural Gas	45-55	%	[**143**] [**172**]
Hydro	Hydro	90	%	[**161**]
	Mini-hydroelectric plant - conventional dam	80-85	%	[**158**]
	Hydro	80	%	[**102**]
	PicoHydro System	50	%	[**163**]
	Micro Hydropower	70	%	[**163**]
	Hydro (large)	100	%	[**140**]
	Hydro (small)	100	%	[**140**]
	Hydro (dam)	78	%	[**165**]
	Hydro (r-o-r)	82	%	[**165**]
	New SHP	70-85	%	[**169**]

	Hydro (Large/Small)	90	%	[**175**]
	Hydro	80	%	[**26**]
	Hydro	80	%	[**166**]
	Hydro	88-91	%	[**143**]
Solar	Solar PV	20	%	[**161**]
	Photovoltaic solar plant - different panels	10-22	%	[**158**]
	Solar thermal - Parabolic trough	10-30	%	[**158**]
	Solar Home System	15-20-22	%	[**163**]
	Solar PV	15-20-22	%	[**163**]
	Solar PV	100	%	[**140**]
	Solar thermal	40	%	[**140**]
	Solar PV	15	%	[**160**]
	Solar CSP	14-18	%	[**160**]
	Solar PV	16	%	[**165**]
	PV	16	%	[**175**]
	Photovoltaic	9,4	%	[**26**]
	Solar	15	%	[**166**]
	CSP	17,6	%	[**176**]
	PV	13	%	[**176**]
	Photovoltaic	4-22	%	[**143**]
	Battery	0,85	-	[**188**]

Battery	Battery	90	%	[**177**]
	Lead acid battery	80	%	[**168**]
	Lithium polymer battery	95	%	[**168**]
	Lithium Iron Phosphate	0,95	-	[**189**]
	Lithium Ion	82	%	[**179**]
	Lithium Ion	87	%	[**179**]
	Lithium Ion	89	%	[**179**]
	Lithium titanate	81	%	[**180**]
	Lead-acid battery	63-90	%	[**181**]
	Nickel-cadmium battery	60-83	%	[**181**]
	Sodium-sulfur battery	75-92	%	[**181**]
	Lithium ion battery	85-100	%	[**181**]
	Vanadium redox battery	75-85	%	[**181**]
	Zinc bromine battery	66-80	%	[**181**]
	Pb-A	70-80-63-90-75-80	%	[**182**]
	Li-ion	90-97-75-90	%	[**182**]
	Na-S	75-90-75-75-85	%	[**182**]
	Ni-Cd	60-70-60-83	%	[**182**]
	Vanadium redox battery	75-85-65-75	%	[**182**]
	Zn-Br	65-75-66-80-66	%	[**182**]
	LFP - lithium iron phosphate	92,4	%	[**190**]
	LFP-LTO	93	%	[**190**]

	LCO - lithium cobalt oxide	91	%	[**190**]
	LMO - Lithium Manganese Oxide	93	%	[**190**]
	NCM - Lithium Cobalt Manganese Oxide	93,8	%	[**190**]
	NCA - Lithium Nickel Cobalt Aluminum Oxide	91,6	%	[**190**]
	Li - ion	95	%	[**190**]

ACCIDENT FATALITIES				
Energy source	**Characteristics**	**Value**	**Units**	**Source**
Biomass	Biomass - Waste	0	Deaths/TWyr	[**160**]
	Biomass-biogas	0,0017	Fatalities/TWh	[**175**]
	Biomass	0,0149	Fatalities/GWyr	[**176**]
	Biomass	0	Deaths/TWyr	[**136**]
Coal	Coal	0,000017	Fatalities/GWh	[**165**]
	Lignite	0,0207	Fatalities/TWh	[**175**]
	Coal/lignite	342	Deaths/TW yr	[**183**]
	Coal	1,08-9,06	Fatalities/GWyr	[**176**]
	Coal/lignite	342	Deaths/TWyr	[**136**]
Diesel	Oil	385	Deaths/TW yr	[**160**]
	Oil	385	Deaths/TW yr	[**136**]
Natural Gas	Natural Gas	85	Deaths/TW yr	[**160**]
	Natural Gas	0,0000094	Fatalities/GWh	[**165**]

	CCGT	0,0051	Fatalities/TWh	[**175**]
	Natural Gas	85	Deaths/TW yr	[**183**]
	Natural Gas	0,202	Fatalities/GWyr	[**176**]
	Natural Gas turbine	85	Deaths/TW yr	[**136**]
	Natural Gas combined cycle	85	Deaths/TW yr	[**136**]
Hydro	Hydro (dam)	0,0000058	Fatalities/GWh	[**165**]
	Hydro (r-o-r)	0,0000058	Fatalities/GWh	[**165**]
	Hydro	0,0003	Fatalities/TWh	[**175**]
	Small hydro	0,0003	Fatalities/TWh	[**175**]
	Hydro	883	Deaths/TW yr	[**183**]
	Hydro	883	Deaths/TW yr	[**136**]
Solar	Solar PV	3	Deaths/TW yr	[**160**]
	Solar CSP	3	Deaths/TW yr	[**160**]
	Solar	0,00000013	Fatalities/GWh	[**165**]
	PV	0,0011	Fatalities/TWh	[**175**]
	PV	0,000245	Fatalities/GWyr	[**176**]
	Photovoltaic	3	Deaths/TW yr	[**136**]

CO_2 EMISSIONS				
Energy source	**Characteristics**	**Value**	**Units**	**Source**
Biomass	Biomass	45	gCO2/kWh	[**161**]
	Biomass - Waste	50	T-CO2/GWh	[**160**]
	Biomass-Biogas	54,26	gCO2eq/kWh	[**175**]
	Biogas	5,37	gCO2eq/kWh	[**163**]
	Biomass gasifier	5,37	gCO2eq/kWh	[**163**]
	Biomass	71,64	gCO2/kWh	[**176**]
	Biomass	58000	mg/kWh	[**136**]
Coal	Coal	1192	gCO2eq/kWh	[**165**]
	Lignite	1067,15	gCO2eq/kWh	[**175**]
	Coal	94,6	g CO2/MJ	[**171**]
	Coal	986	g/kWh	[**166**]
	Coal	815	kg/MWh	[**172**]
	Coal	926,87	gCO2/kWh	[**176**]
	Coal	1000	gCO2/kWh	[**143**]
	Coal/Lignite	986000	mg/kWh	[**136**]
Diesel	Oil	750	tCO2/GWh	[**160**]
	Oil	0,31	tCO2eq/MWh	[**173**]
	Diesel engine - 1	77,4	g CO2/MJ	[**171**]
	Diesel engine - 2	77,4	g CO2/MJ	[**171**]
	Diesel engine - 3	76,3	g CO2/MJ	[**171**]

	Diesel engine - 4	76,3	g CO2/MJ	[**171**]
	Diesel engine - 5	76,3	g CO2/MJ	[**171**]
	Diesel engine - 6	77,4	g CO2/MJ	[**171**]
	Diesel engine - 7	76,3	g CO2/MJ	[**171**]
	Diesel Gen Set	800	gCO2eq/kWh	[**163**]
	Oil	1131178	mg/kWh	[**136**]
Natural gas	Natural Gas	500	T-CO2/GWh	[**160**]
	Natural Gas	482	gCO2eq/kWh	[**165**]
	Natural Gas	0,484	t CO2/MWh	[**169**]
	Natural Gas	0,237	tnCO2eq/MWh	[**173**]
	Natural Gas	509,96	gCO2-eq/kWh	[**175**]
	Gas Turbine - 1	74,1	g CO2/MJ	[**171**]
	Gas Turbine - 2	74,1	g CO2/MJ	[**171**]
	Gas OC	575	kg/MWh	[**172**]
	Gas CC	400	kg/MWh	[**172**]
	Natural Gas	479,1	gCO2/kWh	[**176**]
	Natural Gas	500-600	gCO2/kWh	[**143**]
	Gas-fired power plant	0,188	kgCO2/MJ	[**188**]
	Natural Gas turbine	560000	mg/kWh	[**136**]
	Natural Gas combined cycle	450000	mg/kWh	[**136**]
Hydro	Small hydropower	33,17	kg/kW	[**167**]
	Hydro	26	gCO2/kWh	[**161**]

	Hydro (dam)	50	gCO2-eq/kWh	[**165**]
	Hydro (r-o-r)	11	gCO2-eq/kWh	[**165**]
	New SHP	0,005	t CO2/MWh	[**169**]
	Hydro	42,18	gCO2-eq/kWh	[**175**]
	Small hydro	2,21	gCO2-eq/kWh	[**175**]
	Hydro	22,69	g/kWh	[**166**]
	Pico Hydro	56	gCO2-eq/kWh	[**163**]
	Micro Hydro	56	gCO2-eq/kWh	[**163**]
	Hydro	22696	mg/kWh	[**136**]
Solar	Photovoltaic solar energy	2472,07	kg/kW	[**167**]
	Solar PV	85	gCO2/kWh	[**161**]
	Solar PV	85	T-CO2/GWh	[**160**]
	Solar CSP	25	T-CO2/GWh	[**160**]
	Solar PV	3,6	gCO2-eq/kWh	[**165**]
	PV	44,71	gCO2-eq/kWh	[**175**]
	Solar	49,17	g/kWh	[**166**]
	Solar PV	90	gCO2-eq/kWh	[**163**]
	CSP	111,94	gCO2/kWh	[**176**]
	PV	107,46	gCO2/kWh	[**176**]
	Photovoltaic	49174	mg/kWh	[**136**]
Battery	Li-ion battery	0,25	kgCO2eq/KWh	[**191**]
	Lead-Acid Storage	92	tonCO2eq/GWh	[**192**]

	Vanadium Storage	72	tonCO2eq/GWh	[**192**]
	LFP - lithium iron phosphate	77,6	g/kWh	[**190**]
	LFP-LTO	25,1	g/kWh	[**190**]
	LCO - lithium cobalt oxide	93,3	g/kWh	[**190**]
	LMO - Lithium Manganese Oxide	70,6	g/kWh	[**190**]
	NCM - Lithium Cobalt Manganese Oxide	85,6	g/kWh	[**190**]
	NCA - Lithium Nickel Cobalt Aluminium Oxide	68,11	g/kWh	[**190**]
	NiMH – Nickel metal hydride	3,5/50	kg CO2-eq/MJ	[**193**]
	NCM - Lithium Cobalt Manganese Oxide	1,9/50	kg CO2-eq/MJ	[**193**]
	LFP - lithium iron phosphate	1,4/50	kg CO2-eq/MJ	[**193**]

EXTERNAL COSTS				
Energy source	**Characteristics**	**Value**	**Units**	**Source**
Biomass	Biomass	0,17-4,25	€c/kWh	[**140**]
	Biomass - Waste	0,0028	$/kWh	[**160**]
	Biomass	1700-42500	€/GWh	[**164**]
	Biomass	2,65	€cents/kWh	[**136**]
	Biomass	2,65	€cents/kWh	[**26**]
Coal	Coal	1,02-7,65	€c/kWh	[**140**]
	Coal	10200 - 76500	€/GWh	[**164**]
	Coal/lignite	8,4	€cents/kWh	[**136**]

	Coal/lignite	8,4	€cents/kWh	[**26**]
Diesel	Oil	0,056	$/kWh	[**160**]
	Oil	2000-8000	€/GWh	[**164**]
	Oil	6,75	€cents/kWh	[**136**]
	Oil	6,75	€cents/kWh	[**26**]
Natural gas	Natural Gas	0,2-0,8	€c/kWh	[**140**]
	Natural Gas	0,028	$/kWh	[**160**]
	Gas	2000-8000	€/GWh	[**164**]
	Natural Gas turbine	2	€cents/kWh	[**136**]
	Natural Gas combined cycle	1,33	€cents/kWh	[**26**]
	Natural Gas turbine	2	€cents/kWh	[**136**]
	Natural Gas combined cycle	1,33	€cents/kWh	[**26**]
Hydro	Hydro (large)	0,02-0,67	€c/kWh	[**140**]
	Hydro (small)	0,02-0,67	€c/kWh	[**140**]
	Hydro	200-6700	€/GWh	[**164**]
	Hydro	0,56	€cents/kWh	[**136**]
	Hydro	0,56	€cents/kWh	[**26**]
Solar	Solar PV	0,438	€c/kWh	[**140**]
	Solar thermal	0,438	€c/kWh	[**140**]
	Solar PV	0,000056	$/kWh	[**160**]
	Solar CSP	0,000056	$/kWh	[**160**]
	Solar	4380	€/GWh	[**164**]

	Photovoltaic	0,24	€cents/kWh	[**136**]
	Photovoltaic	0,24	€cents/kWh	[**26**]
Battery	Battery	10	$/MWh	[**194**]

PARTICLE EMISSIONS				
Energy source	**Characteristics**	**Value**	**Units**	**Source**
Biomass	Biomass - PM10	335,6-403,41	Kg/GWh	[**164**]
	Biomass – PM2,5	291,16-350,16	Kg/GWh	[**164**]
	Biomass - 1	255,1	mg/MJ	[**171**]
	Biomass - 2	255,1	mg/MJ	[**171**]
	Biomass	269	mg/kWh	[**136**]
Coal	Coal – PM10	175,5-210,98	Kg/GWh	[**164**]
	Coal – PM2,5	65,44-146,25	Kg/GWh	[**164**]
	Coal	40	mg/MJ	[**171**]
	Coal - fine dust emissions	15	g/MWh	[**172**]
	Coal/Lignite	347	mg/kWh	[**136**]
Diesel	Oil – PM10	203,5-246	Kg/GWh	[**164**]
	Oil – PM2,5	147,25-178,25	Kg/GWh	[**164**]
	Diesel Engine - 1	13	mg/MJ	[**171**]
	Diesel Engine - 2	13	mg/MJ	[**171**]
	Diesel Engine - 3	13	mg/MJ	[**171**]
	Diesel Engine - 4	13	mg/MJ	[**171**]

	Diesel Engine - 5	13	mg/MJ	[**171**]
	Diesel Engine - 6	13	mg/MJ	[**171**]
	Diesel Engine - 7	13	mg/MJ	[**171**]
	Oil	128	mg/kWh	[**136**]
Natural gas	Gas – PM10	5,67-7,06	Kg/GWh	[**164**]
	Gas – PM2,5	5,67-7,07	Kg/GWh	[**164**]
	Gas turbine - 1	5	mg/MJ	[**171**]
	Gas turbine - 2	5	mg/MJ	[**171**]
	Gas- fired power plant – PM2,5	0,00000259	kg/MJ	[**188**]
	Gas- fired power plant – PM10	0,000000754	kg/MJ	[**188**]
	Natural Gas turbine	34	mg/kWh	[**136**]
	Natural Gas combined cycle	6	mg/kWh	[**136**]
Hydro	Hydro – PM10	0	Kg/GWh	[**164**]
	Hydro – PM2,5	0	Kg/GWh	[**164**]
	Hydro	5	mg/kWh	[**136**]
Solar	Solar – PM10	0	Kg/GWh	[**164**]
	Solar – PM2,5	0	Kg/GWh	[**164**]
	Photovoltaic	101	mg/kWh	[**136**]
Battery	Li-ion battery	0,000444	Kg/kWh	[**191**]
	NiMH – Nickel metal hydride	0,023/50	kg/MJ	[**193**]
	NCM - Lithium Cobalt Manganese Oxide	0,0036/50	kg/MJ	[**193**]
	LFP - lithium iron phosphate	0,0021/50	kg/MJ	[**193**]

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