Multi-criteria Preference Aggregation Framework for Sustainable Energy Planning

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PhD Thesis

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CONTENTS

FIGURES

TABLES

EQUATIONS

SIMULATIONS

EXHIBITS

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DECLARATION

I, Raquel Santos-Ramos, the Candidate, am the author of the thesis. Unless otherwise stated, all references cited have been consulted by me; the work of which the thesis is a record was been done by me, and it has not been previously accepted for a higher degree.

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ABSTRACT

In the energy field, the decisions need to take into consideration several factors such as the needs of the population, the environment, suitability, capital cost, sustainability, political goals and the actors involved, with their interests and preferences. The lack of homogeneity in all the factors that must be consider makes it necessary to design a process that guides the analysis process of any type of decision-maker. Decision analysis methods have been developed to aid decision-makers identify a problem, determine the criteria to be consider and their importance, recognize the stakeholders that need to be involved and pose the different alternatives to resolve or to best address the problem. These techniques range from simple to more mathematically oriented ones, from single criterion evaluation to multiple criteria, and from purely qualitative or quantitative to mixed techniques. Within the field of decision analysis, multi-criteria techniques are better suited to aid in decision situations in the energy field as these decisions require several considerations beside economic ones. This thesis uses theories and notions of decision analysis to construct a framework to be used in any energy related decision situations by non-experts. The framework tackles common challenges faced by multi-criteria decision analysis methods, including the identification of stakeholders and decision-makers, the aggregation of various decision-makers, preferences and heterogeneous inputs, and the selection of suitable criteria, alternatives and methods.

ABBREVIATIONS

AHP	Analytical Hierarchy Process
AIP	Aggregating Individual Priorities
AIJ	Aggregating Individual Judgments
DAM	Decision analysis method
DM	Decision-maker
ELECTRE	Elimination Et Choix Traduisant la Realité
GDP	Gross Domestic Product
LMS	Least Mean Square
MADM	Multi-attribute decision making
MAUT	Multi-Attribute Utility Theory
MCA	Multi-Criteria Analysis
MCDA	Multi-Criteria Decision Analysis
McPAF	Multi-Criteria Preference Analysis Framework
MODM	Multi-Objective Decision Making
PEST	Political, Economic, Social, and Technological
PESTEL	Political, Economic, Social, Technological, Environmental, and Legal
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluation
SMART	Simple Multi Attribute Rating Technique
TEES	Technical, Environment, Economic, Social
WSM	Weighted Sum Model

1 INTRODUCTION

Since the mid-19th century, societies have been dependent on oil to fulfil basic daily needs, such as heat and food preparation, and secondary needs, such as transportation. The reality that resources are finite and thus there is a need for sustainability came to the forefront during the 20th century as the dependence on oil was challenged through various crises and environmental concerns. These crises and concerns included the increase in the prices of oil and gas, fear of fuel scarcity, and energy insecurity for the population. Regarding environmental concerns, once the damage caused by the abuse of oil as a fuel was acknowledged and recognized as scientifically sound, governments understood the need to set international agreements with ambitious political goals of emission reduction. Examples of these agreements include the Kyoto Protocol and the EU Renewable Directives. These crises and concerns exacerbated the need to seek alternative fuel sources and decrease reliance on oil; Governments found, in addition, secondary reasons to pursue alternative fuels. These secondary reasons have broad social and economic undertones. They include the creation of direct and indirect employment, an increase in the national gross domestic product (GDP), and an increase in government revenues.

Despite how praiseworthy or noble the reasons behind them, all decisions, including political and commercial, should be done in a conscientious manner based on sound grounds and thorough analysis; for the purpose of achieving successful and sustainable results. A fundamental step to make a conscientious decision is to possess comprehension of the situation. Lack of in-depth understanding of the problem can lead to serious errors in situation assessment and, as a result, lead to errors in the final decision analysis process. A situation can be wrongfully assessed due to various reasons like insufficient information or the overlooking of important elements. Overlooking can happen because the element's importance was downplayed or simply because it was unknown.

Owing to the primary and secondary reasons mentioned earlier, decisions taken in the energy field affect not only the supply for fuel, but also the economic, environmental, and social surroundings. An incorrect project investment decision can create a strain in a country's budget, thus producing a negative domino effect on social services and the quality of life for the population. While a conscientious, well-informed decision does not guarantee successful results, it does increase the probability of achieving it/doing so. Across the world, countries are analysing how to establish local energy industries to exploit indigenous resources that may, in great part, help to substitute current fuels used for various purposes, including the generation of electricity. During the early stages of this research, the most talked about/popular options for power generation were shale gas and renewable energy technologies. Countries like China, Argentina and the U.K were trying to duplicate the success of the United States' shale gas revolution. However, technological challenges have forced the consideration of more options.

For countries looking to substitute current fuel source, part of fully understanding the situation prior to making any decision regarding the energy pathway to be followed, it is key to identify available local energy resources and create a comprehensive account of the energy needs of the country. A comprehensive account of a country's energy needs should cover the following: current energy needs; whether current resources are meeting the needs of the population, both primary and secondary, and to what extent; how would alternative fuel sources impact the current needs; what is the expected population growth; what are the forecasted needs of future generations; and whether current resources would be sufficient to fulfil the projected future needs. Future needs mean energy (not solely constrained to power) that will be required to meet basic needs, maintain the country's infrastructure technological advancement and for the well-being of the population, and other operations.

Once a comprehensive assessment of the energy needs of the country is prepared, the country must decide what paths are available and their feasibility. For example, in the case of power production, a country may decide to follow a green path geared towards fewer emissions. In this case, electricity produced from renewable sources is an option. Still, regarding feasibility, renewable energy has always been compared, regarding cost and effectiveness, to oil and gas, with the result being that renewable energy is considered costlier and less trustworthy of an alternative, due to its intermittent nature. A counterargument for this assertion is that, for any industry, technological advances is a driver force for decrease in the capital costs of any project. This reduction in capital expense, should, in theory, translate to a reduction in the end-price paid by the consumers. The renewable energy industry is no exception. Without the continuous development and improvement of renewable technologies the production costs will remain higher than the costs of developing other fuels, whether conventional or unconventional. As the forces of the market indicate, investment tends to move towards areas that involve lower costs with higher revenues, meaning that, from this strict point of view, investment is expected to move away from the renewable energy industry, which in turn negatively affects the advancement of technologies that could potentially reduce the capital cost of any project.

Yet the energy industry is not only moved by economics. Considerations on security of supply and fulfilling the needs of the population also have a heavy weight on a government's decision as to the energy path they want to pursue. If the needs of the population are not met, due to inefficiency or the high cost of providing energy, the difference amongst the various groups may cause social unrest, as it is perceived as a widening of the gap between socio-economic groups. This widening can create resentment, which may turn into frustration, which is grounds for civil unrest and terrorism. On the other hand, although populational needs and energy security are important, distresses over pollution brought on by the exploitation of resources, natural resource curse, public health, distribution of wealth, energy uses, and conservation are other factors that have to be considered because of the effects these issues may have on the wellbeing of the citizens. The combinations of all these issues have helped to create the need to develop both non-renewable sources (conventional or unconventional) and renewable ones.

In the energy field, the decision of following a pathway (e.g. to import fuel or to exploit local resources) and which pathway to follow (for example, invest in solar photovoltaic, windfarms, both or none) needs to take into consideration factors such as the needs of the population, the environment, suitability, capital cost, sustainability, political goals and the actors involved, amongst others. Not only the variability of the criteria and the variability of the stakeholders involved must be taken into account, but also their interests and the level of importance of each criterion for each party involved. Since there is no homogeneity in all the factors that must be taken into consideration, it is necessary to delineate a process that guides any decision-maker at how to arrive at a solution or solutions that better satisfies the identified needs. This process must also provide the greatest availability of information possible. Decision analysis methods have been developed to aid decision-makers identify a problem, determine the criteria and its importance, recognize the stakeholders that need to be involved, and pose the different alternatives to resolve or to best address the problem. As there are various factors, besides economic ones, to take into consideration when planning, many models and techniques have been developed to aid in analysing a situation which requires decision-making. These techniques range from simple to more mathematically oriented ones, from single criterion evaluation to multiple criteria, and from purely qualitative or quantitative to mixed techniques. The development of these techniques has been the result of needs and are designed to be able to assist in any type of decision situation. This said, none have been composed with the specific aim of being used for decisions related to the energy industry. There is not a guideline of how nor which of these methods could or should be applied to energy related decisions.

Within the field of decision analysis, multi-criteria techniques are better suited to aid in decision situations in the energy field, as these decisions require several considerations besides economic ones. The industry needs to take into consideration matters such as emissions, use of land and water, greenhouse gases, other pollutants, costs, price of raw materials, and political conditions, amongst others. In addition to the matters just mentioned, any development within the energy industry requires the element of sustainability.

This thesis aims at developing a non-expert step-by-step framework, based on multi-criteria decision analysis techniques taking into consideration the problems previously discussed, specifically:

- energy field-oriented framework
- addressing multiple inputs and multiple decision-makers
- addressing different types of inputs
- applicability to any energy-related situation (should not be constrained only to decide between renewable energy options or only to decide between shale gas and renewable energy)
- comprehensiveness while user-friendly.

1.1 THESIS PROBLEM

How can sustainable energy planning decisions be comprehensively analysed?

1.2 RESEARCH OBJECTIVES

To provide a framework that will aid in comprehensively analysing situations that require decision-making in energy planning, which incorporates various options, benchmarks, preferences, and participants.

1.3 OVERVIEW OF THE LITERATURE REVIEW

At the beginning of the research, the emphasis of the literature review was on preparing a comparison of the characteristics of renewable energy and shale gas, as the two sources of potential competition for investment. During this early stage of the literature review, multi-criteria decision analysis techniques emerged as promising options in tackling the focus of this thesis. However, during research, international interest in shale gas dwindled. The more in-depth information found regarding decision analysis origins, methods, techniques, suitability, and applicability in the energy field together with the diminishing attractiveness of shale gas in the international arena, shaped the need to broaden the original concept of the framework to one that could aid in any decision situation in the energy field.

The final product is that the literature review includes information on the relationship between the energy field and decision analysis, the definition of sustainability and its importance, the concept of decision analysis and in particular of multi-criteria decision analysis, as well as information examined during the early stages of the research which, although may not have an important impact on the final product of this thesis, did significantly influence the beginning of the research, and eventually shaped it to this thesis. This other information examined includes system dynamics, development of shale gas, differences between shale gas and renewable energy markets, investment and development, integration of cost, and Dutch disease.

1.4 TERMS AND SCOPE

The purpose of this thesis is not to propose a new decision analysis technique, nor does it provide a process to obtain a final decision to be implemented. More accurately, the aspiration of this thesis is to provide an operational tool. This tool, in turn, is based on what is already known about the application of decision analysis methods in the energy industry. This operational tool will be achieved by building a step by step process that can be used by non-experts to better understand the components and the data required to obtain a full picture of the situation to be analysed and thus be equipped to reach an informed decision that takes into account different points of view.

1.5 OUTLINE OF THE CURRENT SITUATION

The discipline of decision analysis has provided interactive, quantitative and systematic approaches to evaluating a situation. The methods have been designed to be used in any situation requiring decision-making. Yet, although these methods have been used in the energy field, none have been particularly designed for it. In addition, the use of decision analysis methods encompasses a series of challenges which are not addressed in a uniform manner. This means that the possible solutions to these challenges can be found in different areas of the literature, but not in an aggregated form. No guideline currently exists that addresses each of these challenges and provides possible solutions to confront them.

1.6 IMPORTANCE OF THE RESEARCH

This research will fill an important gap by providing a step by step framework to be used for the analysis of decision-making involving energy planning. The framework will explain why multi-criteria decision analysis methods are better suited to be used in the energy field, acknowledge and provide solutions to the common challenges faced while using these methods, explain the importance of having several points of views and decision-makers, and provide a manner in which to aggregate these different views and preferences objectively.

This research delivers a superior framework, with concrete improvements to the structure for decision analysis, leaving no unseen areas, including the addition of cost benefit analysis. It is a tailored framework that was developed in the context of sustainable energy, but which components can be changed, added or discarded to be used as a wider tool. Its applicability to sustainable energy relies in that, because it ensures the four main points of view identified in the literature are considered, (technical, environmental, economic, social) it unambiguously takes into consideration current and future needs to find an arrangement that aims at meeting current needs without compromising future ones.

1.7 ORDER AND INFORMATION IN THE THESIS

This thesis is composed of 7 chapters:

- Chapter 1 – Introduction
- Chapter 2 – Literature Review
- Chapter 3 – Decision Analysis
- Chapter 4 – General Multi-criteria Analysis Framework
- Chapter 5 – Decision Analysis Framework Specific for the Energy Industry: Introduction to McPAF
- Chapter 6 – Case Study
- Chapter 7 – Conclusion

The Literature Review provides an overview of scholarly articles related to decision analysis, decision-making, multi-criteria decision analysis, renewable energy, shale gas, system dynamics, multi-criteria decision analysis methods, methods including fuzzy logic, method selection, aggregation of preferences, selection of criteria, and selection of decision-makers amongst others. The Chapter is subdivided into sections discussing the relationship between decision analysis and the energy field, the reasons why these methods are applicable in the energy field, and the definition and importance of sustainable energy planning.

The Decision Analysis chapter discusses the basics of decision analysis, providing an overview of its history, its application in energy planning, multi-criteria branch development, and examples of multi-criteria methods. The General Multi-criteria Analysis chapter provides an in-depth description of the general framework that is used in all methods, discusses each of the steps, identifies the challenges in each, and collects potential solutions to these challenges that have been published in scholarly articles. Chapter 5 introduces the framework developed for this thesis. This framework addresses the challenges identified in Chapter 4 and provides a solution selected from those proposed in the same chapter. The reasoning behind the selection of each of the solutions is provided. Chapter 6, Case Study, puts the framework proposed in Chapter 5 into practice. It explains the framework step-by-step, how it can be used, the difficulties experienced during the exercise and how the obstacles were overcome. Chapter 7 summarizes the findings of the previous chapters and suggesting areas of further study.

1.8 ANALYTICAL METHOD

The analytical method used throughout this thesis is a theoretical analysis. The literature aims to find and review the trends for the use of decision analysis tools in the energy industry, provides general background information on each of the topics, and identifies challenges in their use. Once the challenges in the use of decision analysis methods have been pinpointed, further literature is researched to collect possible solutions. The thesis goes through the general decision analysis process, and the challenges of each step are addressed, the possible solutions discussed and the preferred solution, along with the reasons why, is provided. For the proposed framework, the most commonly used multi-criteria decision analysis methods in energy planning and in the implementation of renewable energy policy, as determined by the literature, were selected to create a model framework that will aid in comprehensively analysing a sustainable energy decision situation, while considering the goals and concerns of those involved in the decision process. All these elements are compiled in a guideline to be tested with a case study.

The thesis problem is addressed by applying the basic ideas of decision analysis, together with identified issues related to energy planning while applying notions and concepts identified from the literature.

2 LITERATURE REVIEW

This chapter provides an overview of the literature reviewed during the research phase of this thesis. This review, however, does not contain all articles that were perused; rather, this chapter focuses on those articles that caused the greatest impact. The first section of this chapter discusses the relationship between decision analysis and the energy field, including defining the concept of decision analysis and multi-criteria decision analysis methods, the reasons why these methods are applicable in the energy field, and the definition and importance of sustainable energy planning. The articles reviewed are described in separate paragraphs, each providing a summary and evaluation of the article, including its influence in the final work. The second section of this chapter discusses other decision analysis methods that were consulted–but ultimately not used—in the creation of the framework. The third section of this chapter discusses literature that was accessed during the early stages of research, but was not used in the final product. This section further explains the reasons why these references were not used. The fourth section of the chapter explains the gaps identified in the literature and which of these this thesis aims at solving.

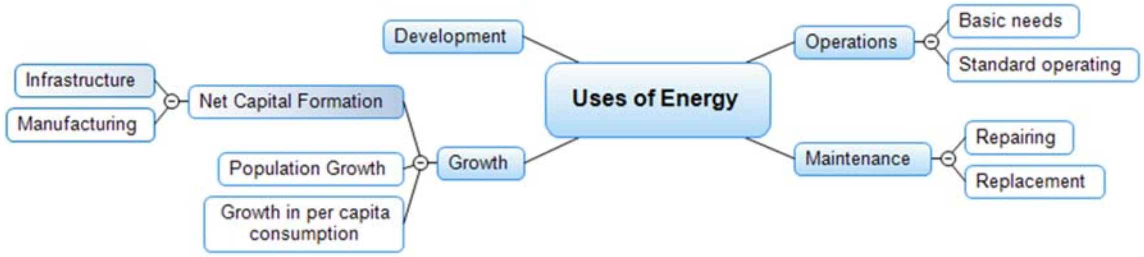
2.1 RELATIONSHIP BETWEEN THE ENERGY FIELD AND DECISION ANALYSIS

Throughout this section, there is a general overview of the comments of various authors who have discussed in their works the basic concepts of decision analysis, as well as the relationship between energy planning and decision analysis, is provided. This section provides the basis for Chapter 3, which will discuss the notions and impressions of the authors in greater detail. These impressions and notions are then placed in context to explain the root reasons and the need for developing the framework, which is the final aim of this research.

2.1.1 Understanding Energy Uses and Needs

Matutinovic (2010) explained that, in order to better understand and, therefore, fulfil the energy needs of the population, a difference has to be made between (1) energy used to grow the economy and (2) that of which is used to maintain the existing infrastructure and production. The author finds that economic growth and energy usage are closely interrelated as unequal access to natural resources and energy, in addition to other environmental challenges that further ostracize groups belonging to lower socioeconomical levels. This ostracism of socio-economic levels, in turn, creates discontent, and this discontent is prolific in the occurrence of terrorist activities and unforeseen international disagreements, which affects economic growth and access to natural resources, creating a never-ending cycle. Following this line of thought, the author has identified the five major global threats are: i) competition over resources, ii) climate change, iii) marginalization of the world's majority populations, iv) international terrorism, and v) global militarization. Furthermore, the author elucidates that energy has four main uses from a socio-economic point of view: (1) operations, (2) maintenance, (3) growth and (4) development (see Figure 2-1 below).

Figure 2-1: Main Uses of Energy



Matutinovic (2010) further states that dividing energy usage in this way helps nations make informed decisions on their main concerns, from social and economic points of view, while considering the need to reduce general poverty in other countries. The argument in favour is the following: if a State can fulfil its own needs, including energy needs, then it can spare resources to help other countries maintain peace. This separation of energy usage is especially beneficial to developing countries as it aids in prioritizing areas that require investment and provides some certainty in the knowledge of the quantity and the type of energy available to advance economic growth. The author explains that the operations element encompasses basic needs (e.g. food and heating) and the "standard operating energy", which is required for the daily activities, (i.e., all activities beyond the basic population needs). Meanwhile, the maintenance element is subdivided into activities conducing to the repair and replacement of existent infrastructure, such as roads and buildings. This use is important because if a country is not able to invest in upkeep of its existing infrastructure, the wear and tear will undoubtedly lead to collapse; an example of which is unusable roads or bridges that connect different regions. To avoid infrastructure collapse, the continuous use of energy and materials is required to maintain the infrastructure at its current levels.

The next element, growth, is divided into three aspects: 'net capital formation, population growth and growth in per capita consumption.' (Matutinovic (2010) Net capital formation is the sum of the factors needed for economic development (e.g. vehicles, machinery, and buildings) minus depreciation. The responsibility of providing net capital formation for infrastructure depends on the socio-political system in place. In some cases, it relies on the State, while in capitalist societies it is the private sector's responsibility; consequently, the private sector benefits the most from using this net capital formation for manufacturing processes. The manufacturing processes encompass everything that satisfies the material needs of the citizens, like food processing. Through the use of technology, it is this net capital formation that allows for the development of more thoroughly varied energy sources, such as shale gas and renewables. The development of more thoroughly varied energy sources, in turn, comes back as increased return requiring more investment and energy. This cycle of more energy need is a driver as to why a country should develop local energy sources. Population growth is also another factor to consider when talking about general growth in a country. In countries where there is positive population growth, it becomes necessary to implement policies to fulfil the necessities of this new individuals, including energy. From an economic point of view, population growth and its necessities, if not correctly tended to, may bring a myriad of challenges; the growing social and economic inequality, poverty, and famine could potentially become grounds for terrorism, social unrest, and civil wars. On the other hand, growth in per capital consumption refers to an increase in personal consumption because of a faster increase in the product of investment in infrastructure and manufacturing when compared to the growth of the population. As the trend continues, people will get increasingly used to living at a certain standard and as such, what used to be an anticipation of this new standard becomes an expectation and a norm, rather than a goal. Governments can maintain political stability by passing on this bonanza to lower economical classes through a cascade effect. To maintain this political stability, developing countries must continuously aim to decrease the gap between higher and lower economic classes. This closing-of-the-gap concept has been driven from the Western cultures to others. However, if the main objective of energy policy focuses solely on the energy used for consumption and maintenance, national security could be jeopardized. Energy should not only be used to replace or repair what is damaged, but rather to substitute what needs improvement for something better and more advanced thanks to technical progress and productivity. This concept is referred to as energy use for development. It is vital to have extra energy to meet future trials, both external (e.g. environmental concerns) and internal (e.g. population changes.) This article alludes to the threat of competition over resources, which is a reason why sound decision analysis is important when dealing with energy planning issues and, as such, is one of the reasons for the need of the framework creation that is proposed in Chapter 5. The idea is for the framework to provide a more comprehensive analysis for allocation of resources and for the alignment of needs and resources available.

2.1.2 Definition and Importance of Sustainable Energy Planning

Munasinghe and Meier (2008) defined energy planning as the identification of energy issues, their analysis and the development of policy options to address them. The need for energy planning did not really come into play until the 1970's. During this decade, increase in the price of oil and other fuels and their repercussions, required the development of energy policies and analytical tools that would help overcome the crisis. Prior to this time, energy policy was basically matching supply and demand only. The energy crisis of the 1970's required more sophisticated coordination of supply and demand, plus effective use of energy, demand management, and conservation creating, requiring the use of more complex modelling and analytical tools. This crisis also made it necessary to look at energy from a bigger perspective, as a global one and as such finding suitable fuel substitutions gained importance. During the 1980's, the economics of energy shifted towards a decrease in the price of oil, which affected oil exporting countries. This change in the economic horizon also required planning, but from another perspective focused on planning for low prices. In addition, other environmental factors started to gain importance, such as deforestation due to the use of wood as fuel. In this case, planning had to take into consideration a change in the fuel used plus a solution to the environmental consequence of the exploitation of said resource fuel. During the 1990's, the concerns shifted again, but this time towards environmental issues and how to balance these new needs with incentivizing investment, capital mobilization, and infrastructure needs. Energy plays an ever-increasing role in social and economic development. As such, identifying and analysing energy issues as well as improving policy options that deal with these issues are vital topics for the private and public sectors. The authors explained that an essential tool for analysing energy is the energy balance table, which presents current statistics and future alternatives. The second main tool is the demand projections tool which allows for planning how much lead time is required to supply energy needs. However, these are purely economic tools that allow for planning with current resources, but do not allow for planning and analysis that take into consideration different points of view, needs, and objectives. The authors provided an overview of what constitutes policy planning for the energy sector and a background on when and why the need to use analysis tools in the energy sector began. This discussion further sustains the need for the framework proposed in Chapter 5 as history shows that the need for energy planning is continuous and, although the reason why the planning is needed may influence prices and/or environment factors to be considered; what is constant is that planning is required. From this reading and from history, it can be learned that an analysis framework has to be open enough to account for future needs that are not envisioned at the moment. This requirement of an inclusive and open analysis framework is used in the analysis structure proposed in Chapter 5.

Berke and Conroy (2000) proposed principles to delineate the concept of sustainable development. For the application of these principles, the authors evaluated sustainability plans of different regions, and determined the appropriateness of the policies included in those plans to support sustainable development. They found that there was no difference between the plans that specifically included sustainable development into their objectives and those that did not. In their research, the authors define sustainable development as meeting a society's present needs without denying future generations of the facility to satisfy their own needs. Although it may be a simple concept, the authors state that in practice there is no agreement on how to achieve this, and the concept may fault in being too vague and idealistic to be attainable. However, the authors reveal that the literature has provided some features that can be used to create a more realistic definition: reproduction, balance, link between global and local concerns, and dynamic process. Reproduction, they state, is the ability of the system to reproduce and regenerate itself, while balance is a reflection of equilibrium among environment, economic and social issues, which sometimes require negotiation, coordination and compromise. The authors estimate that if any of these elements—economic, social and environment—are not included in a sustainability plan, the plan will not achieve its goal since these elements are interrelated. Ignoring any of these elements would be detrimental to the final goal. Linking the local and global concerns means that local plans need to acknowledge global needs. The reason for this thought is that communities are not isolated, but rather work within a global context and, as such, global concerns are connected to local concerns and vice versa. In addition, as the needs and objectives are always changing, which requires an incessant assessment process of the current, future and emerging tendencies, the plan needs to be dynamic. This dynamism must occur while encouraging ongoing participation from the locals, constant negotiation of conflicts, and review of the plans. The authors developed guidelines for evaluating sustainability plans. The guidelines include: i) the use of land and related activities should support the life-cycle of the related ecosystems, ii) physical environments should be built to accommodate the needs of the inhabitants while encouraging unity in the community and encouraging access to land, iii) an economy that operates with the natural system, iv) land pattern use should improve the living conditions of populations with low income, v) polluters should bear the cost of polluting, and vi) communities should not think only of themselves and if they do should bear the consequences of their actions. Applied to energy, sustainable energy planning allows governments to safeguard the achievability of national sustainability goals by creating harmony between decisions taken and the needs of stakeholders. This research provided background for the definition and importance of sustainable energy planning. The idea to create the framework that is further discussed in Chapter 5 is based on the importance of energy planning explained in this article.

2.1.3 Overview of Decision Analysis

Keeney (1982) provided a general description of what decision analysis is, its reach, its pitfalls, its importance, and how it works. The author describes decision analysis as the formal way of using informal thinking by improving the manner in which insight is obtained. The term decision analysis encompasses a viewpoint, concepts, and approaches that are not substitutes for ingenious or ground-breaking manners in which to resolve the situation, but instead encourages and uses this energy to grant a level or awareness of what is important in the problem or situation. The analysis relies on two assumptions: the first, that one scenario, later referred to as an alternative will be more attractive than the others because of the chances that this alternative will lead to certain results, and second, the preference of the decision-maker in obtaining those results. The formal analysis of a decision provides an individual answer to both assumptions and ways in which these answers can be integrated. The analysis's foundation is that the alternative with the highest expected utility—an aggregation of the individual objectives and risk averseness—will be the favourite. What makes decision analysis unique is the manner in which it is structured, which provides a framework for the formal introduction, integration, and processing of subjective judgments, such as values, utilities, and preferences, together with data to analyse the overall repercussions of different alternatives. When analysing the alternatives in a decision, value judgements can be integrated with professional judgements, and trade-offs can be taken into consideration, aspects which, if omitted, could result in the core of the situation being ignored. The setbacks facing decision problems include the high stakes involved in the problem and the alternative solutions, the complicated structure of the problem, the lack of a know-it-all expert, and the need to justify the decision. Some of the factors listed in the article that contribute to the complexity of problems requiring a decision, include: multiple objectives, how to identify suitable alternatives, intangibles such as governmental bureaucracy, impact over time, effect on groups, risk, uncertainty, dangers, diverse group of decision-makers, need for interdisciplinary input, trade-offs, attitude towards risk, consecutive decisions. The authors introduce us to the methodology of analysing a decision, which includes the following steps: structure of the situation, studying possible effects of the alternative solutions, defining the preferences of the decision-makers involved, and appraising and compare the alternatives. These steps are interdependent and are repeated throughout the analysis process as well as instances where more focus is given to certain steps over others. The rationalizations of the author in his article provided background information of the definition of decision analysis, which is further explained in Chapter 3. In Chapter 4, the author's input is used for the description of the general decision analysis framework, particularly for the importance of understanding the decision analysis situation, the importance and process in which objectives can be determined, the reason behind data collection, and the definition of alternatives methods to find the suitable ones. All these elements are used to create the framework illustrated in Chapter 5. (Keeney 1982)

2.1.4 Multi-criteria decision analysis (MCDA)

Greco, Figueira, and Ehrgott (2005) provide a comprehensive survey that encompasses all aspects related to multi-criteria decision analysis. The survey includes the history and development of the field, hypothesis, challenges, bases, methods, and variations within the methods, (e.g. fuzzy logic) applications, and software. Throughout this thesis, the accounts and descriptions provided by the authors are used to provide background information on what decision analysis techniques are, specific information regarding multi-criteria decision analysis techniques, explanation of to the different methods that have been used for situations involving energy planning, the definition of criteria, and alternatives. The considerations collected by the authors are used in Chapter 3 in this thesis for background information on multi-criteria analysis and to explain the ELECTRE method. Furthermore, the surveys of the authors are also used in Chapter 4 to explain the concept or alternatives and criteria.

Pohekar and Ramachandran (2004) reviewed the applicability and trends of MCDA techniques in different energy issues, zooming in on their applicability to the field of sustainable energy planning. For the first part, they provide a brief description of the most popular methods, including Analytical Hierarchy Process (AHP), Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE), and ELECTRE. In the second part of their paper, they reviewed the literature available and divided it into two sections—pre-1990 and post-1990. As a result of their analysis, the authors first found that the literature provided that MCDA methods had been used in six general areas: renewable energy planning, energy resource allocation, building energy management, transportation energy systems, project planning, and electric utility planning. In these areas, they pointed out that what these areas have in common is that they required lower cost and higher benefits, they incorporate high degrees of uncertainties, units are disparate, and they involve socio-economic aspects. Second, the authors found that the most used prioritizing method was AHP, which was not only used in problems involving energy management for buildings, but which also referred to the design, selection and installation of computer-based systems that monitor the mechanical and electrical equipment in buildings. Third, the review also found a trend of growth in the use of MCDA techniques after 1990. The information gathered by the authors is used for background information on multi-criteria analysis and the methods which are discussed in Chapter 3.

San Cristóbal Mateo (2012) explains the benefit of using MCA methods for decision analysis in the renewable energy industry. He further explains the concept of MCA, the stages of building a model, and explanations on some of the most used methods applied to the renewable energy industry: AHP, Weighted Sum Method, PROMETHEE, ELECTRE, TOPSIS, and others. The description provided by the author is used in Chapter 3 to explain the methods that are used as a basis for the pre-selection of models in Chapter 5. In addition, the explanation of the decision analysis process is used to explain the overview of a multi-criteria decision analysis framework in Chapter 4.

Velasquez and Hester (2013) proposed a process to study the literature by using keywords in the search such as looking for common multi-criteria decision analysis (MCDA) methods in the title or abstract of papers published in famous scholar journals. This concept was used as a basis on how to approach the method selection of method, which is further discussed in Chapter 4. The authors also grouped the most used methods, provided a description and a comparison between each of the methods. Their evaluation and results of what they found were the most popular methods is used as a basis in Chapter 3 to discuss in detail the functioning of some of these MCDA methods work. The authors notice that the trend is a combination of methods where one picks up where the other is lacking; this is used as basis in Chapter 5 for the proposed methodology.

Niekamp, Bharadwaj, Sadhukhan, and Chryssanthopoulos (2015) developed a multi-criteria decision analysis framework to incorporate a sustainability point of view over the whole life cycle to support sustainable management of industrial assets. The authors used a life cycle assessment to evaluate environmental impacts. They combined this method with a life cycle cost so as to be able to evaluate the financial implications through the life of the asset. The authors then reviewed decision analysis frameworks that incorporate risk and uncertainty to study their capabilities and limitations. The authors argued that the decision analysis method should be selected prior to collecting the weights; the procedure to obtain these weights may vary according to the technique. This research will divert from this suggestion and follow the mainstream line of thought— assigning weight to the criteria is the step prior to selecting the appropriate method.

Mardani, Jusoh, Zavadskas, Cavallaro, and Khalifah (2015) provided a review of MCDA techniques and approaches as used for sustainable and renewable energy decision situations. The authors selected articles from 2003-2015 that addressed two areas: sustainable and renewable energy systems. The authors decided to set this timeframe because they found that majority of publishing of MCDA techniques in renewable energy system decision situations commenced after 2003. During their research, no downloadable papers were omitted, and each document was summarized, highlighted, and was used only if the paper thoroughly discussed the application and development of MCDA for problem solving in sustainable energy and renewable energy system issues. The authors found that the most common criteria used in environmental, political/legal, institutional, market, functional, technical, financial, social, and economic attributes include: government support, climate change, CO_2 emissions, investment cost, time, quality, risk, capital investment, efficiency of energy and resources. The methodology proposed by the authors is used for this research as the methodology for the literature review. For this thesis, articles were selected from scholarly journal papers which focused on multi-criteria decision analysis, multi-criteria decision analysis in renewable energy systems, and/or multi-criteria decision analysis in sustainable energy with a publication date cut-off of 2016. The scholarly article was read, summarized, and highlighted, just like the authors did. Extending upon the author's technique, for this thesis, the citations in the scholarly articles were first used to identify how many times that article had been cited by later articles and authorities with similar discussions to that of the original article, thus analysing the current value of the scholarly article used. The second use of the citations of the original scholarly article was to obtain further research ideas and topics.

Kahraman and Kaya (2010) suggested a multi-criteria decision analysis technique based on fuzzy logic to determine the most appropriate energy policy in their case study. They used four main criteria, seventeen sub-criteria, and nine alternatives. The authors used previously published scholarly articles to consider the main criteria, and found that it should be technological, environmental, socio-political and economic. Different from other literature reviewed and discussed in this literature review, the authors decided to combine political criteria with social, while other authors have used social criteria sans political connotations. The sub-criteria used by the authors includes: feasibility, risk, reliability, preparation phase duration, local technical know-how, political acceptance, compatibility with national energy policy, implementation cost, need of waste disposal and pollutant emission. The use of fuzzy set theory is due to the uncertainty caused by incomplete or vague information and is based on the analytical hierarchy process. The authors used a methodology of eight steps in which they requested the experts to provide their judgements for different factors based on their knowledge and expertise. Then, these factors were compared pair-wise to be calibrated as either crips or fuzzy. The preferences are then standardized using a trapezoidal fuzzy number (STFN). The individual STFN are then aggregated into group and then converted into values that can represent the group preferences. After they are converted, the priority weights are calculated, and with the weights the final fuzzy scores are calculated. These final fuzzy scores are then ranked. The findings in regard to the main and sub-criteria are further used in Chapter 5 of this thesis.

Strantzali and Aravossis (2016) reviewed the literature for decision support methods applied to sustainable energy as well as renewable energy technologies focused on energy planning with the objective of finding the trends in the evaluation of investments in renewable energy systems. The authors noted that a problem facing MCDA methods is deciding how to choose among the methods, since each has its own advantages and disadvantages. The authors also found that the selection of the method relies on the user's preference. The authors suggest user friendliness, suitability, and validity as measures when selecting the multi-criteria technique to be used. This article provided further basis on selecting the multi-criteria decision analysis methods explained in Chapter 4, which are used as examples in Chapter 5 of this thesis. The suggestion stated by the authors regarding using more than one decision analysis method was also basis for suggestions provided in Chapter 5 of this thesis.

2.1.4.1 Selection of MCDA Method

Løken (2007) reiterates the criteria that should be considered when selecting an MCA method. It also states that the method selected should reflect the DM's values, should be compatible with the available information, should be easy to use and should deliver the results in a straightforward manner. Furthermore, explains the three main categories of MCA methods applied to energy planning: i) value measurement models, ii) goal, aspiration and reference model and iii) outranking models. In the first category, the author discusses the pros and cons he found in the literature of two techniques: MAUT and AHP. Regarding the MAUT technique, the author mentions that the method's ability to evaluate utility functions is an advantage, which might help to prioritize issues and analyse alternatives and that is a method proposed to deal with risks and uncertainties. On the other hand, a downside to this method might be the evaluation of probabilities and assignment of utilities to the criteria. Regarding the AHP technique, the author states that its attractiveness relies on its simplicity, flexibility, and ability to manage both quantitative and qualitative data. The downside found for this technique is that the amount of time required for its use is directly related to the number of alternatives/criteria evaluated and how non-numerical values to numerical ones are converted. On the subject of the advantages of goal, aspiration and reference models, the author discusses how these techniques are less subjective, more direct, easy to understand, and fitted to be incorporated into models that handle one criterion. Some of the disadvantages of these techniques include the assignment of weight, determining a goal, normalizing variables, and that these methods are usually useless if used for non-quantitative data. For the third category, outranking models, Løken discusses that the principal advantages of the techniques include how they model the DM's preferences, how they help understand the configuration of the problem, and the depiction of the results. Nonetheless, he advocates that these techniques be used for the opening vetting process instead of the end result. The key aspect of Løken's paper, for the purpose of this research, is his endorsement to use more than one MCA method, as appropriate. This suggestion is used as the base to construct a decision analysis framework that benefits from the use of more than one MCA method.

Guitouni and Martel (1998) propose some instructions to aid in selecting an MCDA method. They appreciated that none of the multi-criteria decision analysis methods are applicable in all decision analysis situations, and that this represented a problem in selecting the suitable one. Taking into consideration that the way human's reason is not patterned by the rules of logic or calculations, the way in which the results are presented influence the predilection by the user, and the use of compensatory or non-compensatory schemes, their goal was to develop a theoretical framework that would guide the user in finding and selecting a fitting decision analysis method. The study includes background information on multi-criteria decision analysis, the description of a decision analysis situation (incorporating the need to structure the situation), dealing with the preferences of the decision-makers, and the classifications of the decision methods. As far as the framework goes, the authors propose a set of 7 guidelines to take into consideration when deciding on the fitting methods. The authors found that their framework does not "allow to make a clear unequivocal choice." The concepts expressed by the authors are used in Chapter 4 to explain the step of method selection. The guidelines conceived by the authors are used in Chapter 5 as part of the framework developed in this thesis.

Kurka and Blackwood (2013) introduced a scheme for selecting and justifying the selection of an MCDA method for a decision-making situation involving renewable energy developments. The first step in their proposed process was to develop a generic case study. The situation in the case study was used to develop the criteria used to evaluate the possible MCA methods. These criteria were extracted from the literature reference by the authors using as a starting point, their relevance to the case study. The selected criteria are: how the method deals with uncertainty, user-friendliness of the method, simplicity of method for more transparency and acceptance of the results, and whether the method allows for the inclusion of various stakeholders. The second step was to pre-select MCA methods. This pre-selection was founded on the most popularly used MCA methods in the literature, which were determined to be: The Analytical Hierarchy Process (AHP), the Delta Method, and the Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE). Each method was then judged against each criterion using a scale of low, medium, and high scores, as the third step. The results found that AHP ranked best of all the methods, with three high scores and one medium score. However, the authors state that the results were influenced by various components, including the subjective nature of selecting the criteria against which the methods were evaluated; they state that different criteria could have led to different results. The authors conclude that the scheme to select an MCA method mostly relies on the specific circumstances of the case study and that the criteria selected to evaluate the possible methods should centre on the most critical and pertinent items of the specific decision-making situation. In Chapter 5 below, this thesis builds on the MCA method selection scheme presented by Kurka & Blackwood and proposes a framework that will apply this scheme in the method selection phase of other decision-making situations, besides those regarding renewable energy developments.

Greening and Bernow (2004) suggest that energy decision-making contains several dimensions, stages, and stakeholders, including convoluted geopolitical, ecological, social and economic issues that must be considered in the framework which, at the same time, must be adaptable enough to incorporate the diverse capabilities, styles, motivations and institutional settings of those involved in making the decisions, particularly when the issues to be solved involve or affect different nations. However, and considering the above discussion, the main problem with MCDM methods is identifying the important attributes in a group setting. Since each method has its owns strengths and weaknesses and may be more or less, appealing to the individual basing its decision on the analysis method used, the paper recommends using various MCDM methods. Comparing the results of more than one method brings more legitimacy and confidence in the results and a better understanding of the issue and the possible solutions. This suggestion is applied in Chapter 5, for the MCDM method selection phase.

Wimmler, Hejazi, de Oliveira Fernandes, Moreira, and Connors (2015) studied the use of MCDM for sustainability assessment of renewable energy system on islands. Although this research does not limit its scope to islands, it is useful to keep in mind the author's perspective being that each island represents a different and individual energy system and, as such, requires case specific energy planning. They also suggested that, due to the high seasonal changes in energy demand in islands, which usually have a high dependency on tourism as an economic sector, it is important to consider long-term planning in a frame of at least twenty-five (25) years. This would allow to better accommodate future changes in demand due to population changes. This recommendation is applied in Chapter 5 below.

Polatidis, Haralambopoulos, Munda, and Vreeker (2006) state that the evaluation of energy projects is a major challenge for policy makers because of the environmental, economic, social, and political importance of energy planning. According to the authors, what makes renewable energy sources (RES) a good candidate for MCDA are its decentralized production, short-term and localized cost compared with long-term benefits, the number of stakeholders involved, and the different criteria that needs to be evaluated when making a decision. This requires specific instruments to be used in order to arrive at the optimal solution. The authors also provide a brief overview of the different sub-groups which encompass MCDA methods and provides a list of prerequisite and MCDA method should have when dealing with RES planning. The formulate guiding principles for the selection of a MCDA method are as follows: i) the method should include the sustainability issue, ii) should model the DM´s preference, iii) should handle various technical features, iv) should include uncertainty, and v) should have practical considerations. With sustainability issues, the authors mean that the method should be able to aid the stakeholders involved in reaching compromises between the different criteria and their differing points of view. With 'technical features', the author mean the type of data required for the model to work, and the model's capability to handle both qualitative and quantitative data; the parameters the DM has to evaluate- such as preference, indifference veto and weights; and the use or a hierarchy scale. Although this is a preference of the authors, they argue that the use of this type of scale helps the DM have a better understanding by having him or her familiarize with the different priorities from the beginning of the process. The authors then proceeded to develop a methodological framework, based on these five guiding principles, against which to compare the MCDA methods to select the appropriate technique for renewable energy planning. The authors conclude that no one method performs superiorly to the others in all the guidelines used. This finding as well as the methodology used to develop the framework is used in Chapter 5 as basis to the proposed method selection technique presented in this research.

2.1.4.2 Criteria

Wang, Jing, Zhang, and Zhao (2009) reviewed the most used criteria in decision analysis that involves sustainable development, provided principles and methods for the selection of criteria, as well as methods for the selection of weights. The methods explained by the authors to help select the criteria are the Delphi Method, the Least Mean Square Method (LMS), the Minmax Deviation Method, and the Correlation Coefficient Method. On selecting the criteria weight, the authors argue the importance of selecting the weight in a rational and accurate manner as these weights can directly influence the results. They contend that three factors of the criteria must be taken into consideration to obtain the weights: their variance degree, independency, and the subjective preference of the DM. Some of the methods proposed for determining the criteria weight are: equal weight, simple multi-attribute rating technique (SMART), SWING, SIMOS, pair-wise comparison, AHP, entropy, Technique for Order Preference by Similarity to Idea Solution (TOPSIS), vertical/horizontal and combination methods. Taking into consideration their complexity and the purpose of this research, which is to provide a simple user-friendly framework aimed at policy decision-makers that are not experts in the decision analysis field, not all of these methods are used in this research. However, they will all be briefly explained for reference. Based on the author's work, Chapter 5 further develops a method to select the criteria, based on the principles provided by the authors which is further explained in Chapter 4.

Xingang, Jiaoli, and Bei (2013) recommend utilizing the SWOT analysis method for decision analysis because it allows for the understanding, planning and recognizing of the various points: strengths, weaknesses, opportunities, and threats. Some of the things each country has to take into account when considering the development of either or both industries is—the abundancy of resources. There is an abundance of renewable energy, but not all countries have the adequate amount of every renewable resource. Another strength factor is whether or not a country has developmental potential (e.g. a clearly established plan or policy by the government); and environmental benefits and lifecycle of exploitation (e.g. how many years is exploitation expected according to the existing economically feasible reserves). An integral part of the study is to analyse the weaknesses (e.g. lack of technology), investment environment, and availability of water resources. All the countries can mention market as an opportunity, but the extent of it has to be carefully analysed as to not overestimate. It is important to also look at neighbouring countries and to determine the function of the exploitation, whether it is to supply to other countries or only to satisfy local demand. Policy support will fall into different categories dependent on the advancement of each country for this arena. A country which will put policies in place to develop the resource is able to place this in the opportunity column as the policy can be tailored to the needs. If the country already has strong policy and/or legislation in place, then the legislation could be seen as a strength or as a weakness, whether it helps develop or hinders the industry. The same happens with foreign investment. It is important to consider the investor(‘s’) point of view when deciding under which category to place this item. The problem is that the country may have one opinion, but foreign investors see it differently. This, in connection with the previous author, would suggest that it is recommended to create segments among the foreign investors to differentiate between them as to better adjust the SWOT analysis.

2.1.4.3 Eliciting Stakeholders’ Preferences

Stefanopoulos, Yang, Gemitzi, and Tsagarakis (2014) proposed a system to obtain stakeholder input by using an application based on the Multi Attribute Value Theory (MAVT) method. They meet with the stakeholders in two phases. During the first one, they requested the stakeholders fill and assign weight to a score matrix based on the information they had of the problem, alternatives, and criteria with no additional information provided. This first draft of preferences was identified. Then the authors proceeded to give more information to the stakeholders, explaining in detail the problem, and the pros and cons of each alternative. After the information was given, the stakeholders proceeded to give a second round of scores and weights. This second round was used to present rankings and make a sensitivity analysis to provide policy recommendations to the stakeholders. Although the basis of the authors' argument, how to obtain representative preference when dealing with different stakeholders is further discussed in Chapter 5. This thesis does not apply the method provided by the authors in a decision to try to avoid the use of MCDA methods to elicit any of the information or inputs required to run an MCDA method for the analysis of the problem.

Forman and Peniwati (1998) propose two methods to obtain a group preference when there are several decision-makers involved: the aggregation of individual judgments and the aggregation of individual priorities. The authors discuss that the use of either of the methods will depend on whether the group is acting as a unit working towards one common goal or working as individuals. For the first instance, the authors propose the aggregation of individual judgments, while for the second scenario, the authors suggest the summation of the individual priorities. The authors also explain how the concept of the Pareto principal is obtained with the use of these methods and whether the geometric mean or the arithmetic mean is more appropriate. The Pareto Principle as well as geometric and arithmetic means are better defined in Chapter 4. The methods presented by these authors are used in the framework proposed in Chapter 5 to obtain a group preference in regard to the weight of the criteria to be used in the evaluation of the alternatives.

Chen and Li (2010) proposed intuitionistic fuzzy entropy as an objective method to elicit weights for MCA processes. Fuzzy sets are mathematical sets whose elements have a degree of membership to the set. On the other hand, intuitionistic fuzzy sets are sets whose elements have degrees of membership and non-membership to the set, while entropy measures the degree of membership. The authors classified the different points of view of entropy measures based on probability, non-probability, hesitation degree, and geometry, and found that geometry and non-probability measures can give similar results. They concluded that with the use of their proposed method, they were able to obtain more precise values from the information. This main concept of Chen and Li's research—objective methodology to elicit weights—fuels the ideas presented later on in Chapter 5.

However, because of the proposed method's complexity and the heavy reliance on mathematical and computational calculations, the framework proposed in this thesis will not rely on the method presented by the authors. One of the goals of the framework proposed during this research is simplicity of use for the decision-maker and stakeholders, so that they feel included and be able to fully comprehend the analysis, problem, preferences, criteria and options.

Wibowo and Deng (2013) explain the different approaches available to obtain group agreement when using a multi-criteria decision analysis method with several decision-makers. The authors explained the majority-based, the ranking-based, and the consensus-based approach. They proceeded to present an example using the consensus-based approach to solve the problem of achieving a compromise between the decision-makers. The consensus-based approach can be further divided into hard and soft consensus. Hard consensus can have a numerical representation between 0 and 1, with 0 indicating no compromise and 1 indicating complete compromise. These exact results are almost impossible to achieve due to the particular idiosyncrasies and imprecision of the process. On the other hand, the soft consensus considers that an agreement has been reached when most of the participants involved agree, thus allowing for more flexibility when assessing the opinions. In their approach, the authors developed an interactive algorithm and a decision support system framework. The literature review provided by the authors is used in Chapter 4 to explain the importance of reaching a group agreement. However, the time-consuming nature and the complexity of the mathematical algorithm used—considering the focus of this thesis to be users without an exceptional mathematical proficiency—in the method selected by the authors provides the reasoning behind why this approach will not be used in Chapter 5.

Haralambopoulos and Polatidis (2003) developed a dynamic framework to attain group consensus using multi-criteria decision analysis methods. The authors used the PROMETHEE II multi attribute method to solve a situation involving a decision regarding the exploitation of renewable energy sources by following the basic steps of a multi-criteria decision analysis method: they selected the decision-makers, gathered the data, selected the alternatives and criteria used to assess the performance of those alternatives, determined the thresholds necessary to run the PROMETHEE II method and determined the weight of the criteria. The authors tested the proposed framework via case study, using the real-life example of the island of Chios, Greece. The authors conclude that the use of a sensitivity analysis throughout the process is connected to achieving group consensus although this iterative process does not guarantee a consensus. The research done by the authors is used to lay the foundation in Chapter 4 of the importance of group consensus between the decision-makers.

Wu and Xu (2012) explains the difference between consistency and consensus and provides a model to help in the group consensus process. The authors explained that while consistency explains the steadiness behind the preference of the group itself, consensus describes how much accord there is between the opinions of the individuals and of the group as a whole. As part of their research, the authors proposed new consistency and consensus measures and a framework that would elicit preference relations from the participants of a group decision analysis. The work of the authors is heavily used in Chapter 5 for the proposed framework which relies of the preferences of various decision-makers.

Okoli and Pawlowski (2004) provides a guideline on how to select suitable experts for the use of the Delphi Method. The authors defined the Delphi method as effectively organizing the way a group communicates to accomplish a goal. In order to achieve this communication, the group provides feedback on t individual contributions; an opportunity to review as well as anonymity are required. One of the advantages of the method is that it avoids confrontation amongst the members of the group. This method has been applied for forecasting and pinpointing issues as well as for developing conceptual frameworks. Although the authors find that the method is versatile and can be applied to many issues, they found that a major problem is identifying fit experts with whom run the method. They proposed a guideline that includes identification of skills that may further the objectives: identifying experts within each of the skill areas, requesting nomination of other experts from these experts, and ranking all the experts according to their profiles. The concept of the Delphi Method is explained in Chapter 4. Due to the time requirement for both the election of the experts as well as the process of the method per se, the method is not suggested in the framework proposed in Chapter 5.

San Cristóbal (2011) declared that, when deciding the type of energy project to invest in, several factors have to be considered as they shape the realization of the project. Among these factors are the environment, the political atmosphere, the current and expected state of the economy, and technology. To do this, stakeholders have to be identified each as bringing different perspectives and issues that need to be answered. According to the author, the reality of creating a policy for the substitution of fossil fuels with renewable energy requires the use of multi-criteria context instead of single criteria due to the complexity of planning and project-making. It proposes the use of the Compromise Ranking Method (VIKOR), and it measures the 'closeness to the ideal solution'. The author stated that a benefit of using multi-criteria decision analysis methods is that they can handle quantitative and qualitative criteria, but face unit differences and difficulties in choosing alternatives. The challenges presented by the author for the use of multi-criteria decision analysis was used as a focus for the solutions that the framework being proposed in this thesis aims to provide.

2.2 OTHER DECISION ANALYSIS METHODS

Chapter 3 of this thesis explains in detail five multi-criteria decision analysis methods, which are later used in Chapters 5 and 6 as part of the framework developed in this study. Nonetheless, as part of the research process for this thesis, other methods were studied and found to be worthy of an explanation, even if they were later disregarded from the framework. This section will discuss these other methods. Although all the techniques discussed here are worthy and could bring more value to the framework developed, the focus of this thesis is on methods that consider various criteria since literature has explained that these methods furnish more than one point of view to the decision-maker which, in turn, enhances their evaluation of the situation.

2.2.1 Fixed-Effect Vector Decomposition (FEVD)

Yi and Feiock, (2014) use a fixed-effect vector decomposition (FEVD) model to estimate renewable energy adoption in the states of the US based on data set that includes variables, such as socioeconomic, political ideology, interest groups, and electricity generation capacity by capturing the percentage of renewable energy used out of the whole electricity generation capacity portfolio of the State. To provide for the effect of long-term inducement of these variables, this research took over 18 years to be finished. This model improves over other models whose shortcoming was dealing with heterogeneity and different autocorrelations. The benefit of this model is that, if the regressors and unit-effects are correlated, then the model generates consistent estimation parameters. Another benefit is that it does not require the regressors be independent of the unit-effect. On the downside, the model could reduce total variance if the variance between units is large. It also does not model with time variants that with little or no change. The regular fixed effect model could not test the effects of political institutions on selection mechanisms or the size of regulatory commission. This model allows for the use of time-invariant variables, autocorrelation and unit-heterogeneity. The model is divided in three parts: estimating a fixed-effect model, dividing the effects into time-invariant or rarely changing variables plus an error term, and re-estimating the first stage with pooled OLS. The problem with this method is that the standard errors of time-invariant variables are correct when the between-unit variation is larger than the within variation and this needs to be satisfied for by the FEVD model. The model looks for the percentage of renewable energy capacity in the whole electricity generation capacity portfolio. The formula is:

$$\Upsilon_{s,t=}\alpha_0 + \beta \mathrm{X}_{s,t} + \gamma L_{s,t-1} + \delta Z_s + \tau_t + \varepsilon_{s,t}$$

This formula takes into account lagged impact of policy instruments and the political environment on renewable energy development ($L_{s,t-1}$), variables that do not change over time (Z_s), and time fixed effect vectors (τ_t). The authors reason that they measure the percentage of renewable energy capacity out of the whole electricity generation capacity to reflect the competition between technologies at the time of adoption and because an increase in renewable energy capacity is not an opposite correlation to conservative electricity generation capacity. Their study found that smaller public utility regulatory commissions are more willing to take modern actions towards the promotion of renewable energy. It also found that selected officials are keener on the needs of interest groups. On the other hand, appointed officials are not. It also proved that allowing for the purchase of RECs outside of the State has a negative impact on the in-state development of renewable energy projects. In the United States, at least, the development of renewable energy was not affected by the prices of electricity. On the other hand, the states that had the highest prices of gas also showed the highest development in renewable energy, as an alternative to the high price of gas. Although the method integrates various criteria (e.g. socioeconomic and political factors), the method was ultimately not used in the development of the framework because the use provided by the authors is limited to renewable energy and the focus of the framework is broader, in the sense that it is developed to be used with any type of fuel.

2.2.2 TIAMS

(Gracceva & Zeniewski, 2013) state that the most used methodology for analysing shale gas development is analogical reasoning, by which the U.S. experience is used as a reference to examine the circumstances under which the success of the U.S. in exploiting shale gas can be replicated elsewhere. The perspectives of energy technologies are assessed using the MARKAL/TIMES system models. These models allow the systematic analysis of worldwide energy concerns, including environmental impact mitigation, full-scale renewable energy development, and other alternatives for transportation. Similar to the FEVD model previously introduced, this model was also disregarded because of its focus on shale gas development.

2.2.3 Life Cycle Assessment

Strantzali and Aravossis (2016) provided a review of other approaches used to model energy systems: life cycle assessment (LCA) and cost-benefit analysis (CBA). LCA analyses the whole cycle of a product, from the processing, manufacturing, transportation, distribution, and waste by-products of raw material, to its usage, re-usage, maintenance, recycling and/or discard. This includes how they impact the environment. The purpose of this analysis is to obtain a better return of input versus impacts. Both LCA and CBA were disregarded for the purposes of the framework created for this thesis because their view is narrowed only to economic considerations. Chapter 3 discusses, in detail, why a multi-criteria approach was selected for this thesis.

2.2.4 System Dynamics

Santos, Belton, and Howick (2002) argue that the use of MCA techniques and System Dynamics (SD) can improve performance within an organization. System Dynamics was developed during the 1950's and 1960's. The process illustrates, analyses, and describes the behaviour and subtleties of intricate systems with the goal of understanding why the behaviour occurs, and, with this, anticipate after-effects of policy changes on the system over time. The system is dynamic because of how it is structured and how its components interact amongst themselves. The model is designed to help understand the behaviour, not to evaluate it. Although the idea of integrating system dynamics and multi-criteria decision analysis in one framework was appealing, it would have made the scope of this thesis too broad. In addition, the purpose of the framework developed in this thesis is to aid the decision-maker in supporting the decision made at one point in time; the purpose is not to understand the reasons behind certain behaviour as the concept of the framework here developed is not for the establishment of a policy, but rather the support of a decision. However, the idea presented by the authors is used as a suggestion in the conclusion for further analysis.

Naill (1992) discussed an example of how the United States of America implemented a model based on system dynamics to address the issue of national energy policy. He concludes that part of the success in the implementation of the model is because there was a great need for this type of modelling plan, yet computer modelling had not been used that much. One of the more important aspects of the model is that it evolved with the needs of its user, the U.S. Department of Energy, and that it involved the perspectives of the stakeholders.

2.3 OTHER INFORMATION RESEARCHED

The original purpose of this thesis was to propose a framework that would provide support for deciding whether to invest in the simultaneous development of shale gas and renewable energy technologies. Throughout the duration of this research, the need to have a broader framework became apparent; a framework that would provide the tools to analyse any alternatives, instead of being developed to be limited to two specific generation alternatives became preferred. Even with the change in scope, the information collected at the beginning of this research provided the foundation and motive to pursue the construction of the framework. For this reason, this information, although not relevant for the final product, is nonetheless incorporated in the literature review.

2.3.1 Developing Shale Gas

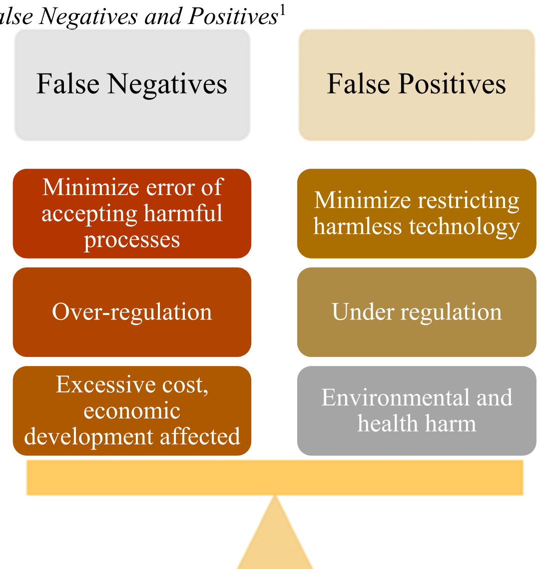
(Schackmann, 2013) stated that it is well known that the United States has been able to successfully exploit shale gas commercially. For this reason, many other countries are looking into the possible exploitation of their own shale resources, although there is no assurance that the exploitation, if possible, may be even remotely successful as it is in the U.S. One of the main problems for the development of shale gas outside of the US is the cost. In Europe, for example, due to high population density, drilling costs are greater than they are in the US. Furthermore, shale formations are deeper in Europe, requiring drilling at a greater depth, which in turn boost costs. Western European countries, in particular, have a desire and/or need to exploit shale gas resources in order to cut their dependency on Russian gas and OPEC's oil. These reasons apply to Eastern European countries, as well as the lack of monetary capacity to fund renewable energy projects and the lack of access to water needed to import liquefied natural gas (LNG).

Jenner and Lamadrid (2013) found that the major concern for the development of shale gas is related to the environment. An advantage is that the use of gas as a fuel achieves the three main objectives of energy: affordability, security of supply, and it is less of a pollutant than other non-renewable options. On the downside, shale gas has a greater Greenhouse gas (GHG) footprint than conventional gasses, but it is still smaller than coal's. The process to extract shale gas requires up to 100 times more water than the same process for conventional gas.

As an industry, the exploitation of shale gas does not affect renewables' technology developments when prior renewable obligations, such as renewable portfolio standards, remain in place. Better yet, shale gas can be used as leverage in negotiations. It may be used as back up for intermittent energies, and, as a consequence, offer a more balanced portfolio. In order to create a better incentive for the development of both industries, the authors propose that taxes and royalties from shale could be used to subsidize renewable energies. From the point of view of price, the authors understand that shale gas and renewable technologies do not compete for price; rather shale gas competes in price with other conventional fuels such as coal while the price of renewable energy is dependent upon technological advances. In regard to a possible competition for investment between the industries, the article states that the production factors, including capital, labour and land, are not limited, and thus do not compete between shale gas and renewable energy projects. It theorizes that the surplus in labour for the exploitation of conventional fuels will cause employees with conventional fuel-related skills to move towards unconventional instead of competing with specialized renewable energy labour. It further argues that shale gas projects and renewable energy projects do not compete for land either, as renewable projects focus on the most part on being a decentralized source of energy. It also presents the point that, at the end of the day capital flow is policy driven and it is policy what will finally determine where capital is invested.

de Melo-Martín, Hays, and Finkel (2014) state that the use of shale gas is highly divided amongst interest groups. Social, economic, and environmental reasons are used by both sides to sustain their arguments. For example, the groups against the development of shale gas may use examples of economy boom and bust cycles of other energy industries to deter others from the development of shale gas. Meanwhile, groups in favour of the development of this natural resource may use arguments focusing on the benefits to the environment when compared to the use of carbon. The debate pretty much pits economic gains, employment, national security, and energy independence against environmental concerns and public health. On the other hand, when exploiting shale gas, methane is released into the environment which, although has a shorter cycle-life than CO_2, is more dangerous as a greenhouse gas, and affects the climate. From this point of view, the development of shale gas may be even worse than the use of coal for the environment. However, natural gas is still regarded as a transition fuel away from oil and coal towards cleaner energies like renewables. A form in which the exploitation of shale gas can move forward with less resistance is by avoiding false positives or negatives. The authors believe that it is the job of the policy-makers to avoid this. Figure 2-2-2 below shows the chain of events each result brings. A false negative is when a theory is rejected proposing that no connection exists between two actions when it does exist. This, in turn, leads to overregulation that may symbolize an increase in cost and a decrease in economic development. On the other hand, false positives occur when a theory is rejected, thus suggesting that a non-existent causal relationship does indeed exist. This, may in turn, create under regulation which may bring harm to the wellbeing of people and the environment. False positives may occur since it is more acceptable in some scientific circles to forfeit on the discovery of a novel reality instead of consent to a falsehood. In the case of shale gas, however, because the environment and the health of the citizens come before any economic development, this causes policy-makers instead to prevent false negatives, contrary to the custom in science fields. The authors understand that the economic benefits of developing shale gas, both direct and indirect, may be less significant than previously expected. It is believed that the industry has been over-hyped, minimizing the extent of the actual costs due to the deep decrease in production. The study explains that the jobs related to the development of the industry are temporary and for out-of-state employees. In the specific instance of shale gas policy making, the worst-case scenarios are weighed more heavily than the best-case scenarios. The authors present the idea that decreasing the impact of false negatives is considerate towards the self-rule of the citizens; it respects that people have no option regarding the risks that are imposed on them when it is decided to go ahead with the development of shale gas. Compensation measures have to be taken into account when there is a possibility of imposing unwilling risks. An example of these compensation measures can be the distribution of benefits. Information is required to determine how willing the citizens are to accept risk, but there are reasons for withholding information, such as if a law establishes it. Because people would be exposed, involuntarily, to the risks without having complete information, policymakers choose to side with the minimization of false negatives. For this reason, false negatives should be diminished to allow for alternatives that may provide comparable economic benefits while reducing damages to health and the environment, such as renewable technologies. The potential harm that shale gas exploitation may bring could be offset by predominant benefits. Therefore, it is the duty of the policymakers to minimize false negatives in all forms, including bans, moratoria, and stricter regulation schemes as protecting the citizens is priority number one over economic benefits.

Figure 2-2: Balance of False Negatives and Positives[1]



[1] (de Melo-Martín, Hays and Finkel, 2014)

Papatulica (2014), like Shackmann, states that countries may be more inclined to exploit shale gas resources for various reasons including their perception of their reserves, cutting back on dependence on imported gas and/or creating competition to the main regional supplier to manage a reduction in price. However, the U.S. experience may not be directly replicated in other countries because, as previously mentioned, of geology, topography, land-ownership regime, population density, costs, environmental restrictions, available technology, available skilled labour, experience, and public sentiment. In the majority of the cases in the U.S., land is privately owned, while this is not the case in the rest of the world. The market distribution is also another factor (like in Europe's case) if infrastructure is mostly owned by a few companies, they are the ones that end up deciding the composition of the market. All these reasons make exploitation of shale gas resources costlier in other parts of the world than in the U.S. The author also concurs with Jenner and Lamadrid in the fact that environmental externalities related to the extraction technologies used for the exploitation of shale gas are perceived as the key hazard for the advancement of the industry. In the environmental externalities, the author also cites water contamination and availability as reasons, along with the use of harmful chemicals for fracturing, handling of waste water, its treatment and disposal, noise, impact on biodiversity, air quality, seismic activities, and GHG emissions. However, regional acceptance for the exploration and/or exploitation may be granted with the compliance of stricter environmental rules and country sovereignty on deciding what and when to exploit.

2.3.2 Markets

(Stevens, 2010) states that a main difference between shale gas and renewable energy is that the first benefits from the development of the LNG market, suggesting that international gas trade will continue to expand. Nonetheless, the growth in this type of trade could either nurture or discourage investment in the production of shale gas and other unconventional gases. The problem relies in that while this market can give confidence to countries to boost the exploitation of the natural resource for exporting if the cost of constructing a regasification terminal is lower than the cost of exploiting the unconventional gas, then the country may rather decide to become a gas importer.

Gracceva and Zeniewski (2013) stated that technology had led to a decrease in costs for LNG liquefaction plants, from capital to operating, until the early years of the 2000's.

However, recently the costs have increased almost 20%. The combination of economic factors affects the total cost of shale gas exploitation when compared to the exploitation of conventional gas sources and/or other sources of energy, such as renewables. This shift in economics can have two effects: supply side benefits from replacing the more expensive conventional gas with unconventional gas while the demand side's benefits are that other energy sources (e.g. oil) are replaced with natural gas. From the supply side point of view, this substitution shrinks the costs related to the gas entering the energy system, which could later translate into a reduction in the consumer's price. This sway is different in each region. From the demand side, the decrease in the gas price has a domino effect on the price of the end-use sector (e.g. electricity), which in turn increases demand and thus production. How big or how small this change in growth is will depend on the price elasticity of demand of gas because an optimistic outlook towards shale gas exploitation may imply higher demand while an abundance of supply may cause regionalism rather than globalization of the market. The latter is worrisome because if an abundance of supply decreases the cost of transportation, in the case of LNG, this may in turn decrease interest in developing shale gas when compared to the lower cost of importing LNG.

2.3.3 Investment

Papatulica (2014) affirmed that the U.S. shale gas industry boomed because of various reasons like previous experience in exploring and exploiting gas. This, in turn, brought on technological advances for the extraction process; the areas to be exploited had low population density which permitted for more drilling in large areas with little resistance; the land-ownership regime which permitted for landowners to back up the exploitation of the resource; a robust, varied and competitive energy sector combined with a sturdy service industry; lenient tax incentives and regulatory system and fully liberalized markets with access to pipelines which allowed for the easy transportation and sale of the gas. The key direct benefits the U.S. experienced from the exploitation of shale gas at a great scale was a decrease in the price of gas (which was 3-4 times lower than Russian gas) and thus a reduction in the price to end-consumers, the creation of about 800,000 new jobs, and reduction in the reliance of pricier LNG imports. As secondary benefits, the chemical industry in the U.S. became more competitive as chemicals were used in the production of shale gas and because of the decrease in electric prices. The boom in both industries, in turn, increased overall GDP. Also, the decrease in the price of electricity is expected to reflect an increase in overall industrial production.

(Gracceva & Zeniewski, 2013) maintained that the shale gas industry faces the following risks: geological, technology and viability, regulatory and public acceptance risks. These risks are influenced by operator and service sectors and by the pricing environment. As previously discussed, the development of shale gas industries is highly dependent on geology first, costs second, and regulatory constrains inside the country third. These in-country constraints include uncertainties regarding the adoption of mitigation measures for GHG emissions. The nature of the mitigation measures is not only in-country, but rather globally and directly affects the possibility of a future global gas market.

Buchan (2013) expressed that outside of the U.S., the price of gas is mostly sold via long-term contracts indexed to the price of oil. This makes it extremely volatile. Because of the shale gas bonanza, the U.S. has experienced, some countries have opted to export coal, which is pricier in the U.S. than local shale gas. This exported coal is still cheaper than gas in some European markets and, as such, a better option. Renewables may present competition in countries that have a high share of total generation coming from renewable technologies, such as the case of Germany or Spain, and as such the use of gas-fired plants has decreased. The author recommended that Europe invest first in logistics and planning of the infrastructure to be used prior to commencing any drilling for shale gas. The author agrees with the rest of the literature in that the cost of drilling for shale gas in Europe will be higher than in the U.S. and may not be the sought-after solution it is expected to be. As previously mentioned, an important aspect to consider is that the rights to the exploitation of minerals and resources rely on the government whereas in the U.S., it relies on the owner of the land in the majority of the cases. Because of the ownership situation, Buchan proposes that the optimal practice applicable would be to drill various wells on a single surface site as it simplifies traffic and reduces visual impact while avoiding the practice of performing massive well drilling. It estimates that the cost for European shale gas would be double or triple the cost than in the U.S., making breakeven price approximately USD $8-$16 per thousand cubic feet. Because there is no current transatlantic free trade agreement between the U.S. and Europe, the latter cannot benefit from importing gas from the former.

2.3.4 Developing Renewable Energy

Yi and Feiock (2014) compare the development of renewable energy in various U.S. states. They divide their research in two areas: the first one zooms in on the adoption of state policy tools, and the second one on the evaluation of the renewable energy capacities and policies in each of the states. This study is helpful as it gives a regional comparison of the stage of renewable energy development in areas that differ politically, even if just a little bit, which can be used as an example of a basic framework for a bigger comparison. According to their research, the adoption of tools such as net metering, Renewable Portfolio Standards (RPS), and incentives is done for different reasons, of which economic development, climate change, and energy independence are some of them. Their study states that some of the literature highlights that financial incentives are most effective when combined with other measures, such as tax credits. They found that the employment of RPS is directly correlated with the development of the renewable energy sector in the states, meaning that an increase in the RPS obligation signified an increase in renewable energy development. Renewable energy development is affected by direct politics effects and indirect ones. The last one is the way of policy instruments adopted and implemented; the first one is through regulation, market forces, and policies. Policies, markets, and politics influence renewable energy development through regulatory, entrepreneurial, and interest group politics, but they remain independent from one another, yet evolve together.

Zhang, Andrews-Speed, Zhao, and He (2013) establish that state energy policy aimed at renewables should be differentiated between those policies which promote the development and advancement of renewable energy for maintaining a stable market-- policies aimed at increasing competition-- from policies towards the capacities of the manufacturing sector of the renewable energy industry. The reasons and advancement of domestic schemes to encourage the utilization of renewable energy depends on the drives of the main players and the modernization of nationwide structures. The author identified four groups of home incentives for the development of the industry: economic gain in growing industrial capacity by manufacturing technology, fulfilment of domestic energy needs, political motivations, and social principles.

Pohekar and Ramachandran (2004) also discuss renewable energy policy stating that energy planning and the allocation of resources means the drawing together of possible energy plans and the distribution of different options. Similarly to Zhang, the authors find that the main aspects to be considered are "investment planning, energy capacity expansion planning and evaluation of alternative energies." In order to establish effective energy management, it is important to design, select, install, and build options considering an environment with multiple factors. This is not only used for the development of end-use renewable energy, but also in the application for transportation and project planning.

Woodman and Mitchell (2011) indicate that, in the particular case of renewables, a lesson to be gained from the Renewable Obligations (ROs) failure in the United Kingdom is that two emerging energy industries cannot compete between technologies in order to reduce cost. Instead, the focus should be on reducing investors' risk. The authors study the possibility of including certain risks for ROs, but these certainly can be taken into consideration for shale gas projects as well as price, volume, and electricity market balancing. Learning from the UK experience, prices should be guaranteed to have more certainty over the rate of return of the project, volume should be controlled for output, and course of action should be outlined to obtain steady generation for the electrical system. Another thing that can be learned from the article's explanation of the U.K. system is that if the country establishes a renewable obligation, it must ensure that the buyout price is never lower than the price at which distributors buy the electricity. If the market is open to competition, it is necessary to make undeveloped technologies attractive. If these technologies are not attractive to investors they will not be deployed, which was the case in the U.K. with biomass plants, wave, or offshore wind projects. Because the system was built on redistribution of income obtained from the payment of penalties due to incompliance, complying with the ROs signified a lower return. This in turn increased the risk for investors and ensured the failure of the system as more compliance meant a decrease in the buyout, making it lucrative for the suppliers to not fulfil their obligations. Investment risk, such as the one explained, can deter new entrants into the market. The U.K. government has set a high standard for renewable energy supplying approximately 30% of the electricity. To fulfil this heavily depends on the fast development of the offshore wind sector. A lesson can then be drawn from this example to not put all the eggs in one basket by counting on the development of a new industry to fulfil energy needs. To improve the situation and attract more investment, some of the risks were mitigated by changing the way the ROCs worked. Instead of making the RO a maximum they changed it towards a minimum so that more Renewable Obligation

Certificates (ROCs) are required than expected generation. In addition, banding of technologies permits for the newer ones to enjoy more investment as established technologies received fewer ROCs compared to newer ones. And lastly, give producers a greater price certainty by establishing contracts for differences.

2.3.5 Investment

According to the Economist, ("Renewable Energy Not a Toy," 2015) investment in renewable energy for the year 2014 increased by a sixth, to USD $270 billion. This is due in part to net metering programs which provided tax credits for people to produce their own energy and sell it back to the system. The federal credit was specific for solar technologies. China, in particular, is looking towards the development of renewable energies for two main reasons: energy security and cleaner air. Solar technologies are expected to decrease in cost by 90% by 2025, although it does not say compared to the prices of what time. Renewable technologies benefit not only the development of big projects, but also home-based ones. Part of the planning for a renewable energy sector does not have to depend solely on a big project, but it can also include the planning, analysis, and policy phases the implementation of household systems have that heavily influence energy supply and demand.

Wüstenhagen and Menichetti (2012) state that in order for a country to determine which path is the most beneficial, policymakers need to use decision-making tools related to the energy industries, and compare, contrast, analyse, and balance the benefits and disadvantages. The authors indicate that, currently, private investment is the largest source of capital for the energy industries, whereas ten years ago, it was the government. This change is due to technological improvement and policies that have improved market opportunities for investment from the private sector. The authors understand that in order to keep CO_2 emissions at a constant level of a 2°C increase require an annual investment of approximately USD $400-$500 billion until 2020. This is less than the expected global investment of USD $1,360-5,100 billion for the decade of 2010's and USD $1,490-$7,180 billion for the following decade. The authors cite other studies that have found that variations in the level of risk for the investors influences the outcomes of the policies. Because of this, different tools that are expected to provide similar outcomes—but which do not take risk into consideration—may actually provide very different results, even one outperforming the other. If the risk is lower and the investment greater, it is considered to be safer. Policies that help decrease perceived or real risk are more beneficial for the development of the industry. Following this reasoning, the author proposes that it is important to include the perspective of the investor at the moment of drafting energy policy. They further suggest seeing investment in renewable energy as a function with three variables: risk, return, and policy. To decrease perceived risk, a portfolio approach is best since it combines different assets. Mixing renewable and conventional power generation diversifies the risk as well as investing in different renewable technologies. Applying it to this thesis, it is convenient from the government point of view to promulgate investment in both areas of the industry. Undervalue of diversification may lead to underinvestment. If policy-makers want to increase investment in the renewable sector, they should adjust their policies towards a wide range of investors, not only those involved in the electricity market; investment is a financial instrument, not strictly a utility-focused one. It should also be taken into consideration that policies need to be tailored to the technology. For example, newer technologies need policies with different aims or processes than more established ones. These policies may be more efficient if investors are divided into segments. Furthermore, regarding the perception of risks, the author suggests that the policy-maker should manage expectations hand-in-hand with lowering real risk and increasing real return. Recurrent changes in policy or blurred objectives can negatively influence the perception of risk versus return. The author points out that the perception of risk is important and that it is swayed by rational considerations which include status quo, anchoring and adjustment, and representativeness. One way to tackle these rational considerations is through education and training or collaboration with experts in the financial world. Another rational consideration is, what the author terms, path dependence, which is none other than how prior situations affect future choices. Investors may utilize their rate of return experience in conventional fuel projects and decide to stay with that rather than venture into the unknown world of renewable technologies. The author suggests that leaving optimal allocation of resources in the renewable energy field in the hands of the market may not be adequate as investors may stick to prior investment experiences in case of hesitation or uncertainty. Convincing actors to change paths may require a push (i.e. feed in tariffs). It suggests surveying the attitude of investors to be able to better prioritize the relevant risks that need to be addressed, and that these compliment the aims and objectives of the policy maker, rather than compete. Another question the author proposes is whether policies should aim at providing incentives to well-known energy market participants so that they may invest in other technologies, or that, rather, it should direct these enticements in the direction of novel participants. It summarizes other studies providing a mixed approach: an amalgamation of various strategies that address the need for both, the decarbonization process of established players and the entrance of new ones. The paper suggests further research for understanding the correlation between risk, return, cost of capital for investments, importance of portfolio investment, and investor segmentation for the development of custom made regulation and/or legislation.

2.3.6 Cost of Integrating into the Grid

The U.K. Department of Energy and Climate Change, (*Electricity Generation Costs*, 2013) articulates that understanding electricity generation costs is vital for the analysis and policy design of energy markets. Cost is itemized throughout the lifetime of the project: planning, construction, operating, and decommissioning by capacity or generation. This is particularly important to use to be able to compare shale gas and renewables at the same level—electricity production. Due to the nature of both, gas has other uses, but this thesis will focus on the development of both industries to produce electricity. Levelized cost is the average cost per MWh generated throughout the plant's lifetime.

Zhang et al. (2013) found that countries with fast economic growth, such as China, face the difficulty of trading this short-term growth with sustainable development in the long term. A rapid growth in the renewable industry requires that the power grid of the country and the reform mechanism grow at the same rate.

Zyadin, Halder, Kähkönen, and Puhakka (2014) found that there is a vast difference between perceptions of the reasons why renewable technology has not advanced between academics and the general public. While the literature places lack of finance, both public and private, as the hindering factor in the advancement of renewable technology, the people interviewed believed it was lack of governmental policies that hindered the advancement of renewables. This is important because investors are not part of academia, while policy-makers usually look for theory, and academic experts in the subject look for consulting when establishing policies. If academia and reality differ so vastly, then the policy implemented will not be adequate to incentivize development.

Buchanan (2013) says that French policy-makers and other European environmental groups suggest that the idea of developing new hydrocarbon resources does not go along with the climate change goals that guide European energy policy. While some of the countries may see shale gas as a cheaper alternative to the costlier renewable technologies, others may consider this price perception to be used to balance the investment scales in favour of unconventional fuels and away from renewable energy, and environmental commitments against climate change.

2.3.7 Dutch Disease

Brown (2014) found that the literature suggests the exploitation of resources in countries that have plenty may bring about two scenarios. In the first scenario, the exploitation aids the economy to grow through an increase in the demand for labour in the energy sector, and this increase in demand will have a spill-over effect into other areas of the economy. In the second scenario, economic areas that are not related to the natural resources exploited may suffer as the production of energy gets bigger. The best example for this would be employment. If the energy industry has a high demand for workers, the salaries will be higher, taking away employees from other areas where the wages are not comparable, making it challenging for these other businesses to subsist. Also, because the demand for services is greater, prices and costs will increase making it difficult for all business to survive. This second scenario is what is referred to as the natural resource curse or Dutch Disease. This phenomenon has different implications at the local and at the national level. On the one hand, the costs related to the extraction of the resource increases demand for other goods and services, such as housing, construction materials, fuel, vehicles, food, and other necessities for daily life. As a result, this benefits the businesses that fulfil these needs, increasing their income, and thus employment. In the case of the U.S., land-owners receive some type of payment, whether lease or royalty payments. An increase in their income reverberates in an increase in their personal consumption. Taxes and royalties paid to the government also increase overall GDP, making the economy grow in general. The extra need for goods and services increases employment and income, which, consequently, amplifies the consumption cycle. However, this very cycle can get out of hand and become prejudicial to the economy. For example, the extra workers required for the extraction of the resource will make housing limited and, as such, prices will increase disproportionately—a housing bubble. This increase in the price of housing may force people with lower incomes that cannot afford that price to leave. Adding the high cost of living with the quality of the environment plus the look of a production site, visitors and tourism may be negatively affected. This affects housing, with housing property values and property tax revenues are affected. Another setback is that the increase in vehicles needed for both the production and as a consequence of the growth in workers may degrade roads and bridges faster than expected, and as such the budgeted maintenance will no longer hold as cost will increase and be required more often. The cycle described above helps understand why resource rich countries may develop slower than other economies. While at the beginning the economy may grow, in the long run the growth in the extractive industries shrinks all other economic activity. The surge in the need for labour for the exploitation industries increases wages, cost and services for other industries.

2.4 Gaps in the Literature

Throughout the literature studied, it has been found that different authors provide suggestions and guidelines as to how to confront the challenges inherent to the use of multi-criteria decision analysis. However, there is no handbook, book or article that attempts to gather these challenges in one piece of literature. Neither is there a single piece of literature that combines these challenges, as a whole, with possible solutions. Instead, both the challenges and the solutions are distributed in different pieces of literature, which require assembly to provide a whole picture of a multi-criteria decision analysis method to the user. This gap in the literature is what this thesis aims at fulfilling. These challenges are discussed in detail in Chapter 3. Still, some of the authors researched had identified gaps in their own works. Although these gaps are not addressed in this thesis, they are included as suggestions for further research.

2.4.1 Specific Gaps Discussed by Various Authors

Matutinovic, (2010) points out that energy-accounting studies look at the energy needed to keep the operation level previously discussed but do not consider future or alternative uses, such as development, maintenance, or growth. It is suggested that, in addition to the energy return of investment, growth, development, operations, and maintenance are considered for energy accounting.

Yi and Feiock (2014) found that in the specific area of shale gas, there is a lack of information regarding costs, making it difficult to compare it with other alternatives. For example, the authors cite studies that say that renewable energy creates almost three times the number of jobs than the oil and gas industry, but this would have to be reviewed on a country-by-country basis or at least regional in order to determine if there is a trend or these are outliers.

Likewise, de Melo-Martín et al. (2014) found that, for renewable energy, there is also a lack of information in regards to the implementation of renewable energy development and social sciences.

Wüstenhagen and Menichetti (2012) realized that, at least from the literature, it seems that academia is not addressing questions as to how investors make decisions based on risks and opportunities, how economic models explain these decisions, or how path dependence and bounded rationality influence the perception of risk. Above all, the literature does not address what can policy-makers learn from these gaps in order to improve the policies created.

Brown (2014) observed that, regarding the natural resource course, not much has been said on how the local economy can be affected by economic development if the majority of the wealth created is captured at this level.

2.5 CONCLUSION

This chapter provides an appraisal of the literature that served as motivation for this research. It also offered information that would later on be used to develop the framework. The chapter should be used by the reader to have an insight of what the articles referenced discussed in general terms, as the specific instances of their use will be explained in the following chapters. Even if the article was not used in the final thesis, the summary and explanation provided as to why there were discarded can be used by the reader who is interested in furthering research based on this thesis.

The literature evaluated also help in identifying what was missing, in other words the gap this thesis aims at completing. With the help of the literature review, this thesis pinpointed that there is a lack of a structure that provides the user with a guide on how to face the characteristic challenges inbuilt in multi-criteria decision analysis methods.

3 DECISION ANALYSIS

3.1 INTRODUCTION

Every day, people are faced with the task of making decisions. These decisions vary from the commonplace—choosing the outfit of the day, the best route to take to work, or best meal option—to the more consequential—job choice, and furthering education location choice. When it takes more than just a flip of a coin or the use of simple decision-making, and the decision is taken after careful consideration, the process is called decision analysis.

A simple decision analysis process can be depicted graphically, for example, with the use of decision trees, diagrams, or framing tools. For more complex decisions, various methods for analysis can be used, all with varying degrees of difficulty and many issues to be taken into consideration, such as the probabilities of an action taking place, the groups involved in the decision or affected by it, or the resources required. Through a theoretical analysis, this chapter provides the foundation to better understand what decision analysis is, how it is applied to energy planning decisions, the categories and sub-categories of decision analysis methods and what are multi-criteria decision analysis methods. This chapter also gives examples of four popular multi-criteria methods, according to the literature, for analysing decision problems mainly concerning energy planning in the energy industry. This chapter concludes that, between single and multi-criteria methods, multi-criteria analysis is the preferred type of methodology when considerations involve energy planning. This is the conclusion reached because these methods allow for the exploration of various points of view, preferences, and values, which permit deeper analysis of the problem.

3.2 OVERVIEW

Decisions, particularly those in which a central government, a government corporation, government agency, or any other type of government entity is involved, are taken in a complex environment. These entities are required to study and substantiate their choices. They also face greater exigency for responsibility, accountability, and public consciousness from consumers, shareholders, and employees. Legal matters, social impacts, financial aspects, and political issues are some of the concerns that must be taken into consideration by these entities when deciding. Many of these decisions cannot be made considering only one factor, (e.g. cost-benefit). Instead, they require the inclusion of different and often conflicting points of view from diverse populations. These are some of the factors that contribute to the complexity of making decisions. The formal analysis of the problem provides better insight and a comprehensive outlook of the intricacies of the issue at hand (Keeney, 1982).

Decision analysis is nothing more than the "formalization of common sense for decision problems which are too complex for informal use of common sense" (Keeney, 1982). It is a discipline that utilizes the tools and concepts of mathematical models (e.g. optimization, probability, and statistic) while accepting the inputs of other disciplines (e.g. economics, management, and psychology). It aims at structuring the decision-making process so that it leads to rationally deciding the solution to a problem. The guides for analysing decision problems are based on a set of statements that hint towards an alternative being preferred based on the prospect of the occurrence of the conceivable results of each alternative and the inclination of the decision-maker for those results. Another benefit of using a formal system for decision analysis, or a decision analysis method (DAM), is that these methods help overcome biases that the decision-makers may be due to culture, background, prior knowledge, or misconceptions. This is because DAMs focus on the problem, rather than external factors and contain consistency checks. The term "decision-making" is incorrect, and "decision aid" or "decision analysis" are better suited to refer to these processes since the idea of the methods is to help the decision-maker (DM), not to provide the solution. The use of these methods gives the DM more confidence in the prospective decision as the results presented to the DM undergoes a process of collection, organization, and analysis of important criteria (Keeney, 1982).

In other words, the purpose of DAMs is to aid in filtering and suggesting, or preferring, a conduct or decision that will best merge the objectives and values of the decision-maker, based on scientific methods, hypothesis, formulas, and propositions. DAMs help to structure the problem by defining the stakeholders involved, identifying the different possibilities of action, outcomes, and challenges, determining the decision criteria, and unifying the values and goals with the chosen alternative. Once the potential solutions are determined (after the completion of the analysis process) they are offered to the decision-maker(s) who make the final choice over the different alternatives (Figueira, Greco & Ehrgott, 2005).

Decision analysis focuses on the essential traits of all problems: a desire to fulfil an objective, the availability of various alternatives of which one must be selected, the different results that can be obtained with the selection of the alternatives, uncertainty in regard to the result of each alternative, and the possibility that one consequence is preferred over another. The problem is divided in smaller sections to attend to all these traits. This partition is essential to tackle interdisciplinary problems. In general, a decision analysis problem can be segregated into four sections or steps: i) structuring the problem, ii) studying the possible effects of each alternative, iii) determining preference/value of the DM, and iv) the assessing and comparing the alternatives (Keeney, 1982).

DAMs do not provide the answer to the problem in question. Instead, they facilitate the analysis with which the DM can base the decision, but it is finally the DM who ultimately takes the decision, and thus resolves the problem pondered. In other words, rather than a step-by-step process, DAMs are more of a guide on how to tackle the problem. With this train of thought in mind, it is easier to understand why the objective of the DAMs is not to find the "right" choice, but rather the "best" one, according to the set of circumstances considered. These circumstances incorporate the purpose, goals, and values of the stakeholders, which may be aligned or be complete opposites. Decision can be categorized as rational, irrational, or non-rational. A rational decision is that in which the solution maximizes the DM's satisfaction after evaluating all the available alternatives. A non-rational decision is one where the decision is based on the experience and knowledge of the DM because the DM does not have the ability nor the time to analyse the alternatives. The irrational decision is taken by only considering personal ambitions and distastes. DAMs require addressing how to recognize the measure of the DM´s preference of a choice and how to properly represent this preference in the mathematical framework of the method (Figueira, Greco & Ehrgott, 2005) (Guitouni, 1998).

Decision analysis models are based on the unrealistic hypothesis that a function is optimised by a set of solutions, and that the solution the DM will prefer will always be the one where welfare is maximized. The problem with this assumption is that it supposes that the problem is static, isolated, with defined edges, a good structure capable of handling mathematical modelling, and has a DM that can clearly express his or her preferences and indifferences. This ability to express preferences and indifferences allows for the positioning of the alternatives in preferential order. The inference is not realistic as it assumes that the problem is viewed without taking into consideration any subjectivity. This issue with the basic models has led to the development of various DAMs which, to some degree, deal with different aspects of the problem, such as the expression of preferences and indifferences of with the subjectivity of the DM (Guitouni, 1998).

DAMs offer many advantages over unsupported decision-making. For example, the methods include the use of weights to illustrate the DM's preference. Using weights allows for the corroborating, cross-referencing, and changing of results, if required, for a sensitivity analysis. In a sensitivity analysis, a DM can evaluate results of changing some of the circumstances, such as the impact in a change in the weight of the criteria. Another advantage is that, because the methods are based on mathematical functions, they are clear-cut. A third advantage is that, if, throughout the process, the criteria and the objectives are found to be unsuitable, they can be scrutinized and modified. A fourth advantage is that a DAM can be a powerful communication tool between the decision-makers themselves and between the decision-makers and stakeholders. A fifth advantage is that the DM does not have to measure the performance of the results; instead, the method assesses the performance of the alternatives against the criteria (Dogson, 2009).

3.3 APPLICATION OF DECISION ANALYSIS METHODS (DAM) IN ENERGY PLANNING

DAMs were first applied in the field of energy planning during the 70's and 80's. The main intention for their use was to investigate the relation between energy needs and economics by forecasting energy demand. As the aim was to identify the cheaper yet efficient option, single criteria analysis techniques were used. However, by the 1980's environmental factors came into consideration when analysing energy planning situations, and, as such, arose the necessity of approaching these situations from a multi-criteria point of view. Since then, these techniques have been used in areas such as energy planning, resource allocation, building and transportation management, project planning, exploitation, sustainability, and electric utility planning. DAMs can also be used to determine suitable future energy policies, to select between different projects taking into consideration production, efficiency and environmental performance, and to determining how to build and advance novel or alternative sources of energy (Figueira et als 2005) (Wang et al., 2009) (Pohekar & Ramachandran, 2004) (Kurka & Blackwood, 2013).

Table 3-1 illustrates some MCA methods and how they have been applied for decision analysis involving different elements of energy planning.

Table 3-1: MCA Methods Applied in Energy

Scope	Method
Energy Alternatives	Preference Ranking Organization Method for Enrichment Evaluation *(PROMETHEE)*
Energy Planning	PROMETHEE Elimination and Choice Translating Reality *(ELECTRE)* Analytical Hierarchy Process *(AHP)* Strength, Weakness, Opportunity, and Threats analysis *(SWOT)* Weighted Sum Methodology *(WSM)* Weighted Product Method *(WPM)* Technique for Order Preference by Similarity to Ideal Solutions *(TOPSIS)*
Energy Adoption	Fixed-Effect Vector Decomposition
Shale Gas Development	*TIAMS*
Evaluation of technical options	Simple Additive Weight Model
Energy Policy	Multi-Attribute Utility Theory *(MAUT)*
Environmental Impact Assessment	MAUT
Resource Allocation	AHP
Project Planning	AHP
Sustainability Assessment	Analysis and Synthesis of Index at Information Deficiency (*ASPID)* General Sustainability Index

(Wang, Jing, Zhang, & Zhao, 2009) (Pohekar & Ramachandran, 2004) (Kurka & Blackwood, 2013)

3.4 Decision Analysis Methods: Multi-criteria Analysis (MCA)

Decision problems can be divided into two types: single criterion and multi-criteria. Single criterion problems are those in which the objective is to maximize the result. A common example of a single criterion problem would be which computer to buy, from a set of alternatives, taking only the laptop's weight into consideration. In this example, the buyer wants to buy the best of the alternative with the lowest weight. Single criterion decision methods are based on the unidimensional utility theory, which is useful particularly when there is uncertainty. The results provided by these methods can be measured in terms of a single attribute, such as money, or any other easily quantifiable criterion. In simple terms, a reason to use methods based on a single criterion for the decision analysis is to reach a decision that will maximize the benefits of that specific criterion while minimizing the costs related to it. However, in real-world decisions, results are related to different attributes, aspects, or dimensions. This type of problem is known as multi-attribute or multi-criteria decision problem (Figueira, 2005) (Pohekar, 2004) (Wang, 2009).

Multi-criteria Analysis (MCA) methods have been created to address these complex multi-attribute problems. They developed from a change in the paradigm of finding the optimal solution to finding a solution that would provide the DM with satisfaction (Guitouni, 1998). These problems involve various degrees of uncertainty, objectives that are not always harmonious amongst themselves, and different sets of data that may not always be comparable (e.g. quantitative and qualitative data). Because MCAs are designed to manage different criteria, they are better suited for enhancing the understanding of essential aspects of the problem, such as allowing for more participation of those involved in the decision-making while easing compromise and joint decisions. It also enlarges the understanding of how sensitive the results can be in the real world, and how these real-world sensitivities can consider alternatives while working with different and conflicting objectives. MCA methods help the user by: defining a comprehensive range of items expected to assemble the decision analysis process, developing a criteria matrix that will retain the meaning of the evaluations and facilitate the discussion on the role of each criterion. Although the basic function and purpose of the methods remains the same, MCA methods are not comparable between themselves. Each method works with different assumptions, weights, criteria, utilize different preference structures, and process information differently. (Pohekar, 2004) (San Cristóbal, 2012) (Wang 2009).

The term MCA includes all methods that could be used in deciding according to preference. The way in which MCA aids in finding a solution to a complex problem is by allowing the problem to be divided, analysed smaller segments of the problem to be analysed, and making a decision on those segments; with the smaller decisions made, reconstructing to give the DM better representation. (Loken, 2007).

MCA is a general class of Operation Research and the methods can be classified as deterministic, stochastic, fuzzy, single, or group method. They can also be grouped into multi-objective decision methods (MODM) and multi-attribute decision methods (MADM). The difference between them is that, in MODM, the alternatives or options are not pre-determined, but rather a set of "objective functions" is enhanced depending on certain limitations. The aim of these techniques is to find a fitting and effective result, meaning that the execution of one objective cannot be enhanced without making another one worse off; in other words, these MODM methods demonstrate the trade-off between various issues. On the other hand, in MADM, a pre-determined number of alternatives or options are evaluated against a set of criteria or attributes with the goal of finding the best suited option or alternative by assessing each alternative to each criterion or attribute (Pohekar & Ramachandran, 2004).

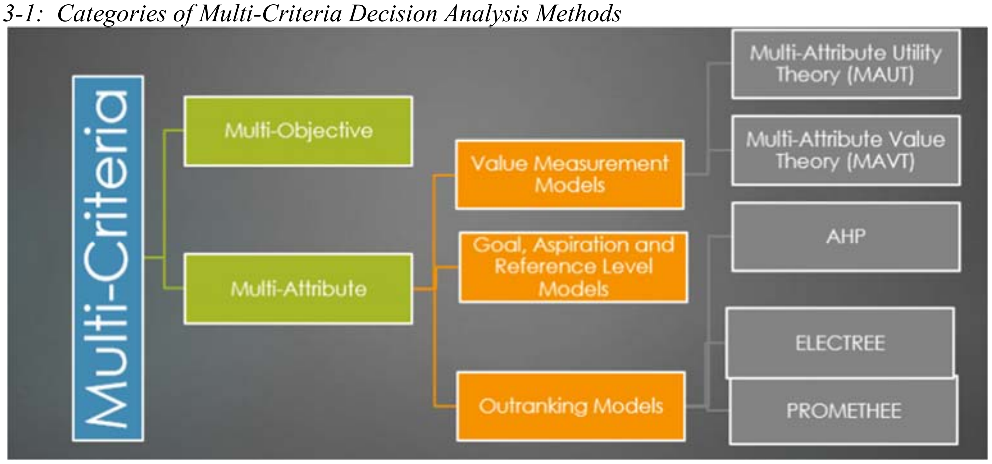
An example of a MODM situation is evaluating possible routes for pipelines. The objectives desired may include minimizing health and safety hazards, maximizing economic benefits, minimizing environmental impact, maximizing social impact, plus having all stakeholders leave the negotiation table content with the decision. Since all the objectives cannot be achieved with just one alternative, it is crucial to evaluate the degree to which each of the different alternatives helps fulfil the objectives. An example of MADM is deciding which computer to buy while considering the following criteria: weight, price, hardware, and software compatibility (Keeney, 1982). This example of the computer to purchase will be used throughout this chapter to explain how the different methods work.

Although both groups, MODM and MADM, face clashing criteria, disparate units, and intricacies in proposing/choosing substitutes, they differentiate in the number of alternatives assessed. Multi-objective methods handle a vast selection of alternatives which are limited by pre-determined variables. This means that in the case of multi-objective decision analysis, the alternatives or options are not pre-determined but rather the functions are improved dependent upon a set of limitations, so that the function of one variable cannot be enhanced without worsening the function of another variable. These models sought the most efficient yet satisfactory solution. Multi-attribute models, on the other hand, are mostly constructed to allow the user to pick out a distinct alternative. To achieve this, a limited selection of alternatives is analysed against certain criteria. This limited selection can be as many or as little as the DM considers necessary, but it has to be defined (San Cristóbal Mateo, 2012) (Pohekar & Ramachandran, 2004).

MCA methods can be further subdivided into three categories: value measurement models; models for goal, aspiration, and reference level; and outranking models. Value measurement models are those that use utility functions to include risks and uncertainties in their evaluations. A utility function measures the preference of the decision-maker over a set of alternatives. The value measurement models' classification includes those methods that allocate a numerical value to each alternative as a result of the expressed preference of the DM for each criterion to represent the influence of each criterion against each alternative in the final result. This is known as the weight of the criterion. Examples of methods that fall under this subdivision are the multi-attribute utility theory (MAUT), and multi-attribute value theory (MAVT) which are further explained in this chapter. The second subdivision, goal, aspiration and reference level models are programming methods, requiring the use of algorithms based on mathematical programming. These methods are used when trying to decide the alternatives that are the nearest to accomplish a particular objective. The third sub division, outranking methods, are primarily used to compare (pairwise) the alternatives against the criteria. Examples of methods that fall under this subdivision are: the analytical hierarchy process (AHP), the *Elimination et Choix Traduisant la Realité* (ELECTRE) and the Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) (Kurka & Blackwood, 2013)(Løken, 2007).

The basic idea for outranking methods is that the dominating alternatives or options eliminate the dominant ones. However, this dominance is not straightforward as it relays on weights to influence some attributes over others. An option, or alternative, is believed to outrank a second one if it surpasses the second on sufficient criteria or attributes of acceptable importance while not being itself outperformed by the second option in any one attribute. However, in outranking methods, two options could be difficult to compare due to lack of information. (Dodgson, 2009). Figure 3-1 illustrates the different categories.

Figure 3-1: Categories of Multi-Criteria Decision Analysis Methods



This research will limit the methods explained and illustrated to those who fall under the MADM category because these methods were found to be the most commonly used methods for energy planning related decisions. Section 3.5 below will discuss five specific methods: MAUT, WSM, AHP, ELECTRE, and PROMETHEE. The theoretical analysis methodology used for their selection required reviewing the literature available regarding the use of DA for energy planning and selecting the methods that have been used for analysing decisions regarding unconventional resources, such as shale gas, and renewable resources.

MCA methods are unambiguous as to how each alternative impact each of the criteria; they focus on how each criterion impacts the alternatives. In relation to the alternatives, these methods can support anything, from telling apart the suitable alternatives from the non-suitable ones, to pinpointing the most preferred alternative, ranking the alternatives, or to short-listing the alternatives for further assessment. The variation in MCA methods available is due to the factors that influence these methods, such as the time available to conduct the analysis, amount and nature of the data available, various kinds of problems or the circumstances surrounding them, dexterity of the analyst, or requirements of the stakeholders. MADM does not indicate whether an option or criterion augments well-being more than it could diminish it, nor does it require for the benefits to be greater than the cost, so there could be an instance where doing nothing is the best option (Dogson, 2009).

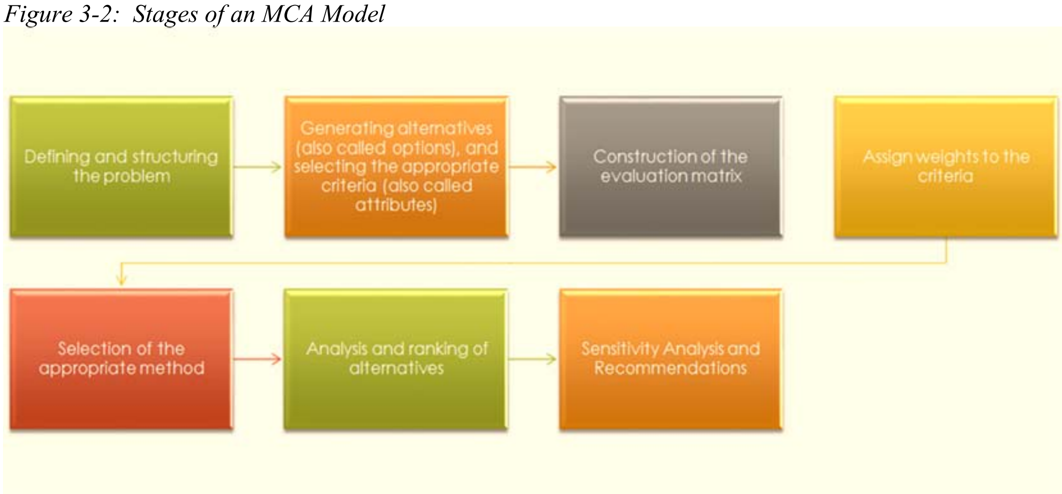
An MCA model has various steps:

- define and structure the problem,
- generate alternatives (also called options), and select the appropriate criteria (also called attributes),
- construct the evaluation matrix,
- assign weight to the criteria,
- select the appropriate method,
- analyse and rank the alternatives and
- conduct a sensitivity analysis and recommendations. (See Figure 3-2.)

The information on the criteria, the alternatives, and the weight is provided by those who have legitimate responsibility in the problem or interest in the result- the stakeholders. With this information, the matrix is populated. MCA methods can be used at different times of the decision analysis process and may contribute to more than one of the stages of the decision analysis process previously mentioned. For example, an MCA method can be used to select criteria while another can be used to run the first analysis, and a different method can be used to run a sensitivity analysis (Kurka & Blackwood, 2013) (San Cristóbal Mateo, 2012) (Keeney, 1982) (Dogson, 2009).

MCA works in two levels: the first level (the supervisory level or DM level) focuses on defining the objectives (first step of an MCA model) and making the decision, while the second level details the alternatives, explains the possible ramifications of selecting any one of these options or alternatives in regard to each of the criterion or attribute, and finally ranks these options or alternatives. In other words, it is this level that encompasses steps 2 through 7 mentioned above (Dogson, 2009).

Figure 3-2: Stages of an MCA Model



The importance of defining the problem is detailing exactly what knowledge is being sought after; in other words, defining the objective or goal. This is what the decision-maker wants to achieve—the question he or she wants answered. The criteria are selected by determining what the main issues are for the DM (in regard to the proposed objective), and what elements are desirable, necessary, or definitively not appropriate. The criteria can be further divided into sub-criteria, but this is not necessary. The same process is used to determine the applicable alternatives for the problem at hand. The weights represent the DM's preference, and as such have to be provided by him or her. There are several forms to elicit the weight preference from the decision-maker, and a simple form is proposed in Chapter 5. As is the case with the weights, there are various techniques that can be used to select the appropriate MCA method. The user´s familiarity with that method can be a reason a specific method is selected. Another reason can be the simplicity in which the analysis is illustrated to the DM, assuming the DM is not an expert in the methods. Chapter 5 proposes a technique for the selection of the appropriate method depending on the problem. The analysis and ranking of the alternatives is the final step of every MCA method, but once the method provides its results, it is beneficial to perform a sensitivity analysis. The purpose of this is to show to the DM how slight modifications to the inputs may affect the results. (Saaty, 2008) (Ishizaka, 2013) (Dogson, 2009).

3.5 Examples of MCA Methods

As previously stated, there are several MCA methods available to analyse a decision. The method preference varies on the level of familiarity the user has with the methods, ease of use, and whether it presents the information in an understandable manner for the DM. (Dogson, 2009). Below, is a discussion of some MCA methods. These methods were selected from the reviewed literature based on their use in all of the following three categories: general use, energy planning decision use, and renewable energy decision analysis use. The methods discussed in this text are value measurement methods (MAUT/MAVT, WSM) and outranking methods (AHP, ELECTRE, PROMETHEE). Below, is a brief explanation of some of the different subdivisions of MCA's, along with explanation of some of the individual methods.

3.5.1 Value Measurement Models

Value Measurement Models are models that assign a value or preference, identified by a numerical score, to each criterion and alternative. This numerical score is used to rank the alternatives, which illustrates the DM's preference. For instance, alternative *a* is preferred to alternative *b* if $V(a)>V(b)$. Each criterion is assessed against another and given a numerical value that reflects the DM´s preference—this is called the weight of the criteria. The more important the criterion is for the DM, the higher the weight. The weight illustrates how inclined the decision-maker is to accept a compromise between that criteria and another one. The way the weight of the criteria contributes to the overall score is that, first, alternatives are also given a numerical value after being assessed against each other under each of the criterion. Then, the final evaluation takes into consideration the value of each of the alternatives under each criterion times the weight of the criterion to obtain the overall score. (San Cristóbal, 2012).

3.5.1.1 Multi-attribute value theory (MAVT) and Multi-attribute utility theory (MAUT)

In a multi-attribute value theory method, the performance of the alternatives is analysed against attributes which measure that alternative's performance. The multi-attribute utility theory methods expand from this premise to take into account and represent uncertainty, which requires stronger assumptions in the model. The term value is used to describe preferences based on ordinal comparisons and strength. When the object is to describe alternatives based on the level of risk involved then the term used is "utility". In other words, the utility vector used in MAUT, different than in MAVT, is a function of the added risks and uncertainties. Another difference is that a MAVT method does not aim to single out the highest-ranking choice. Instead, it aims at involving all the stakeholders and benefits from each other's points of view (Kurka, 2013).

Multi-attribute theories, originally proposed by Keeney and Riffa in 1976, allow for the use of self-evident choices, which in turn, permits to better determine whether these choices or actions are reasonable regular behaviour. Determining whether the actions selected are choices that would be regarded as regular is important because these methods are used when an individual is making decisions for others. Therefore, the techniques and the reasoning used as the foundation of the final alternative selected needs to be justified based on reasonability and the decision should not be hastily taken (Figueira, 2005).

The mathematical representation for MAVT is the following:

Equation 3-1: MAVT

$$V(a) = \sum_{i=1}^{m} WiVi(a)$$

Where $v_i(a)$ reflects the performance of *a*'s alternative on criterion *i*. This formula provides a total value score for each alternative *a*, thus, it needs to be standardized to a handy scale, such as a numeric scale (e.g. 0-10). MAUT is an expansion of MAVT, with a more meticulous approach for integrating risk preferences and uncertainty and uses a function of utility. The formula uses *U(a)* instead of the value *V(a)*, where *U(a)* reflects utility and *V(a)* reflects value (Løken, 2007). A utility function is an "objective function which aggregates all the individual objectives and attitude toward risk". Utility is represented with *u; u(x)*, or the utility of result x. This represents the attractiveness of result x compared to all other results (Keeney, 1982).

MAUT is the most common MCA method utilized, and its main advantage, even over MAVT, is that it formally takes uncertainty into account. Therefore, it is included directly into the models as utility can be assigned to it. A second advantage is that this method includes the participant's preferences in every step of the process, although, this inclusion may require many inputs and data. However, this could be problematic as the data required may not be available for every situation. A third advantage is that the method allows for criteria to interact with each other, instead of only adding them together and obtaining a result (Velasquez, 2013).

All MCA methods share similar steps with the basic MCA model. For example, the steps to use MAUT range from defining the problem to assigning weights. The novelty of this method is that it includes the normalization and finding the marginal utility. Normalization, in the context of MCDA, can be defined as "transformation process to obtain numerical and comparable input data by using a common scale…normalization techniques usually map attributes (criteria) with different measurement units to a common scale in the interval [0-1].” There are different normalization methods that can be used (e.g. vector, linear, linear max, and linear sum) (Vafaei, 2016). These methods will not be explained in this thesis. Nonetheless, MAUT is explained using the min-max normalization method. It was understood to be an easy, user friendly approach for non-experts.

The basic steps of all MCA methods, (steps 1 through 4 in Table 3-2) are further explained in Chapter 4, this section will only explain from step 5 onward.

Table 3-2: Steps to use the MAUT method

1.	Determine the problem
2.	Select the criteria and alternatives
3.	Create a matrix
4.	Assign weights
5.	Normalize the raw utility scale
5.1.	Maximize the criterion
5.2.	Minimize the criterion
5.3.	Combine the maximum and minimum values accordingly
6.	Find the marginal utility
7.	Analyse the values
8.	Rank the alternatives

(Ishizaka, 2013)

A matrix can be created with different criteria that may not be comparable. For example, the problem of deciding which computer to buy make take into consideration price and storage capacity. In MAUT, the actual values used for price and storage would be called the “raw” utility scale. Table 3-3 below shows what the raw scale for the example would look like.

Table 3-3: MAUT Example Computer Purchase Raw Utility Scale-[2]

Computer	Price ($)	Review (out of 5)	Screen (inches)	Storage (GB)
sp1	429	4	4.65	32
sp2	649	4	3.5	64
sp3	459	5	4.3	32
sp4	419	3.5	4.3	16
sp5	519	4.8	4.7	16

[2] Ishizaka, 2013

In order to obtain values that are comparable, MAUT requires the normalization of this raw scale. To normalize the raw scale, the user needs to define which criteria he or she wants to maximize and which to minimize. In this example, the user wants to minimize price (pay the lowest cost) and maximize storage capacity.

The formula to minimize criteria is:

Equation 3-2: MAUT Minimization Criteria Formula

$$uj = \frac{A\,max - Aj}{Amax - Amin}$$

And the formula to maximize the criteria is:

Equation 3-3: MAUT Maximization Criteria Formula

$$u_j = \frac{A_j - A_{\min}}{A_{\max} - A_{\min}}$$

Where A_{max} is the biggest value under the criterion, A_j is the value to be normalized, and A_{min} is the minimum value under the criterion. After raw scale is normalized, a new matrix, "normalized matrix" (for this example) is created combining the maximum and the minimum criteria, accordingly. The results are shown in Table 3-4 below.

Table 3-4: MAUT Maximize, Minimize and Normalized Matrixes

Maximize criteria

	Price	Review	Screen	Storage
sp1	0.043	0.333	0.958	0.333
sp2	1.000	0.333	0.000	1.000
sp3	0.174	1.000	0.667	0.333
sp4	0.000	0.000	0.667	0.000
sp5	0.435	0.867	1.000	0.000

Minimize criteria

	Price	Review	Screen	Storage
sp1	0.957	0.667	0.042	0.667
sp2	0.000	0.667	1.000	0.000
sp3	0.826	0.000	0.333	0.667
sp4	1.000	1.000	0.333	1.000
sp5	0.565	0.133	0.000	1.000

Normalized Matrix

	Price	Review	Screen	Storage
sp1	0.957	0.333	0.958	0.333
sp2	0.000	0.333	0.000	1.000
sp3	0.826	1.000	0.667	0.333
sp4	1.000	0.000	0.667	0.000
sp5	0.565	0.867	1.000	0.000

With the values in this normalized matrix, the user then proceeds to find the Marginal Utility Score. There are various ways in which to define the utility function *U* (Ishizaka, 2013). For this example, an exponential marginal utility function for review and price will be assumed while a linear function will be assumed for screen size and storage. The formula to find the exponential for Marginal Utility Score is shown in Equation 4 below, while the utility values are given in Table 3-5 below.

Equation 3-4: MAUT Exponential Marginal Utility Score Formula[3]

$$U_1(a_j)\frac{\exp\left(f_j'(a_i)^2\right)-1}{1.71}$$

Table 3-5: MAUT Utility Values

	Price	Review	Screen	Storage
sp1	0.814	0.068	0.958	0.333
sp2	0.000	0.068	0.000	1.000
sp3	0.441	1.000	0.667	0.333
sp4	1.000	0.000	0.667	0.000
sp5	0.115	0.652	1.000	0.000

After the marginal utility values are calculated for each alternative under each criterion, the user needs to add the weight of the criteria. The weight can be found in several ways, which will be further discussed in Chapter 4, including being given by the DM without further mathematical input. After the weights of the criteria have been determined, the new values are obtained by multiplying each alternative's marginal utility scores by the weight of the criteria, as shown in Table 3-6.

Table 3-6: MAUT Utility values multiplied by weights

	Price	**Review**	**Screen**	**Storage**
	0.35	0.35	0.15	0.15
sp1	0.285	0.024	0.144	0.050
sp2	0.000	0.024	0.000	0.150
sp3	0.154	0.350	0.100	0.050
sp4	0.350	0.000	0.100	0.000
sp5	0.040	0.228	0.150	0.000

[3]Where "exp (1)= 2.71 which explains the subtraction of 1 in the nominator as well as the division by 1.71 in order to obtain 1 for the best alternative"(Ishizaka, 2013).

The values for each alternative are then added to obtain the utility for the alternative, which are then ranked, as shown in Table 3-7. The formula for the utility is shown in Equation 3-5 (San Cristobal, 2012) (Ishizaka, 2013) (Figueira, Greco & Ehrgott, 2005) (Keeney, 1982).

Equation 3-5: MAUT Utility formula

$$\text{Utility} = \sum_{1}^{30} W_j u_{ij}$$

Table 3-7: MAUT- Utility and Ranking

	Utility	Rank
sp1	0.503	2
sp2	0.174	5
sp3	0.654	1
sp4	0.450	3
sp5	0.419	4

3.5.1.2 Weighted Sum Model

The Weighted Sum Model (WSM) is a very simple MCDA method. In it, when the alternative is assessed against a criterion it is given a value to reflect its performance. Each value is then multiplied by the weight given to the criterion and added together to obtain the score of the alternative. A main disadvantage of the method is that it requires that all the data have the same unit, as if this was not the case the assumptions of the model would be invalid. This however, can be overcome by normalizing the values within the matrix (San Cristobal, 2012). The equation for WSM is given below:

Equation 3-6: WSM

$$A^*_{wsm} = Max \sum_{i}^{j} a_{ij} w_j$$

Table 3-8 shows what the results of the computer example used in Section 3.5.1.1 would be like using the WSM method. The column labelled ‘Results’ shows the application of Equation 6 in the normalized matrix found for Table 3-4.

Table 3-8: WSM Example Computer Purchase

Normalized Matrix

	Price	Review	Screen	Storage	Result
sp1	0.957	0.333	0.958	0.333	2.582
sp2	0.000	0.333	0.000	1.000	1.333
sp3	0.826	1.000	0.667	0.333	2.826
sp4	1.000	0.000	0.667	0.000	1.667
sp5	0.565	0.867	1.000	0.000	2.432

3.5.2 Goal, Aspiration, and Reference Level Models

Replacements for value measurement methods are the methods of goal programming, aspiration, and reference level. These methods are used to establish the options that are keenest to accomplish a specific goal or aspiration. Frequently, these methods are used first to help sort out the various alternatives by initially eliminating, in an efficient manner, the most unfitting options. Expressed mathematically, the intention is to solve the inequalities $zi + \delta \geq gi$ 'where z_i is the value of the attribute, δ is the non-negative deviational variables and g_i is the goals (a desirable level of performance) for each criterion i'. The purpose is to obtain a viable answer that decreases the direction of the deviational variable. The recommended solution would be δi=0, but this is also the least common solution. The most effortless way to obtain this result is 'to minimize the weighted sum of deviations $\sum_{i=1}^{m} Wi\delta i$ where w_i is the importance weight and δi is the deviation of criterion i' (Loken, 2007).

An example of this type of method is the method of displaced ideals, where the idea is to discard undesirable values of the constant *p*, which is the constant that determines the consequence of greater deviations against smaller deviations. Another example is the STEM approach, where the best solution is set as a target of each criterion. In this method, deviations are found by decreasing maximum weighted deviation, in other words, shifting the focus to the area of worst performance (Løken, 2007). Although goal, aspiration, and reference level models are widely used for decision analysis, they are not as popular when the decision involves energy planning. For this reason, this thesis will not include examples of these methods.

3.5.3 Outranking Methods

Outranking methods allow for the comparison of all possible alternatives by constructing and exploiting a binary relation, meaning that if a outranks b, then there is sufficient information to arrive either at that conclusion, or to the conclusion that at least a is as good as b. The mathematical representation of the basic outranking methods is shown in Equation 3-7 below. Outranking methods are the preferred methods to be applied when the input of the stakeholders is vital for the decision analysis process. Because these methods are better suited for capturing inputs, they also benefit the user in that they allow for the determination of the stakeholder's indifference and preference levels. This also represents big debate as the manner in which the levels are defined is somewhat subjective. Additionally, these methods allow the DM to express incomparability between alternatives, which is beneficial if, for one reason or another, the alternatives cannot be compared amongst themselves in the eyes of the DM. In the energy field, these methods are mostly used for environmental and energy planning because they provide the decision-maker the opportunity to express hesitations (Figueira, Greco & Ehrgott, 2005) (Wang, Jing, Zhang, & Zhao, 2009) (Ishizaka, 2013).

Equation 3-7: Outranking Methods

$$(A_i, A_K) \in A \times A: A_i S A_K$$

A pair of alternatives can be compared to determine which one is favoured in regard to each criterion. When all the preference information of all the pertinent criteria is combined, these methods define the extent to which one of the alternatives can be preferred to another. One alternative can be determined to be better than another one if, once all criteria is considered, it is at least as good as the first alternative. If, for example, alternative *A* is better on a specific criterion and alternative *B* is better on another criterion, then the alternatives are not comparable, and a decision cannot be made regarding which one is the best. In a case such as this, additional information is required for the decision-maker to be able to make an informed decision. Some of this additional information can include: trade-offs between the preference or weight the criteria, or a change of the criteria to a single function, which allows there to be a problem with only one criterion against which the performance of the alternatives is measured, instead of a multi-criteria problem. In this example, changing from multi-criteria to single criteria makes it easier to find a solution, once the preference and the boundaries of the DM are given. For this example, the most efficient is found with the alternative that outranks all others (Greco et al., 2005) (Løken, 2007).

3.5.3.1 Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process is a very popular method used in MCA. It was developed by Thomas L. Saaty during the 1970's. AHP´s objective is to rank the alternatives to find the favoured solution. The foundation of this method is that it compares criterion to criterion and alternative to alternative in a matrix. These comparisons are possible because the method relies on the decision-makers' preferences, which is illustrated in a scale system designed for the method, called the Saaty scale. The AHP is popular because of it is easy to use, can be adjusted in size to better suit the decision-maker('s') needs; the decision-maker can choose the number of elements to compare, and the method does not require as much data as MAUT does. Another advantage is that this method can be used when a utility function cannot be constructed. Although the method is very effective and objective, one disadvantage is that the criteria and the alternatives can be dependent upon each other meaning that, for example, alternative x cannot be evaluated if its performance is not measured against specific criteria y (Velásques, 2013) (Ishizaka, 2013) (San Cristóbal, 2012).

As with other MCA methods, the first step in the process towards the evaluation of a decision using AHP is defining the problem. However, different from other methods and the MCA cycle, the second step in the AHP method is the creation of a hierarchical structure for the problem. The rest of the AHP process is as follows: step three is assigning weight to the criteria, step four is finding the local priority and step five is finding the global priority. As with other methods, consistency checks and a sensitivity analysis can be performed either throughout the AHP process or to further synthesize the results. These items can be itemized as additional steps to be performed on the evaluation or can be encompassed in the steps previously discussed. Nonetheless, to consider that the AHP method has been processed correctly, the user should identify and separate a minimum of the five steps discussed above (San Cristóbal, 2012) (Ishizaka, 2013). See Table 3-9 below.

Table 3-9: Steps to use the AHP method

1.	Determine the problem
2.	Create a hierarchical structure for the problem
3.	Assign weight to the criteria
4.	Find the local priority
5.	Find the global priority

A notable difference in AHP is that this method requires the creation of a hierarchical structure in which each level (one for the goal or objective, one for criteria and one for alternatives) is related to its predecessor, as shown in Figure 3-3. Structuring the problem hierarchically allows the user to have a better grasp on what information is missing. The order in the hierarchical structure is; the objective or goal on the first level; criteria are established on the second level, and the alternatives constitute the third level. The hierarchical structure is not limited to only three levels, but three is the minimum number of levels the method needs in order to properly assess the problem. The structure could have more levels such as a sub-criteria level that needs to be evaluated. The criteria in the second level is prioritized in relationship to the first level—the objective or goal. This means that, when selecting the criteria, the user needs to consider how the criteria help in achieving the goal or objective. The same treatment is given to the alternatives, which are related to the level directly above it—the criteria. When selecting the alternatives, the user needs to be able to answer how the alternative fulfils the criteria and the extent to which it might be able to do so for the criteria to achieve the objective or goal.

Figure 3-4 illustrates how the alternatives interact with the criteria and how the criteria interacts with the objective. (San Cristóbal, 2012) (Ishizaka, 2013).

Figure 3-3: AHP Hierarchy Representation

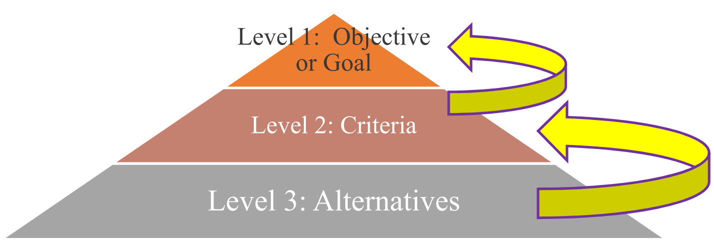
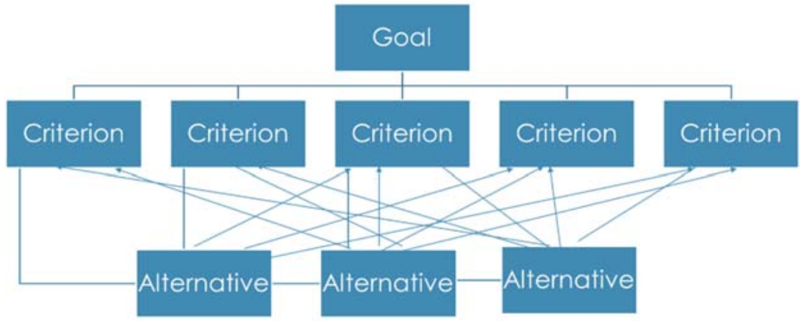


Figure 3-4: AHP Hierarchy Representation: Alternative and Criteria Interaction



The benefit of using a hierarchy structure is that the representation system helps illustrate how changes at upper levels affect the lower levels. The structure provides information on who the actors are at the upper levels and their purpose as well as "information on the structure and function of a system in the lower levels". A third benefit is that hierarchically organized systems evolve more effectively than those systems that do not use this type of organization. Hierarchical structures are also flexible, yet stable: they can be changed—actors or functions can be added yet they remain stable enough that the small changes do not bring any disruption in the performance of the components of the structure. The important thing to do when constructing a hierarchy is to include sufficient pertinent detail to present the situation as completely as possible. Displaying the goals, criteria, concerns, and stakeholders in a hierarchical structure offers an overview of difficult relationships built into the situation. This captures how influence is spread from the main or more important criteria to the less important ones, and it allows the DM to analyse whether the issues that are being compared have the same impact, weight, or magnitude of the possible solution (Saaty, 1994).

After the hierarchical structure is organized, matrices are created to be used on steps 3 to 5. The purpose of these matrices is to find the DM's priorities in three instances: a) criteria priority, b) local alternative priority and c) global alternative priority. The first matrix, for criteria priority, compares the criteria pairwise and obtains a rank which will reflect the DM's point of view in regard to how well he or she considers each criterion will help fulfil the goal or objective. In other words, it reflects the weight the criteria hold, in the eyes of the DM, to fulfil the objective. The values obtained from this first comparison will later be used as the criteria weight. For this matrix, the DM compares the criteria pairwise and establishes his or her preference. Expanding upon the example of the computer mentioned in section 3.5.1.1 above, if the decision-maker feels that review is three times more important than price, that information will populate the matrix. The raw matrix is shown in Table 3-10. In this table, the cells where the same criterion meets should be label as 1, as there is no preference amongst the same criterion. The right side of table should be an inverse reflection of what was included on the left side.

Table 3-10: AHP- Raw Matrix

	Price	Review	Screen	Storage
Price	1	1/3	1/5	2
Review	3	1	1/2	1
Screen	5	2	1	4
Storage	1/2	1	1/4	1

After the matrix is populated with raw numbers, these raw numbers are then normalised. The normalisation process is done by first calculating the matrix product, as shown in Table 3-11.

Table 3-11 AHP Matrix Product

	Price	Review	Screen	Storage
Price	4.000	3.067	1.067	5.133
Review	9.000	4.000	1.850	10.000
Screen	18.000	9.667	4.000	20.000
Storage	5.250	2.667	1.100	4.000

Table 3-12 shows the second step for the normalization, which is adding the values for each criteria row- the results of which is called the 'sum of the rows'- and obtaining the total sum for this column.

Table 3-12: AHP Sum of the Rows

	Price	Review	Screen	Storage	Sum the rows
Price	4.000	3.067	1.067	5.133	13.267
Review	9.000	4.000	1.850	10.000	24.850
Screen	18.000	9.667	4.000	20.000	51.667
Storage	5.250	2.667	1.100	4.000	13.017
					102.800

The final step in the normalization process is for the user to obtain the priority vector. This is obtained by dividing the sum of the row value for each alternative by the total sum of the rows. This priority vector shown in Table 3-13 will be used later on as the weight of the criterion. As a consistency check, the priority vectors should add up to 1.

Table 3-13: AHP Priority Vector

	Price	Review	Screen	Storage	Sum the rows	Priority vector
Price	4.000	3.067	1.067	5.133	13.267	0.129
Review	9.000	4.000	1.850	10.000	24.850	0.242
Screen	18.000	9.667	4.000	20.000	51.667	0.503
Storage	5.250	2.667	1.100	4.000	13.017	0.127
					102.800	1.000

At this point the user can perform a general consistency check to ensure that the preferences, as stated by the DM, are rational. The first step to perform a consistency check is to add the values of each criteria column, as shown in Table 3-14.

Table 3-14 AHP Sum of the Matrix Product

	Price	Review	Screen	Storage
Price	4.000	3.067	1.067	5.133
Review	9.000	4.000	1.850	10.000
Screen	18.000	9.667	4.000	20.000
Storage	5.250	2.667	1.100	4.000
Sum	9.50	4.33	1.95	8.00

This sum is then multiplied by the priority vector corresponding to each criterion to obtain the sum priority vector. The sum priority vectors for all criteria is added to obtain Lambda-max (λ_{max}), as shown in Table 3-15.

Table 3-15: AHP Sum Priority Vector and Lambda-max

	Price	Review	Screen	Storage	Lambda-max
Sum priority vector	1.227	1.048	0.981	1.013	4.269

All these results are used to calculate the Consistency Index:

Equation 3-8: AHP Consistency Index

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

where n is the number of criteria used in the evaluation. The Consistency Index for the example is 0.090. Once the Consistency Index is found, it is then divided by the corresponding value in the Random Index, where n is the number of criteria used in th evaluation- see Table

3-16 – in order to obtain the Consistency Ratio. If the consistency ratio is ≤0.10, the results are considered relatively consistent. If the consistency ratio is ≥0.10, then the results are considered inconsistent. (San Cristóbal, 2012) (Ishizaka, 2013). For this example, the consistency ratio of the first matrix was 0.100, making the results consistent.

Table 3-16: Random Index[4]

N	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.9	1.12	1	1.3	1.41	1.45

If the evaluation includes any sub-criteria, these sub-criteria would undergo the same process to obtain their criteria priority and thus, their weight. The second matrix is the local alternative priority. This is a series of sub-matrices that compares alternatives' performance pairwise -in other words, compares two alternatives at a time- with regards to a criterion. The DM ranks each alternative or option with respect to that particular attribute or criterion. Using, again, the computer purchase example, in this step the user would create a matrix to assess the performance of the different binary alternative options under the criterion 'price,' and would create another similar matrix but to assess the performance under the criterion 'storage'. The raw numbers matrixes are then normalised using the same process as before: first calculating the matrix product, then finding the sum of the rows, obtaining the total sum of the rows, calculate the priority vector, performing a consistency check and finally calculating the consistency ratio (Ishizaka, 2013) (Dogson, 2009) (Saaty, 2008) (San Cristóbal, 2012).

[4] San Cristóbal, 2012

Table 3-17: AHP Local Alternative Priority

Price

	sp1	**sp2**	**sp3**
sp1	1	3	9
sp2	1/3	1	6
sp3	1/9	1/6	1

b)

	sp1	**sp2**	**sp3**	*Sum of Row*	*Priority Vector*
sp1	3.00	7.50	36.00	46.50	0.666
sp2	1.33	3.00	15.00	19.33	0.277
sp3	0.28	0.67	3.00	3.94	0.057
Sum	1.444	4.167	16.000	69.78	1.000
Sum priority vector	0.963	1.154	0.904	3.021	
Lambda Mas	3.021				
CI=	0.011				
CR=	0.019	Consistent			

Review

	sp1	**sp2**	**sp3**
sp1	1	1/2	1/8
sp2	2	1	1/5
sp3	8	5	1

	sp1	*sp2*	*sp3*	*Sum of Row*	*Priority Vector*
sp1	3.00	1.63	0.35	4.98	0.087
sp2	5.60	3.00	0.65	9.25	0.162
sp3	26.00	14.00	3.00	43.00	0.751
Sum	11.000	6.500	1.325	57.23	1.000
Sum priority vector	0.956	1.051	0.996	3.003	
Lambda-Max	3.003				
CI=	0.001				
CR=	0.002				

Screen

	sp1	*sp2*	*sp3*
sp1	1	1/6	1/3
sp2	6	1	4
sp3	3	1/4	1

	sp1	*sp2*	*sp3*	*Sum of Row*	*Priority Vector*
sp1	3.00	0.42	1.33	4.75	0.089
sp2	24.00	3.00	10.00	37.00	0.695
sp3	7.50	1.00	3.00	11.50	0.216
Sum	10.000	1.417	5.333	53.25	1.000
Sum priority vector	0.892	0.984	1.152	3.028	
Lambda-Max	3.028				
CI=	0.014				
CR=	0.024				

Storage

	sp1	*sp2*	*sp3*
sp1	1	1/4	1/6
sp2	4	1	1/3
sp3	6	3	1

	sp1	*sp2*	*sp3*	*Sum of Row*	*Priority Vector*
sp1	3.00	1.00	0.42	4.42	0.083
sp2	10.00	3.00	1.33	14.33	0.269
sp3	24.00	7.50	3.00	34.50	0.648
Sum	11.000	4.250	1.500	53.25	1.000
Sum priority vector	0.912	1.144	0.972	3.028	
Lambda-Max	3.028				
CI=	0.014				
CR=	0.024				

The third matrix is the global priority, shown in Table 3-18. In this matrix, the priority vector obtained for each alternative under each criterion in the local priority matrix is then multiplied by the weight of the criterion, obtained in the criteria priority matrix. The row values are added to obtain a score. As a consistency check, the sum of all scores should be 1, as should be the sum of all criteria weight. After obtaining the score, the alternatives are ranked accordingly, from the highest scored to the lowest (Ishizaka, 2013) (Dogson, 2009) (Saaty, 2008) (San Cristóbal, 2012).

Table 3-18: AHP Global Priority Matrix

	Price	Review	Screen	Storage	Score
Weight	0.129	0.242	0.503	0.127	1.000
sp1	0.086	0.021	0.045	0.011	0.162
sp2	0.036	0.039	0.349	0.034	0.458
sp3	0.007	0.182	0.109	0.082	0.380
					1.000

The main point of the AHP method, the pairwise comparison, works by having the DM state which of the two elements presented before him or her is preferred over the other and by how much. The reason why only two elements are compared at a time is that dealing with such a small number of elements makes it easier for the DM to compare them and express his or her preference. In real world situations, the decision-maker provides judgment based on verbal appreciation- such as very good or bad- instead of one based on numbers. To solve this issue Saaty introduced the 'Saaty scale', see

Table 3-19. This scale provides a conversion from verbal appreciation to a numerical scale from 1 to 9, 1 representing the least preferred choice in the comparison while 9 represents the most preferred choice in the comparison. This scale is widely used, even with other methods. The reason being that a smaller scale (which less numerical denominations, say from 1 to 5) would not provide the same level of detail; on the other hand, a larger scale is difficult to manage. Nonetheless, this is not a fixed element of the method, and a larger or smaller scale could be used. (Ishizaka, 2013) (Dogson, 2009) (Saaty, 2008) (San Cristóbal, 2012).

Table 3-19: Saaty's Preference Scale

Definition	Numeric Rating	Explanation
Equal Importance	1	Two activities contribute equally to the objective
Weak or Slightly more important	2	
Moderate Importance	3	Experience and judgement slightly favour one activity over the other
Moderate to strong significance	4	
Strong Importance	5	Experience and judgement strongly favour one activity over another
Strong to very strong	6	
Very Strong or demonstrated importance	7	An activity is favoured very strongly over another; its dominance demonstrated in practice
Very strong to extreme	8	
Extreme Importance	9	The evidence favouring one activity over another is of the highest possible order of affirmation

The number of comparisons that have to be performed for each matrix can be found by using the formula n^2*-n/2;* where n=number of criteria or attributes. The bigger the number of criteria or attributes to consider, the bigger the number of comparisons. This has to be taken into consideration when selecting the criteria, as more criteria means that the task becomes more time-consuming (Ishizaka, 2013).

3.5.3.2 ELECTRE

The *Elimination Et Choix Traduisant la Realité* (ELECTRE) was first introduced by B. Roy in 1965 at a conference, and then published in 1968. Its creation responded to the need to address and overcome some shortcomings of the multi-criteria analysis method, specifically that "rigorous mathematical axioms are unsuited to describe a complex reality such as the one of a contradiction-laden decision process." (San Cristóbal, 2012). This method uses a partial sum of the preferences of the DM, basing that the DM is not perfectly rational, and can express preference, weak preference, indifference, or incomparability (Figueira, Greco & Ehrgott, 2005) (Ishizka, 2013).

An advantage of the ELECTRE method is that it avoids compensating any normalization process the criteria undergoes, which, in turn, alters the original data. On the other hand, the disadvantage is that this method requires several challenging technical parameters. Currently there are various versions of the ELECTRE model, each one for different purposes and addressing different problems. For example, ELECTRE I was created to allow for the selection of the best action from a given set while ELECTRE II is used for solving the difficulty of ranking actions, starting with the best selection all the way down to the worst. ELECTRE III on the other hand used fuzzy binary outranking relations and quasi-criteria to deal with the imperfect knowledge and uncertainty. ELECTRE IV allows for the categorization of actions without using a coefficient for the importance of criteria while providing a framework to categorize relationships between actions. (Figueira, Greco & Ehrgott, 2005) (Ishizka, 2013).

The structure of ELECTRE methods comprise of two main procedures: an aggregation process that permits the construction of outranking relations for the wide- ranging pairwise comparison of all alternatives and an "exploitation procedure" that gives a choosing, ranking or sorting outcome, according to the nature of problem. The ELECTRE methods are especially useful when the model will include between three and five criteria as more than five criteria is better suited for models that include aggregation procedures. In addition to the criteria requirement, at least one of the circumstances to be mentioned below need to occur:

- At least one criterion of the alternative is assessed by the use of an ordinal or a weakly interval scale. This is particularly relevant when the differences in the scales cannot be reconciled, making it problematic to outline a coding that can present the difference in preferences.
- The evaluated criteria are heterogeneous, making it problematic to create a widespread scale.
- The decision-maker may not be able to accept gaining one criterion while losing another one, necessitating the employment of aggregation procedures that are non-compensatory.
- A small disparity in evaluations may not significantly affect the preferences but the accumulation of various small disparities does, for at least one of the criterion.

A way in which to avoid this is by using discrimination thresholds. (Figueira, Greco & Ehrgott, 2005) (Ishika, 2013).

Of all the models, ELECTRE III is the model most used for energy planning decision problems. This model will be the one explained in this chapter and an example provided in Chapter 4. Similar to the other MCA methods studied in this Chapter, the ELECTRE method process requires defining the problem, selecting the criteria and alternatives, create a matrix and determining the criteria weight. Yet, the difference of this method to others relies in the following, particular, steps: define the threshold function for preference, indifference and veto, calculate the concordance and discordance index, outranking degree and ranking of the alternatives (Ishizka, 2013) (San Cristobal, 2012) (Figueira, Greco & Ehrgott, 2005). See Table 3-20 below.

After steps 1 through 4 have been performed, the DM has to define the threshold function for preference, indifference and veto. Preference threshold indicates up to what point the performance of one alternative is still preferred over the performance of another one. On the other hand, the indifference threshold indicates up to what point the DM is still indifferent between the performances of the alternatives. To illustrate what these thresholds are, continuing with the example of purchasing a computer, in regard to screen size, a user can be indifferent in the size of the screen between alternatives up to 3 inches, but has a define preference for an alternative that is 5 inches bigger. The veto threshold is a value over which the user can reject the hypothesis that *a* outranks *b* in a particular criterion. (Ishizka, 2013) (San Cristobal, 2012) (Figueira, Greco & Ehrgott, 2005).

Table 3-20: Steps to use ELECTRE III

1.	Defining the problem
2.	Selection of the relevant criteria and alternatives
3.	Creation of a matrix
4.	Determine the criteria weight
5.	Define the threshold function for preference, indifference and veto
6.	Calculate the concordance and discordance index
7.	Outranking degree
8.	Ranking of alternatives

The Concordance Index is calculated by adding the raw value of an alternative under a criterion with its corresponding preference and indifference thresholds and comparing it to another alternative's raw value under the same criterion. If the first alternative is greater than the second one, a value of 1 is given, if the second alternative is bigger a value of 0 is given. If in both instances (the preference and the indifference) the value is the same, either both 1 or both 0, then there is concordance and the concordance index would be either the 1 or the 0. If the values are not the same, then value is determined by adding the preference threshold to the alternative's raw number, subtracting the second alternative's raw number and dividing by the subtraction of the preference threshold minus the indifference threshold. The Discordance Index is calculated using the same comparison than the concordance index, but instead, if the first alternative is greater than the second the value is 0 and if the second alternative is greater than the first one the value is 1. (Ishizka, 2013) (San Cristobal, 2012). The formula for the Concordance Index is shown in Equation 3-9 and for the Discordance Index in Equation 3-10.

Equation 3-9: ELECTRE Concordance Index

$$c_j(a,b) = \begin{cases} 1 & \text{if } g_j(a) + q_j \geq g_j(b) \\ 0 & \text{if } g_j(a) + p_j \leq g_j(b) \\ \frac{p_j + g_j(a) - g_j(b)}{p_j - q_j} & \text{otherwise} \end{cases}$$

Equation 3-10: ELECTRE Discordance Index

$$d_j(a,b) = \begin{cases} 0 & \text{if } g_j(a) + p_j \geq g_j(b) \\ 1 & \text{if } g_j(a) + v_j \leq g_j(b) \\ \frac{g_j(b) - g_j(a) - p_j}{v_j - p_j} & \text{otherwise} \end{cases}$$

The concordance and discordance indexes are summarized during the next step, the outranking degree. In this step, a measure of degree of outranking is produced, which assesses how strong is the assertion that *a* is at least as good as *b* (San Cristobal, 2012). The formula is:

Equation 3-11: ELECTRE Outranking Degree

$$S(a,b) = \begin{cases} C(a,b), & \text{if } d_j(a,b) \leq C(a,b) \forall j \\ C(a,b) * \prod_{j \in J(a,b)} & \text{otherwise} \\ \times (1 - d_j(a,b))/(1 - c_j(a,b)), & \end{cases}$$

The final step is to rank the alternatives pairwise. ELECTRE III uses two algorithms to obtain an ascending and a descending distillation process. In the descending the alternatives are categorized from best to worst, and in the ascending the alternatives are categorized from worst to best and a final ranking is obtained from the intersection of the two algorithms. However, some weaknesses have been found with this structure and an alternative ranking method can be used based on a concordance credibility degree, a discordance credibility degree and a net credibility degree. See

Equation 3-12 to Equation 3-14 below. The concordance credibility degree measures how alternative *x* dominates all others. The discordance credibility degree measures how *x* is dominated by all other alternatives, and the net credibility degree is the combination of the concordance and the discordance credibility degrees, which is then used to rank the alternatives (Ishizka, 2013) (San Cristobal, 2012).

Equation 3-12: ELECTRE Concordance Credibility Degree

$$\Phi^{+}(x_i) = \sum_{x_j \in X} S(x_i, x_j), \ \forall x_i \in X$$

Equation 3-13: ELECTRE Discordance Credibility Degree

$$\Phi^{-}(x_i) = \sum_{x_j \in X} S(x_j, x_i), \ \forall x_i \in X$$

Equation 3-14: ELECTRE Net Credibility Degree

$$\phi(x_i) = \Phi^{+}(x_i) - \Phi^{-}(x_i), \ \forall x_i \in X$$

As previously explained, a particularity of the ELECTRE process is that when the user determines which are the criteria that will be use, she or he also needs to decide which of those criteria will be maximize and which will be minimize. An example of a criterion to be minimized would be price- which alternative costs less- and an example of a criterion to be maximized would be durability in years- the more years the alternative will be useful the better (Ishizaka, 2013).

3.5.3.3 PROMETHEE

The Preference Ranking Organization Method for Enrichment Evaluation was introduced for the first time at a conference in 1982. Developed by J.P. Brans, PROMETHEE was first introduced in two models: PROMETHEE I which offers partial ranking and PROMETHEE II which offers complete ranking. From then on various versions of the model have been developed: PROMETHEE III offers ranking based on intervals, PROMETHEE IV presents a continuous case, PROMETHEE V includes segmentation constraints for MCA and PROMETHEE VI is used to represent the human brain. (Figueira, Greco & Ehrgott, 2005)

In the PROMETHEE method the choices are compared in pairs to create a function of preference for each criterion. Grounded on this function an index is concluded. This index gives or takes away support for the hypothesis established when the problem was defined. This method can be viewed as a weighted average of the partialities of the criterion. (Loken, 2007).

This method expects that some issues be taken into consideration, such as: i) that the breadth of the deviations between the analysis of the choices within each criterion be considered; ii) that the solutions obtained does not depend on scales; iii) that at the end the model can answer whether there is a preference, indifference or incomparability between the alternatives; iv) that the method used is understood by the decision-maker; v) that the technical parameters that have no consequence to the decision-maker are not included; vi) that the model may offer information on clashing composition of the criteria; and vii) that the model suggest sensitivity tools as to help the decision-maker in testing alternative sets of weights. PROMETHEE requires the inclusion of information between criteria and within each criterion. The information required is including the weights, which represent the importance of each criteria to the decision-maker, in positive numbers, regardless of the unit of measurement. The higher the value given to the weight, the bigger the preference the decision-maker feels towards that criterion. Within each criterion, the deviation of preference is considered, allotting a minor preference to the finest alternative and maybe even no preference to a deviation considered insignificant. As the deviation grows so does the preference. Q becomes the largest insignificant deviation for the decision-maker. In other words, Q represents the indifference the decision-maker has towards that particular criterion, while P becomes the minor sufficient deviation that may affect the preference selection- meaning that P represents the preference the decision-maker has for that particular criterion. (Figueira, Greco & Ehrgott, 2005).

PROMETHEE ranks the alternatives based on preference degrees, for the DM to study. There are three key steps for this method: i) computing the degree of preference for pairwise criteria on each criterion, ii) compute the outgoing and incoming flows and iii) compute the global flow. The whole process includes the following steps:

Table 3-21: Step to use PROMETHEE

1.	Define the problem
2.	Identify the criteria and alternatives
3.	Create a matrix
4.	Define the Preference Function
5.	Calculate the Preference Index
6.	Outranking Graph
7.	Ranking the global flow.

(Ishizaka, 2013) (San Cristobal, 2012).

The preference function is defined separately for each criterion dependent upon the input from the DM. Almost all of the real-world applications can fall under one of these six preference functions: usual criterion, quasi-criterion, criterion with linear preference, level criterion, criterion with linear preference and indifference area, and Gaussian criterion (San Cristobal, 2012).

Once the preference function is defined, the user calculates the preference index for two actions at a time, to determine what is the preference of action *a* over action *b*, for each criterion. The preference index is calculated using the following formula:

Equation 3-15: PROMETHEE Preference Index

$$\pi(a, b) = \frac{1}{k} \sum_{h=1}^{K} P_h(a, b)$$

The preference index help constructs the outranking graph by helping by finding the outgoing and the incoming flows. The outgoing flow indicates how that action *a* is preferred over all others, while the incoming flow indicates how all other actions are preferred over action *a*. The formula for outgoing flow is shown in

Equation 3-16 below and for incoming flow in Equation 3-17.

Equation 3-16: PROMETHEE Outgoing flow

$$\phi^{+}(a) = \sum_{x \in K} \pi(a, x)$$

Equation 3-17: PROMETHEE Incoming flow

$$\phi^{-}(a) = \sum_{x \in K} \pi(x, a)$$

The global flow is also known as the net flow, which is the result from subtracting the incoming flow from the outgoing flow:

Equation 3-18: PROMETHEE Net Flow

$$\phi(a) = \phi^{+}(a) - \phi^{-}(a)$$

Once the global flow for each action is found, they can be ranked using the formula below:

Equation 3-19: PROMETHEE Global Flow Ranking

$$\begin{cases} a \text{ outranks } b \ (a\ P^{(2)}\ b) & \text{if } \phi(a) > \phi(b) \\ a \text{ is indifferent to } b \ (a\ I^{(2)}\ b) & \text{if } \phi(a) = \phi(b) \end{cases}$$

Thus, PROMETHEE method provides the DM with a ranking of the alternatives according to his or her preference input (Ishizka, 2013) (San Cristobal, 2012).

3.5.3.4 MCA using fuzzy sets

With fuzzy logic inputs that are vague can be included in the analysis of the problem by allowing the decision-maker to express the degree in which a unit belongs to an element. For example, if the element is the colour pink, the different degrees would be the various tones of pink: old pink, baby pink, salmon, fuschia, peach, light pink, dark pink, etc. A fuzzy set would give the decision-maker the opportunity to express, in his or her opinion, how much more pink-the "degree"- the colour salmon is compared to the colour old pink and represent this with a numerical value. Fuzzy sets have been applied in MCA as a way to deal with imprecise and uncertain data as their design makes them better suited to handle uncertainties (Pohekar & Ramachandran, 2004) (Velasquez, 2013).

As the example shows, the concept of a degree of inclusion (how much more "a" belongs to the element than "b") can be difficult to grasp for the non-expert and even to the expert. It may also be difficult to express this inclusion degree and may require the user to run many recreations before applying it to the real world, as these sets do not have a clear theoretical foundation as to how they can be used in the different models. There have been examples of MADM that have applied fuzzy sets, which usually require a deeper understanding of the mathematics involved and thus may complicate the use of the basic method. Because of this extra layer of complexity, the use of fuzzy sets may not be practical to use when governments are involved in the decision analysis process (Dogson, 2009). For this reason, this thesis will not consider the use of fuzzy sets in the methods presented. It is however suggested as topic that requires further research and analysis.

3.6 CONCLUSION

Decision analysis is the name given to the conscious, reasonable way to oversee a problem and decide on the best result, according to the values and preferences of the decision-maker. The concept of decision analysis is based on the perception that a DM needs to accomplish an objective, has several alternatives from which to select, can study the potential consequences of each alternative and is rational. DAMs assist in assessing the alternatives against selected criteria to stream the best possible results that will help fulfil the goal or purpose set by the DM, with the use of scientific methods, mathematics and propositions.

The way DAMs are designed require the user or decision-maker to: i) define who are the stakeholders involved, ii) determine which are the possible actions to be taken, outcomes that may arise from each action and challenges that could be faced for each action, iii) select what will be the criteria against which the actions will be measured; and iii) rationalize how the possible actions or alternatives combine with the values to fulfil the intended goals. This rationalization is the analysis of the decision, and the results of the analysis are then presented to the decision-maker for his final say. DAMs are tools to be used by the DM to analyse possible solutions to the problem but are not a tool to obtain the final answer.

Energy planning started benefiting from the advantages provided by DAMs in the 1970's and 1980's. They were first used to forecast energy demand in order to study the relationship between energy needs and economics. Originally, as the goal was to obtain the lowest cost option and techniques focused on single criteria were used. In time, environmental needs required the models to evolve to multi-criteria to include other aspects beyond costs, such as greenhouse gasses emissions and social impact. The use of multi-criteria allowed for DAMs to branch out to areas such as energy planning, resource allocation, building and transportation management, project planning, exploitation, sustainability, and electric utility planning possible.

Since decision problems can be divided into two types, and the methods can be utilized to analyse them. Single criterion problems and methods are those in which the objective is to maximize the result, without taking any other factors into consideration. As real-world decisions require the inclusion of several and different factors, single criterion methods evolved to include multi-criteria. Multi-criteria Analysis methods aim at finding solutions that can provide satisfaction to the DM taking into consideration his or her expressed preferences, indifferences and values.

MCA can be subdivided into MODM and MADM. MODM techniques have various objectives that may be conflicting among themselves and, because of this, the alternatives that could possibly fulfil the DM’s objectives are not pre-determined. Instead they are limited by pre-determined variables, meaning that one variable cannot be better off without making another one worse off, in order to achieve a balance point. MADM methods, on the other hand, are designed to allow the DM to select a distinct alternative from a limited selection, whose performance has been asses against precise criteria. The DM can use as many or as little criteria as he or she considers necessary in order to measure the performance of the alternatives. MCA methods can be further subdivided into three categories: value measurement models, models for goal, aspiration and reference level and outranking models. Value measurement models utilize numerical scores to represent the DM’s preference over the criteria and the alternatives. Goal, aspiration and reference level methods are used to ascertain the strongest alternatives that will support the fulfilment of a specific goal or aspiration. Outranking models compares all alternatives via pairwise relationships in order to select the more appropriate ones by asking the DM to rank one against the other.

The basic steps of a MCA model include: defining and structuring a problem, generating alternatives or options, selecting the appropriate criteria or attributes, construction of an evaluation matrix, assigning weight to the criteria, selecting the appropriate MCA method, analysis and ranking of the alternatives and sensitivity analysis and recommendations. Out of the methods of MADM, MAUT is the most popular and is commonly used in energy planning. Its main advantage is the inclusion of uncertainty into the model. AHP is the second most common MCA method, also used in energy planning and other energy related decisions. AHP aims at obtaining a rank for the alternatives and with this ranking obtaining a favourable solution. Another widely used MCA method in energy is ELECTRE, which integrates the use of the DM's preference, weak preference, indifference, or incomparability determination on the alternatives. A fourth widely used MCA method is PROMETHEE. Although this method also integrates a specific value to represent the DM's preference, different from ELCTREE, this method uses degrees to represent the DM's preference. Each step of the MCA cycle and the different methods will be further explained in Chapter 4.

4 GENERAL MULTI-CRITERIA ANALYSIS FRAMEWORK

4.1 INTRODUCTION

Decision analysis methods formalize the process of decision-making, by allowing the DM to analyse and filter the different characteristics of the decision analysis situation: i) achieving an objective; ii) study the alternatives available; iii) comprehend the potential results and understand the uncertainty around each one; iv) work with different priorities and v) the diversity of the stakeholders involved which represents conflicting priorities. These methods can be divided into single criteria methods or multi-criteria methods. Single criteria methods assess the situation from a vacuum, meaning that they seek to answer the question taking into consideration only one criterion and foregoing how any other elements may affect the solution sought. Contrarywise, multi-criteria analysis methods take into consideration real world necessities, including analysing the situation from different and conflicting points of view and making compromises in finding the solution. Multi-criteria methods can be further subdivided in multi objective and multi attribute. The multi objective methods look as to how best achieve various objectives. To do so these methods do not limit the quantity of alternatives to be considered as potential solutions. Diverging to this approach are the multi attribute methods, which also aim at finding potential solutions to the problem, but they do so by limiting the alternatives to be assessed. Multi attribute methods have been found to be very useful for decisions related to the energy field, whether the situation requires the selection between renewable energy technologies or for selection between fuels, as they limit the alternatives to be evaluated while allowing for different criteria to be the indicators of the alternatives' performance.

Each MCA model has its own process, but they all share some common steps. This chapter will provide a detailed explanation of each step of the general multi-criteria decision analysis framework through a theoretical analysis of the literature. Various points of views from different scholars where included in each sub section to provide a simple, yet wide ranging explanation. Understanding the basic multi-criteria decision analysis framework is fundamental to build the framework to be used specifically in the energy sector later in Chapter 5. The conclusion of the chapter is for the reader to have a clear understanding of the different basic stages required in a formalized decision analysis without making reference to any particular method or technique.

4.2 OVERVIEW OF A GENERAL MCDA FRAMEWORK

MCA models are analysis processes that involve various steps. In the literature, different authors enumerate varying numbers of steps. Summarizing the literature reviewed, a more itemized list of steps for a decision analysis framework, as shown in Figure 3-2, include:

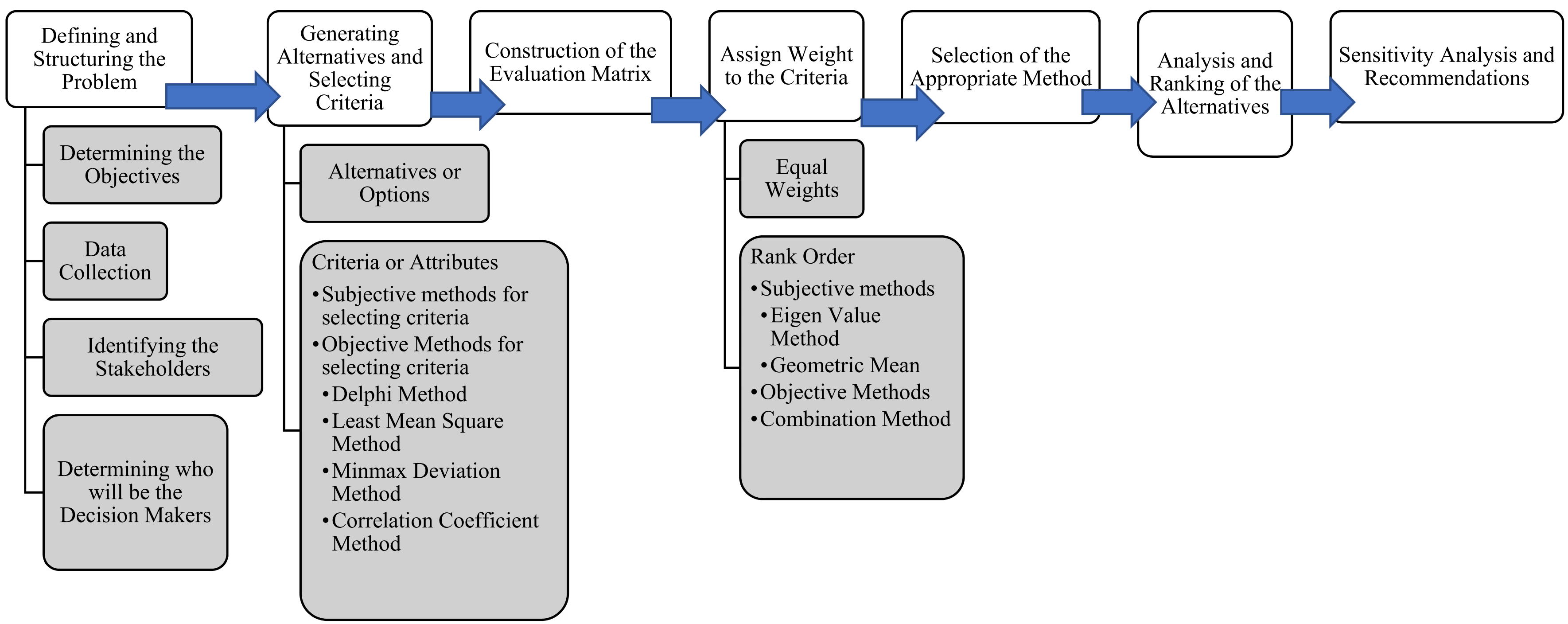
1. Defining and structuring the problem
2. Generating alternatives (also called options) and selecting the appropriate criteria (also called attributes).
3. Construction of the evaluation matrix
4. Assign weights to the criteria.
5. Selection of the appropriate method
6. Analysis and ranking of the alternatives
7. Sensitivity Analysis and Recommendations

(Dogson, 2009) (Kurka, 2013) (San Cristóbal Mateo, 2012) (Keeney, 1982)

For the specific methods, some authors vary the number of steps, some using as little as four steps, while other authors use more. The reason for the difference in steps in the literature has been the author's preference. Some prefer to use main subdivisions which include other steps, while other authors prefer more detail such as including generating the alternatives and selecting the criteria as part of the first step, structuring the problem, and sensitivity analysis as part of the sixth step, analysis and ranking. The time needed to develop the model will depend on the complexity of the issues at hand. Easy matters might take a couple of hours to complete the MCDA process, but more complex issues may take several months. The analysis may be structured in different ways according to the needs. For example, the analysis can be framed to put the alternatives in order of priority, show the areas of more or less opportunity, to show the best ways forward or show differences between the alternatives. The framing is done to help at better understanding of the situation. (Dogson, 2009) (Keeney 1982)

Figure 4-1 below provides a snapshot of the different steps and the issues to be taken into consideration for each one.

Figure 4-1: Snapshot of the MCDA Framework



4.2.1 Defining and Structuring the Problem

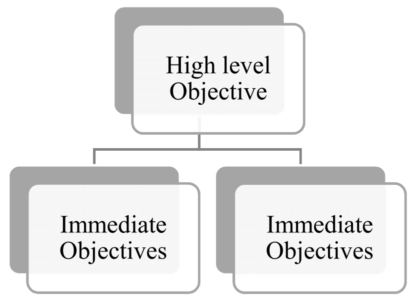
The main reason why the decision context needs to be defined and structured into a tangible problem is to be able to understand it, to know exactly what is involved in the situation an answer is needed for. In other words, to define what are the objectives or goals to be achieved. The problem is considered to have been sufficiently defined when the following answers are found: which alternatives to assess, which specific actors will be involved, the goal, and the conflicting issues with their limits and uncertainties. When answering the question, "what is the problem?", those who have an interest in the analysis process and its results have to take into consideration their own objectives, the urgency of making a determination, the stakeholders, the DMs, and the quality and quantity of information needed to develop the analysis. During the process, new issues and features may raise, meaning that the problem or reason behind utilizing the MCDA may not necessarily be fixed. (Dogson, 2009) (Guitouni, 1998).

When structuring the problem, the following concerns should be taken into consideration: are the goals or objectives, which data is needed, who are the stakeholders, and who, ultimately, will make the decisions.

4.2.1.1 Determining the Objectives

Multi-criteria methods, both multi-objective and multi-attribute, were developed as a response to the existence of conflicting points of view represented in the difference in preferences and priorities of where the focus should be when seeking solutions to a situation and finding one that may bring satisfaction to all involved. Having objectives helps narrow the focus. These objectives are short assertions of what is important. Defining objectives, in other words, defining what is important, and organizing them requires a clear understanding of the whole situation that needs to be resolved. To better narrow down the focus, and thus understand the issue, objectives can be divided in two types: high level and immediate. The hierarchical structure of the objectives is illustrated in Figure 4-2. High level objectives are those that can be found at national level, like reduction of greenhouse emissions by 20% by a certain date or increase in gross domestic product by 1% by the end of calendar year, and are usually described in official publications, such as political manifestos or government communications. The second type of objectives, immediate objectives, are those associated with the turnout of a policy or programme. Objectives should have a hierarchical order, with the broader ones tackling general concerns, followed by more detailed ones at lower levels. Achieving the immediate- or lower level- objectives, should help towards achieving the high-level objectives. Any gaps in the hierarchy should be filled. Starting from the bottom up, the options and criteria (both terms are further explained in section 4.2 below) must be identified as they help appraise the extent to which the objectives are accomplished (Dogson 2009) (Niekamp, 2015) (Keeney, 1982).

Figure 4-2: Objectives



4.2.1.2 Data Collection

After the objectives are pinpointed, empirical evidence that will help enhance their understanding and which will aid in evaluating the progress towards achieving them has to be collected. Data collection, and its assessment, can be a time-consuming task. This is something that has to be kept in mind when brainstorming the kind of data that needs to be gathered and when determining how to approach the collection of data. No data collection method or technique has been designed specifically for multi-criteria decision analysis methods. Nonetheless, common data gathering techniques such as observation, interviews, or documents (e.g. questionnaires or tests) can be used in MCA. Those involved in proposing the situation that requires decision analysis would need to rely on their experience and knowledge to identify which information needs to be obtained. However, as data collection is very interrelated with generating the alternatives and selecting the criteria those involved in proposing the situation or even the DMs can already have an idea of the plausible alternatives and the criteria that they want analysed. If this is the case, the preconceived alternatives or criteria would be a good starting point for data collection. The contrary can also happen, that the plausible alternatives and criteria are identified as a result of the data collection. (Dodgson, 2009) (Keeney, 1982)

Whichever the process or technique chosen for collecting data, there are two main categories of data: quantitative and qualitative. Quantitative data is that which can be communicated by numbers, whether using ratio, ordinal or interval scales. Qualitative data, on the other hand, is that which is transmitted via words or images, but not numbers. Even though it could make the process more complex, the purpose of collecting qualitative data, in addition to quantitative data, is to gather enough facts and information, including that which cannot be quantified, to be able to describe in detail the situation which requires a decision. Usually qualitative research requires triangulation, or the use of various data sources, to guarantee a wide-ranging and robust collection of the data. If they were not previously identified, the collection of data will uncover the main issues or points of view of the situation (Plonsky & Gurzynski-Weiss, 2014) (Guthrie, 2010) (Miles & Huberman, 1994).

4.2.1.3 Identify the Stakeholders

At this point in the analysis process, the goals of the MCDA have been set and at least part, if not all, of the information required to assess the progress towards achieving these goals has been obtained. The next step is to identify the stakeholders. Stakeholder is not just any person that is associated with the planning and the decision analysis process, but rather a stakeholder is defined as an individual involved in the planning and decision process that has a legitimate responsibility and/or an interest in the consequences of the decision. Including stakeholders in the process is key as their contributions are essential for ensuring the success of the analysis. Stakeholders represent different points of view and these points of view are needed in different steps of the analysis process, for instance when identifying the alternatives and criteria, or for determining the weight. Although they don't necessarily need to participate in the decision process, they do need to be represented by one or more of the key players. Key players are defined as those individuals who: i) do participate in the decision analysis process; ii) who can make an important and fruitful contribution to the process and iii) who represent all major points of view on the issues at hand, which were identified during the data collection phase. Key players are systematically used to represent the stakeholders as mode to reduce the number of individuals involved in the analysis process and make it more manageable (Dogson, 2009) (Haralambopopulous, 2003).

Although all stakeholders need to be represented by one or more key players, not all key players will be stakeholders. This is the case, for example, of experts, who are considered key players in the process, but are not necessarily stakeholders, because they provide additional experience and information. Which stakeholders and which key players will be involved, the extent of their participation and the timing of that participation is something that must be taken into consideration when designing the decision analysis pathway or framework that to be used. Designing the pathway is the social aspect of designing the decision analysis framework to be used (Dogson, 2009).

At this point where the stakeholders are engaged, the decision structure has not been decided; it would be pointless to engage potential stakeholders without knowing what the objectives are and what kind of data will be needed, particularly because the data may serve as a guide to identify the stakeholders. However, local regulations for the engagement of stakeholders should be taken into account during this process. Local regulation for the engagement of stakeholders will not be discussed as it is out of the scope of this research.

4.2.1.4 Determining Who Will be the Decision-Makers

Once the stakeholders and the key players have been designated, the next step is to nominate the decision-maker or makers. The DM is carefully chosen from within the general stakeholder groups, not necessarily from the key player pool. Due to the nature of multi-criteria problems, which face different interest and objectives, it is reasonable to select more than one decision-maker and for them to not have similar concerns. When the group of DMs does not have similar interests, a more robust evaluation of the problem is safeguarded. In addition, the fact that the DMs are taken from the same sample group does not necessarily mean they all have the same importance within the group. If a DM's opinion is considered to have prominence over the opinions of other DMs, then this has to be integrated into the analysis process via weights at an early stage. The opinion of the selected decision-makers could have the same weight or could vary. The significance of including this variation in the standing of the decision-makers into the model is because this standing may sway the decision analysis process (Haralambopopulous, 2003) (Dodgson, 2009).

Even though having various DMs representing different points of view safeguards the heftiness of the analysis, a challenge that has to be tackled when there is more than one

DM is how to achieve consensus amongst them. To guarantee that efficient decisions are taken, the decision-makers need to arrive at a level of agreement or group consent. Consent is characterised as measuring the dissent between the decision-makers. The process of arriving at an agreement is a way to seek a satisfactory compromise between all the members of the group in a given situation. This process can be complicated and difficult due to a difference of opinion between the members of the group, the manner in which these opinions are expressed- which can be imprecise or subjective- and the demanding nature of the decision analysis process. Some leading approaches to obtain consent include majority approach, ranking approach, consensus approach. Aggregating individual judgments and aggregating individual priorities. (Wibowo & Deng, 2013; Wu & Xu, 2012).

The majority approach is the easiest of all, but, it presents the problem of having a time consuming voting process as well as being subjective and not providing an adequate model for the selection process. The ranking approach requires the allocation of numbers when evaluating the execution of the item, which provide an individual score by decision-maker which is then aggregated to produce an overall index. The consensus approach can be an interactive and dynamic discussion process with several rounds in which the participants can change their opinion (Wibowo & Deng, 2013; Wu & Xu, 2012).

The aggregating individual judgments (AIJ) technique and the aggregating individual priorities (AIP) technique are more mathematical approaches rather than a process requiring group discussion as the previous three techniques discussed in the previous paragraph. In these processes, the decision-makers could have the same weight, as explained above, or their weights can be added in the determination of the final combined group preference. When wanting to use either AIJ or AIP, the user needs to answer: a) whether the group is working as a unit or as individuals, b) which mathematical procedure should be used and c) how to obtain and incorporate the weights of the DMs. If the group is working as a unit, such as is the case of directors of a company working towards company policy, then the individuals have to renounce to their distinctive values or objectives and work together to obtain the good of the company. In this case AIJ method is used. In this method, the individual thoughts and preferences are absent, and it is the group, instead, that becomes one entity. If the individuals are working for their own benefit, such as stakeholders with different preferences, then the method to be used is the

AIP, where individual priorities are added to create a group one. Both methods cannot be used simultaneously (Forman & Peniwati, 1998).

When using either the AIJ or the AIP methods, the user assumes reciprocity in the preference as given by the decision-makers. Reciprocity means that if the DM established the preference of *A* three times over *B,* then when asked about the preference of *B* over *A* the answer should be 1/3. The political interpretation of the Pareto Principle has been applied to complement the concept of reciprocity. Under this interpretation, the Pareto Principle establishes that if the individuals in a group prefer alternative *x* over alternative *y*, then the group must prefer alternative *x* over *y*. Hence, under the Pareto Principle, if the individuals in a group prefer *A* three times over *B* then the group must prefer *A* three times over *B*. In the AIJ method, conformity with the Pareto Principle can be confirmed with the used of geometric mean, while for AIP either the geometric or the arithmetic means can be used. The difference between the means is that the geometric is a type of average that determines the middle term of a set of numbers by using the product of said set of numbers, whereas the arithmetic mean determines the middle term of a set of numbers by using the sum of the set of numbers, divided by the quantity of values belonging to the set. Equation 4-1 to Equation 4-3 show the formulas for AIJ with geometric mean, AIP with geometric mean and AIP with arithmetic mean, respectively (Forman & Peniwati, 1998).

Equation 4-1: AIJ with Geometric Mean

$$J_g(k,l) = \prod_{i=1}^{n} J_i(k,l)^{w_i},$$

Where $J_g(k,l)$ is the group preference, k and, l are factors; $J_i(k,l)$ is individual i's preference of factors k and l and w_i is the weight of the individual.

Equation 4-2: AIP with Geometric Mean

$$P_g(A_j) = \prod_{i=1}^{n} P_i(A_j)^{w_i},$$

Equation 4-3: AIP with Arithmetic Mean

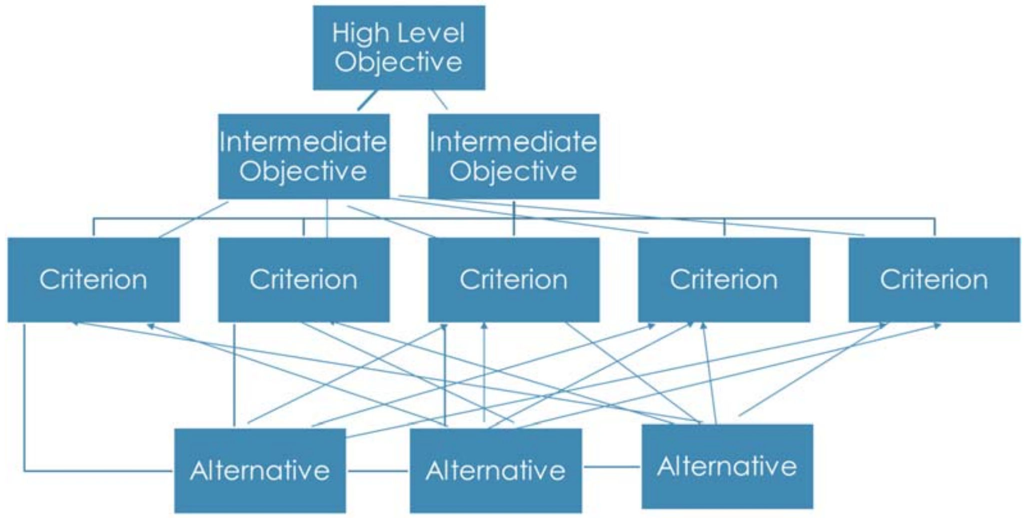
$$P_g(A_j) = \sum_{i=1}^{n} w_i P_i(A_j),$$

Where $P_g(A_j)$ refers to the group preference of alternative j, w_i is the weight of the individual, and $P_i(A_j)$ is the individual's priority of alternative j.

4.2.2 Generating Alternatives and Selecting Criteria

The alternatives -also called options- are potential solutions to the problem that should fulfil the objective[s], or at least fulfil them to an acceptable level. Criteria, also known as attributes, evaluate how each of these alternatives can accomplish the objectives. The selection of alternatives is set in stone; it is a work in progress requiring continuous revisits during the decision analysis process. This is why it is better to first define the problem with its objectives and then focus on which are the possible alternatives or options that may help achieve those objectives and which are the criteria that will assess each of the alternative's performance, instead of deciding on the alternatives and/or the criteria first. Figure 4-3, below, illustrates how the criteria and the alternatives interact with each other and with the intermediate and high-level objectives. This visualization, although not necessary for the development of the analysis methodology, aids to envision the full process and puts in better perspective how each of the separate pieces fit in the process as a whole (Guitouni, 1998) (Dogson, 2009).

Figure 4-3: Criteria and Alternatives Interaction towards the Objectives



4.2.2.1 Alternatives or Options

The purpose of selecting alternatives is to familiarize all participants with the true costs and benefits of the possible decisions. The decision analysis process is aimed towards an action yet, this does not necessarily mean that the action is feasible or can be implemented. When the action can possibly be implemented, it is considered a potential action. In the context of decision analysis alternative could be defined as two different potential actions which cannot be followed at the same time. (Greco et al., 2005) (Haralambopoulos & Polatidis, 2003).

Usually the alternatives have been identified by the decision-makers during or prior to defining the problem. However, there can be several problems when deciding on the alternatives, including generating reasonable alternatives or differentiating between the superior and inferior options. When the setback is related to generating reasonable alternatives, the objectives previously outlined can be used to aid, but they would only be helpful if they are clearly expressed, which includes describing the desired results- and then working backwards from that point to determine what type of alternatives might accomplish that result. For the second situation, differentiating between the appropriate and non-appropriate (superior and inferior) alternatives, options that are considered inferior can be screened and eliminated to allow the DM to concentrate on a lesser number of superior alternatives. While there are no specific techniques designed to remove inferior alternatives in MCA methods, other planning methods could be used to assist in this selection. Analysis such as strength, weakness, opportunities, and threats (SWOT) or a political, economic, social and technological (PEST) are examples of techniques that could be used to weed out the superior options or alternatives from the lesser ones. These options or alternatives may be broad or specific, but the most functional ones should be detailed (Dodgson, Spackman, Pearman, & Phillips, 2009) (Keeney, 1982).

4.2.2.1.1 Strength, Weakness, Opportunity, Threats (SWOT)

A SWOT analysis will assess the strengths, weaknesses, opportunities and threats faced by a sector, company, organisation or industry. It helps to build, fix, seize and minimise the results found, accordingly. The concept of the SWOT analysis started in the 1960's, from the conception that the achievement of the objectives set for an institution is dependent upon how the management of the institution (whether a government, industry or sector) interrelates to both the internal and the external factors it. The external factors are particularly important because even though the institution does not have any control over them, it has to be prepared to face them, while the internal factors are those that are within the institution's control. Strengths and weaknesses are viewed as the internal factors. Strengths are those traits that emphasize the capacities to reach the goal. Alternatively, weaknesses are those traits that, if not addressed and corrected or enhanced, can challenge reaching the goal. Opportunities and Threats are the external factors over which the institution has no control over. Opportunities are economic, social, legal, political, environmental and technical matters that represent the context of the situation being analysed and which may simplify achieving the goal. Threats are those external matters that may preclude the fulfilling of the goal. The advantage of using a SWOT analysis is that it allows the user to stress how internal and external factors interact and affect the institution while allowing for the improvement and execution of long term strategies. The strategies that can be used after performing a SWOT analysis include:

- linking the strength and opportunities- where the strengths may help get the most out of the opportunity
- linking the weaknesses and opportunities- where opportunities are chased to diminish the gravity of the weakness
- linking the strengths and threats- where internal strengths are highlighted to diminish the influence of the threat
- linking the weaknesses and threats- where processes and actions are envisioned to reduce both (Bull et al., 2016).

4.2.2.1.2 Political, Economic, Social and Technological (PEST)

PEST is an "analysis framework that includes macro-environmental factors," such as policy, environmental and social. This framework assumes that it is necessary to have information relevant to the business environment- which is defined as including internal, external, and physical factors used in the decision-making process- in order to understand its success. These internal and external factors can affect how the institution creates value. It can be used to either analyse the position of the institution within its environment or analyse the viability of proposed solutions. Variations of this analysis include: political, economic, social, technological, environmental, and legal (PESTLE) analysis; and the social, technological, environmental, ethical, political, legal, economic and demographic analysis (STEEPLED). The political aspect analyses the intervention of the government in the economy via tax policy, environmental laws, tax laws, tariffs, trade restrictions, security of the judicial system and political stability, among others. The economic factors considered in the analysis include those that affect how a company or industry operates and makes decisions, such as economic growth, inflation rate, exchange rate and interest rates. Social analysis includes aspects that affect the population in general, such as health, population growth, age distribution and safety, amongst others. A technological analysis studies how research and development, incentives and automation affect the industry or company. Legal factors may include regulation against antitrust, employment and consumer protection laws. The environmental scrutiny focuses on changes in weather and climate and their influence on the industry or company (Peng & Nunes, 2007).

4.2.2.2 Criteria or Attributes

After the options or alternatives are identified, the next step is to analyse how each of these alternatives contribute towards accomplishing the proposed objectives. As the DMs are affected by, and in turn affect, the context in which the decision analysis process is developed some of the considerations that influence the assessment of how the selected alternatives contribute towards achieving the goals should include political, sociological, economic, timing and cultural aspects, amongst others (Guitouni, 1998).

Criteria has been described as the metric against which progress towards fulfilling the objective or objectives is measured or as a tool for assessing potential actions according to a well-defined point of view. To evaluate the contributions of the criteria towards accomplishing the proposed objectives, it is necessary to select criteria that will reflect how each alternative will meet the objectives; in simple terms, the analysis shall evaluate, for example, how alternatives A_1 and A_2 compare against one another under criterion C_1, under criterion C_2, etc., as to determine how each of the options accomplishes the objectives (Dogson 2009) (Greco et al., 2005).

These criteria or attributes can be grouped into sets for easier management, known as clustering. Clustering also aids in calculating weight; it is less complex to calculate first the weight within a cluster and then compare this weight with that of other clusters. Clustering is also beneficial to better view the issues and possible trade-offs between the objectives. There are no specific guidelines on how to use the clustering technique in the MCA methods. Any structure can be used, as long as it is clear and logical and has as explanation as to why certain criteria were clustered together. A form of a logical structure to organize the criteria is to divide id into main criteria and sub-criteria, with each main criterion belonging to a different cluster. For example, the main clusters for the computer purchase example presented in Chapter 3 could be hardware and economic, with the sub-criteria for hardware be weight and size while the economic sub-criteria be price and price of compatible software. Categorizing the criteria, such as in main and sub-criteria, is common, however this classification may not be clear as some criteria can fall under more than one category. For instance, the sub-criteria resource depletion can be viewed as an economic, social and/or environmental criterion. For this reason, it is advised not to focus on how to categorize the criteria but rather on how it aids in fulfilling the proposed goal (Niekamp 2015) (Dogson 2009).

The assessment of the alternatives against the criteria should be presented in a scale to allow for easier comparison amongst the alternatives. This scale can be ordinal, whether verbal or numerical, quantitative scale, or any other. Within the scale, the alternative can be measured in degrees: how much does that alternative belong into an element. The range and style of the scale and whether or not degrees are to be used, are issues that are determined by the MCA method chosen and the familiarity of the user with both the MCA method and the type of scale (Greco et al., 2005).

Developing evaluation criteria is necessary to analyse the alternatives. This development requires parameters to identify which elements are appropriate, practical, reliable and their limits for the evaluation. The literature does not identify or suggest a pre-determined quantity of criteria—both main and secondary—should be taken into consideration for optimal analysis. The one parameter discussed in the literature is that the number of criteria or attributes to be used for evaluating the alternatives during the decision analysis process should be a manageable amount which will allow the DM to make an informed decision. No precise definition of what is considered to be a manageable amount is given. However, some theoretical principles as well as mathematical reasonings, have been proposed and used to help in selecting the criteria (Dogson 2009) (Wang, 2009). Some of these principles and mathematical reasonings are described below.

4.2.2.2.1 Principles for selecting criteria

The process of selecting criteria contains its own collection of inherent problems, like how to avoid repetition, how to determine which criteria are relevant for the exercise or how to make sure key criteria has been included. To support a thorough and well-rounded assessment of the alternatives several principles have been put forward to aid the users of MCA methods in identifying the suitable criteria.

Table 4-1 below presents a compilation of various principles that have been discussed in scholarly articles which can be used to select both main and sub-criteria (Dogson 2009) (Wang, 2009):

Table 4-1: Principles for Criteria Selection

Principle	Explanation
Completeness	The user must ensure that all main criteria has been included and within each group (or cluster as explained above) all key sub-criteria. Clustering is used to help the user evaluate whether the criteria selected is extensive enough to provide a well-rounded analysis. An example of what may be overlooked when identifying the criteria is whether the attribute included captures the principal aspects of the stated objectives. In other words, how the criterion would help measuring whether the alternative fulfils the objectives or not.
Redundancy	Any criterion that is deemed as unnecessary or that will cause for all the options to produce the same result should be removed. Eliminating a criterion that will produce the same result for all the alternatives should not affect the alternative's ranking but, instead, would save time during the analysis process. Nonetheless, eliminating a redundant criterion has to be carefully done. Disregarding a criterion at a certain stage, particularly an early one, does not result in total removal of the criterion from the exercise with the implication that it shall not be needed again at a later stage. Continuous revisions during the process may require the disregarded criterion to be re-visited at a later stage.

Independency	A criterion is independent when the preference score for alternative A_1 in regard to criteria C_1 can be assigned without knowing the preference score for the same alternative in regards to another criterion. The importance on the independence of criteria is that each attribute should reflect different facets of the alternative's performance.
Double counting	Because criteria carry weight- which reflects the decision-maker's preferences- if a criterion is used more than once, each time it is used the criterion will be given a weight. This will, in turn, affect the final overall weight of the criteria. Even in the case of possible double counting, care needs to be taken prior to eliminating a criterion. If, for example, two criteria are expected to produce the same result, but one is preferred over the other, it is essential to further study the causes for such preference. In this case, each criterion may have been valued differently and this, consequentially, affects the assessment of the alternatives and the analysis of the decision problem.
Systemic principle	Criteria, as a whole, should completely mirror the crucial components of the decision problem and the overall execution of the options. If the decision analysis is studied by a comprehensive evaluation, including that all criteria meet the key issues within the decision problem, then the result is more informed than if the results are combined after being analysed from an individual point of view.
Consistency	Like the systemic principle, the criteria selected should be consistent with the objectives proposed by the DM. Then again, while the systemic principle ensures that the criteria meet all the key elements of the decision problem, the consistency principle ensures that the criteria coherently direct the analysis towards fulfilling the objectives. In other words, this principle advises that the criteria selected is not contrary to the proposed objectives. Consistency should not be confused with consensus, which measures the degree of agreement within a group, while consistency measures the agreement with the purpose.
Measurability	Criteria selected can be qualitative or quantitative. Qualitative data must be transformed into a measurable unit. This measurable unit could be, as an example, a numeric scale (for instance the Saaty scale explained in Chapter 3 where verbal appreciations were converted into a numerical scale with 1 representing the least preferred option and 9 representing the most preferred one), or fuzzy sets, again as an example. Fuzzy sets are mathematical sets that indicate the degree of membership a unit has in an element.
Comparability	The measurability principle deals with the criterion having a unit it can be measured with. The comparability principle, on the other hand requires the criteria to be normalized. In other words, all the criteria must have a unit norm in order to be compared against each other. The easier it is to compare the criteria the more rational the outcome.

Principle	**Explanation**
Size	This principle alludes to the concept that the quantity of the criteria selected should not be larger than needed as too many criteria would complicate the analysis. Nonetheless, it leaves the determination of what is the amount needed to the user. This principle does recommend, however, that if the analysis requires the use of sub-criteria, then the same quantity of sub-criteria should be used in each cluster. Meaning that if Cluster *X* has 3 sub-criteria, then so should Cluster *Y* and Cluster *Z*.
Impact occurring over time	Because some of the decision problems may have short and/or long-term consequences, attention has to be placed on time-differentiated impacts throughout the life of the project. This attention can be provided by differentiating between permanent consequences and temporary ones and having this in mind when choosing the criteria.

(Kurka, 2013) (Dogson, 2009) (Wang, 2009)

Even though the principles are inclusive and well defined, finding group consensus on whether the criteria meet all the enunciated principles may prove to be a difficult task. In complimenting the compliance with the principles, some mathematical methods have been developed and used to aid in the selection of criteria.

4.2.2.2.2 Mathematical methods to select criteria

This section presents a general overview of some mathematical methods that have been proposed to be used when selecting criteria. Although the following methods are introduced for criteria selection, they can also be used to elicit criteria weight later on in the decision analysis process. Because of the mathematical complexity involved, these methods are succinctly explained, with the only purpose of providing the reader with a basic knowledge but will not be used for the framework proposed in Chapter 5.

4.2.2.2.2.1 Delphi Method

The Delphi method originated during the 1950's as a way to obtain group consensus. Its underlining thinking is divided in two: the first, that experts, rather than laypeople, will arrive at a better answer; the second, that multiple answers will converge into the accurate one. This method works in a minimum of two rounds. It starts by giving a questionnaire to a group of experts to answer. The questionnaire will ask the experts to express the criteria they will prefer to include. After this, and every round, the responses and reasons for their decision are fed back to the participants. In the next round, and after considering the answers and judgements of the group, the contributors can modify their answers or maintain them. The purpose is that, with the aid of the group discussion, the members will eventually converge towards deciding which is the most suitable criteria to be used in the decision analysis process. The Delphi process ends when a pre-determined moment is reached, which can be a specific number of rounds or arriving at a group consensus, for example (Wang, 2009) (Okoli & Pawlowski, 2004).

The selection of the suitable experts may be the trickiest part of using the Delphi Method. A technique to be used to identify these suitable experts may be to classify the skills or the discipline whose experts would provide the most productive feedback. For example, it can be determined that the suitable experts should be biologist that are university professors or work for a private laboratory. Once the skills or disciplines are identified, specific names of individuals knowledgeable in that area are put forward and selected. This selected group is then contacted and asked to nominate other experts. Once there are enough potential experts—and this determination is left for the user to make-- these experts can be ranked based on their qualifications and invited according to their discipline and ranking (Okoli & Pawlowski, 2004). Although this is an objective manner in which to select an expert, the preparation required may be extremely time consuming. The same can be said of the Delphi method in general. The public to which the Delphi method is address needs to be taken into consideration as individuals who hold a position of high-rank within their organization may not have the time availability to see the completion of the process of the method.

4.2.2.2.2.2 Least Mean Square (LMS) method

Similar to the redundancy principle previously explained, the LMS method is based on the belief that if one criterion is less important than others it can be ignored when the alternatives give similar results. (Wang, 2009) The formula representation for the LMS method is shown in Equation 4-4 below.

Equation 4-4: LMS Method

$$s_j = \sqrt{\frac{1}{m}\sum_{i=1}^{m}(x_{ij} - \bar{x}_j)^2} \quad (j = 1, 2, \ldots, n)$$

Where x_{ij} is the ith example of criteria j.

4.2.2.2.2.3 Minmax deviation Method

The Minmax Deviation Method is similar to LMS method in which it helps eliminate criteria that contribute less importance to the analysis. The formula is provided in Equation 4-5 below.

Equation 4-5: Minmax Deviation Method

$$r_j = \max_{1 \le i,l \le m} \{|x_{ij} - x_{lj}|\} \quad \text{and} \quad r_k = \min_{1 < i < n}\{r_i\} \text{ and } r_k \approx 0,$$

Where x_j is a criterion, r_j is the maximum deviation, r_k is the minimum deviation. If criterion k is equal to 0 then this criterion could be removed, taking into consideration that this criterion could be later revisited, as previously explained. (Wang, 2009).

4.2.2.2.2.4 Correlation coefficient method

The purpose of the Correlation Coefficient Method is to demonstrate the relationship between criteria C_i and C_j. This correlation can be represented using the following formula:

Equation 4-6: Correlation Coefficient Method

$$r_{ij} = \frac{cov(C_i, C_j)}{\delta_{C_i}\delta_{C_j}}$$

Where *cov* represents the covariance of C_i and C_j and δ is the standard deviation. If the result is equal to 1, then the criteria are interrelated to each other. These coefficients can form a matrix R_{nxn}. A partial correlation coefficient is included to better define the effect of other variable criteria on the selected ones. This partial correlation is represented as:

Equation 4-7: Partial Correlation

$$\xi_{ij} = \frac{-R_{ij}}{\sqrt{R_{ii}R_{jj}}}$$

R_{ij}, R_{ii} and R_{jj} complement r_{ij}, r_{ii} and r_{jj}, respectively in the matrix. The bigger the partial correlation coefficient, the more correlation between the criteria. If ξ_{ij} is equal to 1 then both C criterions are entirely correlated and thus one can be eliminated (Wang, 2009).

Once the criteria have been selected, the next step is to construct the evaluation matrix.

4.2.3 Construction of the evaluation matrix

At this stage in the analysis process, the problem has been defined, the objectives have been stated, the data has been collected, the stakeholders have been identified, the decision-makers have been selected, the alternatives are articulated, and the criteria are identified. The subsequent stage is to create an evaluation matrix. The construction of the evaluation, otherwise known as performance, matrix is a simple task: each row contains an option (or alternative) while each column contains the criterion (or attribute). The inside of the matrix is filled with the option's performance against the criterion. Table 4-2 below shows an example of a basic matrix. For this illustration, alternatives or options are denoted by the letter *A* while criteria or attributes are denoted with the letter *C* where X_{ij} represents the assessment of alternative *i*th regarding criteria *j*. In the example provided in Table 4-2, $X_{2\,1}$- highlighted below- represents the assessment of A_2 regarding C_1 (Dogson, 2009).

Table 4-2: Basic Matrix Template

	C_1	**C_2**	**…**	**C_n**
A_1	$X_{1\,1}$	$X_{1\,2}$	**…**	$X_{1\,n}$
A_2	$X_{2\,1}$	$X_{2\,2}$	**…**	$X_{2\,n}$
…	$X_{\dots\,1}$	$X_{\dots\,2}$	**…**	$X_{\dots\,n}$

$\mathbf{A}_m$	X_{m1}	X_{m2}	…	X_{mn}

The performances can be assessed in any various ways, including cardinal numbers, binary terms, qualitative terms and linguistic terms. (Dogson, 2009). Table 4-3 below provides an example of how the matrix would look like. The example compares various computer alternatives using linguistic terms as assessment (Grandhi & Wibowo, 2015). When non-numerical figures are used in any basic matrix, these should be transformed into uniform numerical values, as was mentioned when explaining the measurability principle of the criteria.

Table 4-4 below uses the same principle as Table 4-3 but with numerical values instead.

Table 4-3: Example of Assessment Using Linguistic Terms

	Weight	**Price**	**Hardware**	**Software Compatibility**
Dell	VG	F	G	VG
Asus	G	F	MP	G
Mac	G	G	F	G
Lenovo	G	F	MP	F

Where:

Linguistic Term	**Definition**
VP	Very Poor
P	Poor
MP	Moderately poor
F	Fair
MG	Moderately good
G	Good
VG	Very Good

Table 4-4: Example of Assessment Using Numerical Values Instead of Linguistic Terms

	Weight	**Price**	**Hardware**	**Software Compatibility**
Dell	0	3	5	6
Asus	5	3	2	5
Mac	5	5	3	5
Lenovo	5	3	2	3

Where:

Linguistic Term	Definition	Numerical Equivalency
VP	Very Poor	0
P	Poor	1
MP	Moderately poor	2
F	Fair	3
MG	Moderately good	4
G	Good	5
VG	Very Good	6

As an additional for who will receive the explanation, the user or the person preparing the matrix, could complement it with graphs and/or any other type of visual representation. Visual representations help in better analysing the data, as it puts together different pieces and provides an overall view, which help identify any information missing, wrong or duplicated. (Dogson, 2009)

4.2.4 Assign weight to the criteria

Once the matrix is constructed, the next step is to determine the weight each criterion will be given. The inclusion of weights in a matrix is shown in

Figure 4-4, where W_j is the weight given to criterion j (e.g W_2 is the weight given to criterion 2) (Dogson, 2009). The purpose behind assigning weight to the criteria or attributes is to show how important each criterion is for the DM and to give precedence to that specific criterion vis-à-vis the intermediate and high-level objectives. Three subjects should be considered when assigning weight: the independency of the criterion, the variance degree and the subjective preference of the DM. The independency of the criterion was reviewed during the explanation of the principles for selecting criteria, whereas the variance degree measures how much the decision-maker is willing to accept a change or trade-off in a specific criterion and the subjective preference of the DM refers to the likes and dislikes of the DM (Wang, 2009) (Niekamp, 2015).

Figure 4-4: Basic Matrix with Weights

	C_1	**C_2**	**…**	**C_n**
	W_1	***W_2***	**…**	***W_n***
A_1	$X_{1\,1}$	$X_{1\,2}$	**…**	$X_{1\,n}$
A_2	$X_{2\,1}$	$X_{2\,2}$	**…**	$X_{2\,n}$
…	$X_{3\,1}$	$X_{3\,2}$	**…**	$X_{3\,n}$

A*m*	X_{m1}	X_{m2}	**…**	X_{mn}

Continuing with the example of the purchase of the computer used in

Table 4-4 above, Table 4-5 below illustrates how the matrix would be composed with the inclusion of the weights.

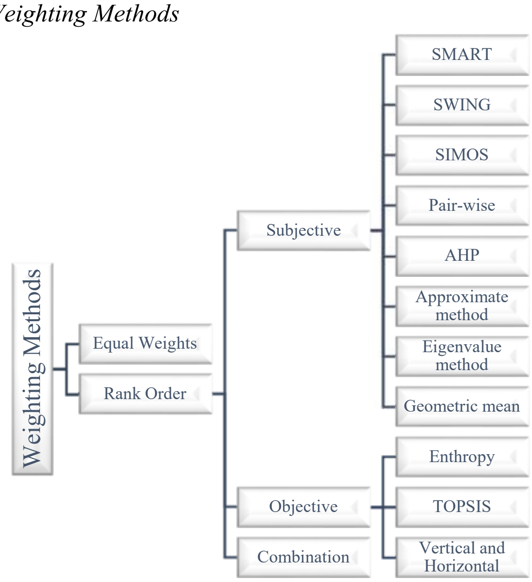
Table 4-5: Assessment Including Numerical Values and Weights

	Weight	**Price**	**Hardware**	**Software Compatibility**
	5%	**35%**	**20%**	**40%**
Dell	0	3	5	6
Asus	5	3	2	5
Mac	5	5	3	5
Lenovo	5	3	2	3

Whether they are called weights or priorities, determining the importance of the criteria in the eyes of the DM is of extreme importance for all MCA methods. There are several methods for eliciting these weights, but they mostly fall into one of these two categories: equal weights or rank order. Within rank order, the methods can be further divided into subjective and objective.

Figure 4-1 below provides an illustration of these categories for easier reference. For the subjective method, the DM is the one that assigns the weights while for the objective method the weight is determined by using the given data (Niekamp, 2015) (Wang, 2009).

Figure 4-5: Categories of Weighting Methods



4.2.4.1 Equal Weights

The equal weights method is the most popular method for situations dealing with sustainability issues in energy as it does not require knowledge of the preferences of the decision-maker. The concept of equal weights was implemented after it was argued that the results provided by this method are as good as those provided with the use of more advanced methods (Wang, 2009). The formula is:

Equation 4-8: Equal Weight Formula

$$W_i = \frac{1}{n}$$

Where w_i is the weight of criterion i, and n is the total number of criteria. This category requires the least input (Niekamp, 2015).

4.2.4.2 Rank Order

The Rank Order Weight Method was proposed as an answer to the criticism to the equal weights method in that it did not take into consideration the importance of one criterion against another for the DM. Under this category, the criteria are organized in consecutive order as follows:

$$w_1 \geq w_2 \geq \ldots \geq w_n \geq 0$$

where the sum of all criteria weight equals 1. This category is further subdivided into subjective, objective, and combination methods. The methods explained do not represent an exhaustive list of methods that can be used to elicit weights from the decision-maker. These methods were selected as they are commonly referenced in the literature (Wang, 2009).

4.2.4.2.1 Subjective Methods

The weight elicited utilizing these methods is only determined by the preference of the DM, not by the quantitative measure of the data. With these methods, the evaluation process is explained in simple terms for the non-math expert (Wang, 2009).

4.2.4.2.1.1 Simple Multi-Attribute Rating Technique (SMART)

Developed in 1977, the SMART method request that the participants rank the importance of the changes in the criteria from worst to best. The least important criteria receive 10 points. As the criteria becomes more important, a higher value is assigned without a cap on the value. The sum of the points is then normalized to sum up to an overall value of 1. This technique was developed for both assigning weight to the criteria and to assess the performance of the alternatives (Wang, 2009).

4.2.4.2.1.2 SWING

The SWING method is an 'algebraic, decomposed, direct procedure' in which the decision-maker is asked to choose the criteria he or she would most fancy to change and rank it from worst to best. The first most desirable improvement for a criterion is given a value of 100. The second most desirable improvement is given a value lesser than 100 and so on until all the criteria is ranked. Once all the criteria are ranked, the values are normalized to add up to 1 (Wang, 2009).

4.2.4.2.1.3 SIMOS

The SIMOS technique consists on associating each criterion with a 'playing card'. First, the decision-maker is asked to rank these criteria—represented by the coloured playing card—from least important to most important, thus the first criterion on the list will be the least important one. If two or more criteria are considered of the same importance, they are placed in the same rank. Then, the participant is given a white set of cards and asked to place these cards between two successive coloured cards. The white cards symbolize the difference in importance between the criteria represented by the coloured cards. If no white cards are placed between the colour cards, it means that the weight of these criteria will be represented by the unit that measures the interval (Figueira and Roy (2002) (Wang, 2009).

To illustrate, let's say criteria family *F* is composed of 5 criteria [C_1, C_2, C_3, C_4 and C_5]. Example 4-1 shows how these criteria could be ranked, the first criterion being the least important and the last being the most important.

Example 4-1: SIMOS- Ranking of the Subsets

Ranking	**Criteria**
1	C_3
2	C_1, C_2
3	White Card
4	C_4, C_5

The second step is that each criterion and white card are given a position, the least qualified one receiving the first position. This is called the weight.

Example 4-2: SIMOS-Weight

Ranking	**Criteria**	**Weight (w)**
1	C_3	1
2	C_1, C_2	2,3
3	White Card	4
4	C_4, C_5	5,6

The third step is to find the average weight. This is found by adding the positions in the rank and then dividing them by the number of cards. In Example 4-3, for Ranking 2 the formula is: (2+3)/2, for the average weight result of 2.5.

Example 4-3: SIMOS- Average Weight

Ranking	**Criteria**	**Weight (w)**	**Number of Cards**	**Average Weight**
1	C_3	1	1	1
2	C_1, C_2	2,3	2	2.5
3	White Card	4	1	4
4	C_4, C_5	5,6	2	5.5

The fourth step is to find the relative weight. This is found by dividing the average weight of the rank by the total sum of the weight. In Example 4-4, the formula of the relative weight for Ranking 4 is (5.5/17), for the result of 0.32 or 32%.

Example 4-4: SIMOS- Relative Weight

Ranking	**Criteria**	**Weight (w)**	**Number of Cards**	**Average Weight**	**Relative Weight**
1	C_3	1	1	1	6%
2	C_1,C_2	2,3	2	2.5	15%
3	White Card	4	1	4	
4	C_4, C_5	5,6	2	5.5	32%

17

These results can be confirmed by multiplying the relative weight of each ranking by its number of cards and adding up the totals, which result should be equal to 1 (Wang, 2009) (Figueira & Roy, 2002).

4.2.4.2.1.4 Pair-Wise Comparison

With this technique, participants are asked to compare two criteria at a time and state which one is more important and by how much more. The importance is then scored using any kind of scale, although a scale of 0-3, where 0 represents equal importance and 3 represents 'absolutely more important' is often used. The scores are then added up and normalized to 1. The benefit of this method is that it allows for each criterion to be compared against all others. Conversely, it does not include a mechanism in which to check for consistency in the preference selection. This revision must be done independently (Wang, 2009).

4.2.4.2.1.5 AHP

What is used from the AHP method, which was previously explained in Chapter 3, for weighting the criteria is the concept of the scale. Criteria are compared pair-wise, similar to the pair-wise comparison explained in the section above, with the difference that, instead of using any kind of scale, the Saaty scale is specifically used to obtain numerical values that represent the participant's preference of the criteria. To obtain the mathematical result, any other method, such as the geometric mean or the arithmetic mean, can be used. This technique, similar to pair-wise comparison in that it does not include a consistency check, which also could be performed independently (Wang, 2009).

4.2.4.2.1.6 Approximate Method

The approximate method is an easy method to use to obtain the weight of the criteria as it only requires the sum and average of the values given. In this method, the first step is for the DM to compare the criteria pairwise, assigning a value that shows each criterion´s importance to him or her. The values given are then used to populate a matrix that compares all criteria. The second step is to sum the elements of each row, which formula is shown in Equation 4-9. The third step is to normalize the sums obtained in step 2. The formula is shown in Equation 4-10 below. The disadvantage of this method is that it does not calculate for consistency of the matrices (Ishizaka, 2013).

Equation 4-9: Approximate Method: Summation of the Elements

$$r_i = \sum_i a_{ij}.$$

Equation 4-10: Approximate Method: Normalization of the Sums

$$pi = \frac{r_i}{\sum_i r_i}.$$

To illustrate this method, we will use the computer purchasing. The criteria which will help decide which computer to buy are: weight, price, hardware and software compatibility. Example 4-5 below shows the DM´s pairwise preference in regards to these criteria, as well as the results of the calculations from Equation 4-9 and aboveEquation 4-10 above.

Example 4-5: Weight: Approximate Method

	Weight	Price	Hardware	Software Compatibility	Sum of Element	Normalization of the Sums
Weight	1	4	6	7	18.00	0.57
Price	1/4	1	3	4	8.25	0.26
Hardware	1/6	1/3	1	2	3.50	0.11
Software Compatibility	1/7	1/4	1/2	1	1.89	0.06
					31.64	1.00

4.2.4.2.1.7 Eigenvalue Method

In addition to the priorities, the eigenvalue method provides an inconsistency degree. With this method, the priorities are obtained by calculating the product of the array composed of the evaluation matrix. The formula representation of the eigenvalue method is:

Equation 4-11: Weight-Eigenvalue Method

$$\mathbf{Ap} = n\mathbf{p}$$

where *p* represents the priorities, *A* is the matrix and *n* is the dimension. The first step is to multiply the matrix by itself, with the results presented in another matrix (Ishizaka, 2013). In this new matrix, the elements are added and normalized to obtain the priority. Using the same values as Example 4-5,

Example 4-6 below illustrates the results using the eigenvalue method.

Example 4-6: Weight-Eigenvalue Method

	Weight	Price	Hardware	Software Compatibility
Weight	1	4	6	7
Price	1/4	1	3	4
Hardware	1/6	1/3	1	2
Software Compatibility	1/7	1/4	1/2	1

	Weight	Price	Hardware	Software Compatibility	Sum of the Elements	Normalization
Weight	4.00	11.75	27.50	42.00	85.25	0.62
Price	1.57	4.00	9.50	15.75	30.82	0.22
Hardware	0.70	1.83	4.00	6.50	13.04	0.09
Software Compatibility	0.43	1.24	2.61	4.00	8.28	0.06
					137.38	1.00

4.2.4.2.1.8 Geometric mean

The geometric mean is also known as the logarithmic least square method, which is a form of regression in which the user tries to minimize or control the sum of the square of the residuals obtained from previous equations ((Ishizaka & Nemery, 2013) The formula is shown in Equation 4-12 below.

Equation 4-12: Geometric Mean

$$p_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}},$$

An advantage of the geometric mean is that it does not require computer software to be calculated, instead the results can be found by hand. The results of the multiplication of either the columns or the rows will provide the same ranking in inverse order, meaning that what was first under row multiplication will be last under column multiplication. ((Ishizaka & Nemery, 2013). Using the same example as above, the ranking of the criteria is provided in Example 4-7 using the geometric mean method.

Example 4-7: Geometric Mean

	Weight	**Price**	**Hardware**	**Software Compatibility**	**Geometric Mean**
Weight	1	4	6	7	**3.60020574**
Price	1/4	1	3	4	**1.31607401**
Hardware	1/6	1/3	1	2	**0.57735027**
Software Compatibility	1/7	1/4	1/2	1	**0.36555522**
Geometric Mean	**0.277761903**	**0.759835686**	**1.732050808**	**2.7355648**	

0.277761903	Weight	0.365555223	Software
0.759835686	Price	0.577350269	Hardware
1.732050808	Hardware	1.316074013	Price
2.7355648	Software	3.600205744	Weight

4.2.4.2.2 Objective Methods

With objective methods, the weights are obtained by analysing the data using mathematics. These techniques evoke the criteria weights by utilizing the estimation information and data, and mirrors the difference degree (Wang, 2009). Some examples of these methods are provided below.

4.2.4.2.2.1 Entropy Method

This method shows how well the criteria reflects the information gathered for the analysis. It also illustrates the degree of uncertainty of the criteria. The entropy method entails three phases: calculation of the vector, contrast intensity and normalize the weight. The formulas for the Entropy Method are shown below (Wang, 2009).

Equation 4-13: Entropy Method Formulas

$$X_j = \sum_{i=1}^{m} x_{ij}, j = 1,2,\ldots,n$$ Calculation of the Vector

$$e_j = -\frac{1}{\ln m}\sum_{i=1}^{m} \frac{d_{ij}}{D_j}\ln\frac{d_{ij}}{D_j}$$ Contrast Intensity

$$w_j = \frac{1-e_j}{\sum_{j=1}^{n}(1-e_j)}$$ Weight normalization

4.2.4.2.2.2 Technique for Order Preference by Similarity to Ideal Solution Method (TOPSIS)

The TOPSIS method "is that the selected best alternative should have the shortest distance from the positive ideal solution in geometrical sense" The weighted distance and optimal model formulas are shown below (Wang, 2009).

Equation 4-14: TOPSIS Formulas

$$h_i = \sum_{j=1}^{n} w_j^2 (x_{ij} - x_j^*)^2$$ *Weighted distance*

$$\left.\begin{aligned} &\min \sum_{i=1}^{m} h_i = \sum_{i=1}^{m}\sum_{j=1}^{n} w_j^2 (x_{ij} - x_j^*)^2 \\ &s.t. \sum_{j=1}^{n} w_j = 1, w_j \geq 0 \end{aligned}\right\}$$ Optimal model

4.2.4.2.2.3 Vertical and Horizontal Method

Similar to the TOPSIS method explained above, the vertical and horizontal method also calculates the weight of the criteria by mirroring, as possible, the difference in the alternative´s performance. In other words, the weight of the criteria is found when evaluating the alternatives against the ideal alternative. In contrast, LMS, minmax deviation and entropy use the difference of alternatives when compared to a criterion in order to find the criteria´s importance. The formula for the vertical and horizontal method is shown in Equation 4-15 below.

Equation 4-15: Vertical and Horizontal Method Formula

$$\left.\begin{array}{l}\max s_z^2 = \sum_{i=1}^{m} (z_i - \bar{z})^2/m \\ s.t.\ \sum_{j=1}^{n} w_j^2 = 1, w_j \geq 0\end{array}\right\}$$

where $z_i = \sum_{j=1}^{n} w_j x_{ij}$ and $\bar{z} = (1/m) \sum_{i=1}^{m} z_i$.

4.2.4.2.3 Combination Method

The combination method uses the DM´s preferences with mathematical analysis of the data to elicit the criteria weights. The mathematical analysis includes a multiplication and an additive synthesis, see Equation 4-16.

Equation 4-16: Combination Weighting Methods

$$w_j = \frac{w_{1j} w_{2j}}{\sum_{j-1}^{n} w_{1j} w_{2j}}$$

Multiplication synthesis

$$w_j = k w_{1j} + (1-k) w_{2j}$$

Additive synthesis

Where w_{1j} is the subjective weight, w_{2j}, is the objective weight, w_j is the combination weight and k is the linear combination coefficient greater than 0. The value k can be found using different methods, for example, optimization based on sum of squares, relational coefficient of gradation or minimum bias (Wang, 2009).

4.2.5 Selecting the Appropriate Method

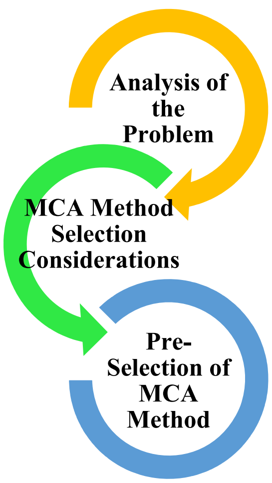
The social phase of building a model dealt with selecting the key players and the stakeholders, which was primarily done in step one: defining or structuring the problem. The selection of the appropriate method, however, is the technical aspect of the design. No single MCDA method is the best for all possible situations, as each technique provides a different point of view to the problem at hand (Polatidis et al, 2006) (Dogson, 2009).

It is important to determine what it is the user is looking for in a method in order to select the correct one. The first issue that should be considered when choosing an MCA technique is the number of alternatives to be examined. From a policy point of view, the choices may be plenty or few, but they are limited. This is important because there are techniques designed to be used with infinite choices, such as multi objective methods, thus allowing the DM to automatically discard the use of these techniques for the decision analysis. The simplicity or complexity of the method selected will be affected by the number of criteria or attributes used (Dogson, 2009).

Usually the selection of a MCDA method relies on familiarity with the method rather than the appropriateness of it in relation to the problem. This, in turn, causes that the problem be structured around the methodology to be used, instead of the methodology being structured around the pre-defined problem. As a way to avoid this, it is best for the user to be familiarized with some of the MCA methods, and with their possible applications, beforehand in order to identify the suitable techniques that would be able to provide the guidance sought. The advantage of a user being familiarized with various MCA methods is the knowledge that each method provides different points of view for the same problem. Accordingly, the results obtained from several evaluations executed from different points of view helps to validate the results prior to the last stage of ranking of the alternatives. Thus, assessing the performance of the alternatives in a decision analysis situation with the help of several MCA methods is, in itself, a way to check for consistency in the results (Guitouni, 1998) (Kurka, 2013).

Because there are several MCA methods that could be applied to different decision analysis situations, it is desirable to use a logical approach for the selection of the techniques that will aid in the decision analysis process. Nonetheless, the challenge is to not fall into the cycle of using an MCA techniques or MCA related techniques to select an MCA method. For instance, the use of pairwise comparison, which is an element of the AHP technique, to evaluate the different methods, although in itself not a method, would be counterproductive for the method selection phase. Although there are no formal parameters on how to select suitable MCA methods, some recommendations have been published in scholarly articles. Figure 4-6 below exemplifies the interaction of the assorted stages to provide for a sensible methodology for the selection of an MCA method. This methodology is divided in the following stages: analysis of the problem, MCA method consideration and pre-selection of MCA method (Guitouni, 1998) (Kurka, 2013).

Figure 4-6: Proposed approach for the selection of an MCA method



4.2.5.1 Analysis of the Problem

As described in the previous sub-sections of this chapter, the decision analysis situation or problem has to be structured and clearly defined in order to commence the evaluation. The problem is considered to be structured and clearly defined when the objectives are established, the stakeholders have been identified, the decision-makers have been selected from the stakeholder group, all the required data has been collected, the possible alternatives have been determined, the criteria has been selected and its weight assigned, and the urgency of the decision has been taken into consideration. The full comprehension of the problem is necessary prior to the section of the method in order to better evaluate suitable MCA methods in regards to the needs of the DM.

4.2.5.2 MCA Method Selection Considerations

Based on various guidelines found in the literature regarding the selection of MCA methods, the following list of considerations was gathered. It includes issues that should be addressed when selecting MCA methods. The facility to view the answer to these considerations are will be related to the degree on which the decision analysis situation is understood.

Table 4-6: MCA Method selection consideration
s

1.	How many DMs involved? This will determine whether a group MCA method should be applied or a method more focused towards a single DM.
2.	Are all appropriate stakeholders engaged? How much is their involvement? At which point do they become involved, at the modelling of the preferences, after modelling the preferences by answering a pre-determined set of questions? The success of a project may be affected if stakeholders are not aptly engaged in the process.
3.	How does the DM prefer to have the data presented? This will help in deciding whether, for example, a pairwise comparison approach is better than a tradeoff approach.
4.	What kind of result is the DM looking for? For example, is the DM is looking to have the different alternatives ranked?
5.	Look for methods for which the data needed is easily obtainable and which can process the data properly. The data should be effortlessly produced by the stakeholders. If qualitative data is used, and the MCA method is unable to integrate it, the quality of the result will be affected.
6.	Is the DM looking for compensations? If not, the methods that include any amount of compensations can be discarded.
7.	The method must meet its central assumption.
8.	Consider the software or decision aid package that may be required for the method, looking for ease of use.
9.	Can the method support many alternatives and criteria?
10.	How does the model quantify the importance of the criteria or their weights? MCA models differ in weighting the criteria. For example, the use of hierarchies can ease the transmission of the results and strategies without the need to dominate technical knowledge.
11.	How does the model deal with uncertainty? If uncertainty is not addressed sufficiently, it could lead to the selection of inappropriate alternatives, which in turn may yield results that are not sustainable. One way in which to include uncertainty is by creating scenarios rather than including them in any model particularly. Another way in which to include uncertainty is by using stochastic distributions or intervals.
12.	Can the decision be re-evaluated using new data? Can it provide an audit trail? Are the results consistent and logically sound?
13.	Is the model transparent and easy to explain? How much time and manpower is required? Can it be updated and adjusted?

(Guitouni, 1998 p. 512) (Kurka, 2013 p. 228) (Polatidis, 2006, p. 189) (Dogson, 2009)

4.2.5.3 Pre-selection of MCA methods

It has been proposed that the user perform a literature review to find MCA methods that have been previously used for similar decision analysis situations in order to pre-select potential MCA methods. In addition to the literature review, several principles for method selection have been offered (Kurka, 2013) (Polatidis, 2006) Various of these principles are expressed in Table 4-7 below.

Table 4-7: Principles to Select an Appropriate MCA Method

Pre-requisites	Justification
Weights	Provides the preference between the evaluation criteria
Threshold values (preference, indifference, veto)	Expresses the ability of the environment to carry waste material without adverse effect on environmental, economic, resource and social base.

Comparability	The easier the comparison, the more reasoned the outcome.
Measurability	Ability to handle both qualitative and quantitative data while keeping the original unit.
Rigidity	To give robust results
Various DM	Includes diverse stakeholders
Easiness of use	Makes it easier for the DM to understand the process and justify the result.
Sensitivity Analysis	Enhances the process ‘transparency
Various alternatives	Tries to incorporate all possible courses of action.
Various criteria	Incorporates different points of view
Consensus seeking	Aids in reaching a compromise between the different points of view.
Intangible and uncertain aspects are included	Takes into account hidden aspects/uncertainties as well as imperfect data.
Compensation	Takes into consideration the degree of compensation the DM is willing to accept.
Temporal aspects	Clarify long and short-term concerns

(Polatidis 2006)

4.2.6 Analysis and Ranking of the Alternatives

Once the method is selected and the calculations performed, the results obtained are then scored and ranked. In the ranking, the most suitable alternative, according to the results, is ranked first, and the least suitable alternative is ranked last. Usually the scales used for ranking can extend from 0 (least preferred) to 100 (most preferred). (Dogson, 2009)

Example 4-8: Analysis and RankingExample 4-8 below shows the result of the computer example. The *Total* column provides the results obtained from multiplying alternative *n*th´s assessment against criteria *i* by the weight elicited for said criteria. These products are then added to obtain the ranking of the alternatives.

Example 4-8: Analysis and Ranking

	Weight	**Price**	**Hardware**	**Software Compatibility**	**Total**	**Ranking**
	5%	**35%**	**20%**	**40%**	**1**	
Dell	0	3	5	6	4.5	2
Asus	5	3	2	5	3.7	3
Mac	5	5	3	5	4.6	1
Lenovo	5	3	2	3	2.9	4

In this example, Alternative 3 (Mac) obtained the highest result and thus ranked the highest, followed by Dell, Asus and Lenovo, respectively. It is usually the case that economics or cost criteria carry the most weight compared to other elements. A way to avoid the analysis being heavily economic influenced is to have the economic or cost criterion discarded during this stage of the assessment as to allow for a fairer comparison between other criteria. Once the other criteria are evaluated in their merits, the weighted assessment can then be contrasted with the costs in a cost-benefit analysis (Dogson, 2009). When the price criterion is given a weight of 0, and the numbers are recalculated, Alternative 1, Dell, is the highest ranked as illustrated in Example 4-9 below.

Example 4-9: Results Recalculated after Eliminated Economic Criterion Weight

	Weight	**Price**	**Hardware**	**Software Compatibility**	**Total**	**Ranking**
	5%	**0%**	**20%**	**40%**	**65%**	
Dell	0	3	5	6	3.4	1
Asus	5	3	2	5	2.65	3
Mac	5	5	3	5	2.85	2
Lenovo	5	3	2	3	1.85	4

A separate analysis can be performed using only prices. The results of that analysis can be combined with the results obtained from Example 4-9 to obtain an even sturdier result, as this analysis can be used to rationalize whether any extra benefit that would be obtained as calculated using the MCDA method is worth an extra cost for the computer equipment, if that were the case (Dogson, 2009).

4.2.7 Sensitivity Analysis and Recommendations

Once the data has been analysed and the alternatives ranked, recommendations are then presented to the decision-maker or makers. In a sensitivity evaluation, small changes are included in the input to find how they affect the final result. These changes in input may include, for instance, changes in the criteria, changes in the criteria weight, changes in the alternatives or changes in the decision-maker´s weights. The purpose of the sensitivity analysis is to provide the decision-makers with different scenarios, not necessarily having been considered by them, that show different impacts to the same decision situation (Haralambopopulous, 2003).

4.3 Conclusion

The purpose of this chapter was to provide a detailed explanation of each step of the general multi-criteria decision analysis framework. The steps discussed included: i) defining and structuring the problem, ii) generating alternatives and selecting criteria, iii) construction of the evaluation matrix, iv) assigning weights to the criteria, v) selection of the appropriate method, vi) analysis and ranking of the results and vii) sensitivity analysis and recommendations. In order to define the problem, the user has to determine the objectives, collect the necessary data, identify the stakeholders and the key players, and select the decision-makers from within the pool of stakeholders. Objectives can be high level, such as those published in government communications, or intermediate objectives, which are associated with the turnout of a policy or programme. The stakeholders are those who have either a legitimate responsibility and/or an interest in the consequences of the decision. Key players are those individuals who participate in the decision analysis process, who can make important and fruitful contributions and who represent the stakeholders. If more than one decision-maker is selected, then their preferences have to be combined to obtain a logical result. Various approaches have been developed to obtain a certain level of agreement. One such approach is based on majority, which, although is the easiest of all approaches, can also be time consuming and does not provide to include for any imprecisions or subjectivity of the DMs. Another technique to obtain group agreement is the ranking-based approach. This approach requires individual DMs or stakeholders to rank the criteria in order of importance and to rank the evaluation of the alternatives or options. While the approach works under specific circumstances and is easy to use, it also requires much reasoning and rationalization by the DM. A fourth approach is the consensus-based. It is a more interactive process which, although practical, requires plenty of mathematical computations; it helps in reducing conflict among the DMs, has more participation and enhances the acceptance of the outcome. Other mathematical techniques that can be used to obtain a combined result include the aggregating individual judgement and the aggregating individual priorities techniques.

No formal technique has been conveyed to specifically select alternatives for MCA methods. Instead ordinary planning methods such as SWOT or PEST analysis can be used to aid in generating alternatives. The same situation happens for the selection of criteria. Although no official technique is used, principles and mathematical methods have been proposed and used to aid in its selection. Some of the mathematical methods include Delphi method, LMS, minmax deviation and the correlation coefficient. Once these inputs are gathered, the matrix can be constructed. In the matrix, the criteria are ordered in columns while the alternatives are ordered in rows. The matrix will represent the assessment of each alternative against each criterion. The assessment can be performed using linguistic terms or numerical values. If linguistic terms are used, particularly with qualitative data, they will later need to be converted into numerical values. This can be done using the Saaty scale, for instance.

Assigning weight to the criteria may be the most consuming step of the decision analysis process. Similarly to the selection of alternatives or the combining of the preferences of the decision-makers, there is no prescribed technique for eliciting criteria weight specifically designed for multi-criteria decision analysis methods. Scholarly literature proposes various techniques to elicit weight including majority, ranking-based, consensus-based- same as for combining the preference of various decision-makers- equal weights, SMART, SWING SIMOS, pair-wise comparison, AHP, approximate method, eigenvalue method, geometric mean, entropy method, TOPSIS, vertical and horizonal method and combination methods. Once the criteria have been assigned their weight, the next step is to select the appropriate method or methods to be used to perform the analysis. There is no set manner in which to select the appropriate method. Instead, the selection of the method is usually done by how familiar the user is with the specific method or how easy it is to understand the results provided by the method. A rational approach that has been proposed to select a suitable method takes into consideration analysing the problem, considerations to be reflected upon and pre-selection of potential methods. Amongst the considerations to be pondered are the number of decision-makers involved, the engagement of the stakeholders, the manner in which the data will be presented, the manner in which the results will be presented, the central assumptions, how well the method supports the alternatives and the criteria, the ability to re-evaluate the data, and the time and manpower required to perform the analysis. The pre-selection of the MCA method can be supported by researching the literature to find which MCA methods have been used for similar decision analysis situations.

Once the method has been selected, the analysis is performed, meaning that the calculations required according to the method are performed, the results are ranked from best option to worst and presented to the DM. The result of the analysis is not to provide the correct or best answer, but rather to present the assessment of all the alternatives to the decision-maker. Usually the cost or economic factor carries bigger weight than other criteria. As such, a separate analysis can be performed taking only into consideration economic criteria, such as cost-benefit analysis, and this analysis can be combined with the multi-criteria analysis to obtain more robust results. A sensitivity analysis is the last step to be performed as either a consistency check or to present to the decision-maker different scenarios. These scenarios will correspond to changes made in the inputs, such as changes in the alternatives, in the criteria, in the weight of the criteria or in the weight of the decision-maker. The purpose of the sensitivity analysis is to provide more choices and a rounder evaluation to the decision-maker. In the next chapter, this thesis will use all the elements studied in this chapter to organize a multi-criteria decision analysis framework specifically design to deal with energy related decision analysis situations.

5 Decision Analysis Framework Specific for the Energy Industry: Introduction to McPAF

5.1 Introduction

The formalization of the decision-making process through decision analysis provides the means for how to channel the efforts towards achieving the desired goals. Within the spectrum of techniques and structures available to probe a situation, methods that involve more than one evaluation criteria, known as multi-criteria analysis methods, provide a more complete view by taking into consideration real world necessities and realities, such as how external and internal elements affect the issues that must be taken into consideration while deliberating on the decision to be made.

Even though the use of MCDA methods is helpful, it is not without pitfalls. A great challenge is how to select the different components that go into an MCDA model: problem, objectives, data to be collected, stakeholders, key players, decision-makers, criteria, alternatives, methods, and weights. Chapters 3 and 4 provided background on both decision analysis and MCDA; this background study was key to pinpoint and understand the challenges faced when using MCDA methods, how they can be resolved, and what would be needed to produce a decision analysis approach customized for the energy field that included a resolution to these challenges. The resulting approach, or framework, is proposed in this Chapter.

This framework, the Multi-criteria Preference Aggregation Framework (McPAF), which addresses the challenges mentioned above, is based on a concept of having various alternatives, several criteria and at least four decision-makers whose preferences are combined to obtain group weight for the criteria. It also provides for the consideration, although minimal, of fuzzy inputs or degrees of inclusion to an element through the use of the SIMOS method for eliciting weight.

The chapter' structure constitutes a system of explanation and illustrations. The illustrations, which are referenced as “Exhibits”, are templates to be used for the method. Each of the steps discussed in Chapter 4 is discussed within; the emphasis provided in this Chapter, however, is how to solve the challenges that were introduced in the previous one.

The framework was purposely created to be very visual, and each step has a corresponding template. The reason for the emphasis on visual representation is because this framework considers that the aim of the analysis is to be able to provide clear explanations as to the decisions made, and thus will need to clearly and transparently explain the analysis process and the results. In McPAF, the term "user" means the individuals who are pursuing the analysis of the decision situation. These individuals may not necessarily be decision-makers, stakeholders or key players.

5.2 SPECIFIC FRAMEWORK

5.2.1 Defining/Structuring the Problem

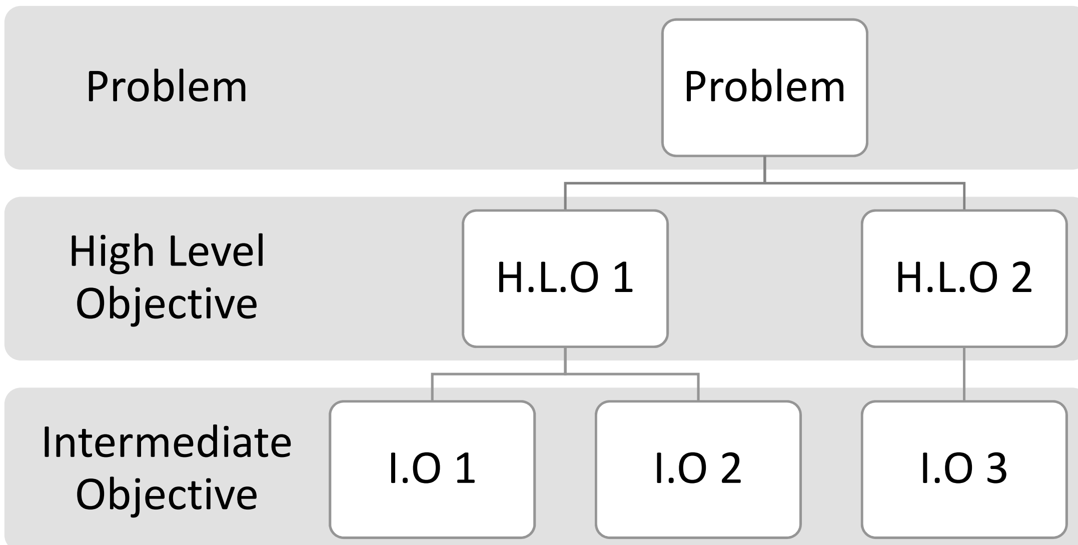
The phases to structuring the problem are: determining the objectives, data collection, identifying the stakeholders and determining who will be the decision-makers. To confirm that the problem has been comprehensively defined in McPAF the problem will be stated in the form of a question. This question will be a guide towards the rest of the analysis process, as it will be a written reference point for each further phase or step in the process. After classifying and categorizing the objectives according to preference, the user must be able to communicate the problem in this form.

5.2.1.1 Determine the Objectives

As previously discussed, the first step is to determine the objectives, which must be short assertions that summarize what the decision-maker is trying to achieve in the situation. Furthermore, these objectives must be organized hierarchically: first stating the high-level objectives, followed by intermediate level objectives. The high-level objectives are identified from national publications, such as government manifestos, and ranked in order of priority according to the local legal system. This means, for example, that objectives established under international treaties have precedence over objectives established at the community level. The most common structure would be objectives set under international agreements, objectives set by the central government then objectives set by the local government.

After the high-level objectives are identified, the user must undergo the same identification process for the intermediate level objectives. Once again, the user must follow the legal order of priority in place. The interrelation between the problem, the high-level objectives and the intermediate objectives is tested out via Exhibit 5-1 below, where these various elements are combined to make sure they are consistent.

Exhibit 5-1: Interrelation between Problem and Objectives



Commencing the decision analysis process by looking at the government's policy may seem like an obvious step that does not require further explanation. However, the hierarchical structure of this step needs to be emphasized as, throughout the development of the decision analysis process, the reason for the analysis may change or the focus could be lost. By having a solid and visual starting point, the user can easily refer to it and make any necessary corrections to stay on course, if need be. Then again, if during the analysis process the objectives change, the process would require a fresh start in order to direct the efforts towards achieving these new goals.

5.2.2 Data Collection

Once the policy objectives have been categorized, the next step is to collect the data that will support decisions aimed towards fulfilling those goals. The user should keep in mind that data gathering is a very time-consuming task. As a manner in which this task may be facilitated, the user can begin the information gathering process by concentrating first in obtaining information related to the Main Criteria for the Basic Cluster.

The literature reviewed associated with decision analysis in energy planning identified four main criteria and various sub-criteria that are commonly used for the evaluation of possible decisions. The four "Main Criteria" are technical, environment, economic and social (TEES). Within each of these four criteria some sub-criteria have been identified as been commonly used when utilizing a MCDA method. These sub-criteria include emissions, social acceptability, cost and efficiency (Berke & Conroy, 2000) (San Cristobal) (Wang, 2009).

Moreover, besides representing criteria, TEES also represent the minimum points of view to be considered in the analysis. As TEES represents the points of view, it will be used in the selection of the DMs. Although not a comprehensive list, Table 5-1 below records some of the sub-criteria in each TEES category. This table is to be used as a starting point for the data gathering phase.

Table 5-1: Main Criteria and Sub-criteria used in Decision Analysis for Energy Planning

Technical	**Environment**	**Economic**	**Social**
Efficiency	CO_2 Emissions	CAPEX	Job creation
Exergy	NO_x Emissions	OPEX	Benefits
Primary Energy Ratio	Land use	Maintenance	Social Acceptability
Safety	Noise	Cost of fuel	
Reliability	Particles Emission	NPV	
Maturity	SO_2 Emissions	Payback period	

Haralambopopulous (2003), proposed three categories of information to be gathered: for the specific country, for the region, and industry specific. This framework will refer to these categories as the "Basic Cluster". For the purposes of McPAF, in addition to the sub-criteria included in Table 5-1 above, other information that can be collected for the regional and country categories includes energy demand and energy production, government and stakeholders' needs and preferences. For the industry category, additional information includes market, demand and supply, current and forecasted production, as well as viability of resources (Dogson, 2009) (Haralambopopulous, 2003).

The pronouncement as to the industries to be considered, following the Basic Cluster, will be motivated by the conveyed problem and objectives. The pronouncement can be general, such as gathering information on renewable energy technologies or conventional fuels without further specification, or it can be more detailed; for instance, the user may gather information on solar photovoltaic technologies or biomass technologies.

The data gathered must be current, as out of date data could compromise the analysis, while taking into consideration that the decision will involve long-term considerations and impacts. For this reason, trends and forecasts should be part of the data collected. McPAF uses a benchmark time frame of 25 to 30 years when considering elements such as demand, supply and economic factors. The basis for selecting this time frame is that 25 to 30 years is ample enough time to capture any noticeable foreseeable changes including changes in climate, population growth and future energy demand. Capturing foreseeable changes is particularly important if the country faces highly variable seasonal changes (Wimmler et al., 2015).

With the intention of keeping cohesiveness in the process, the information to be gathered for the Basic Cluster must refer to the intermediate level objectives. The reason being that the intermediate level objectives aim at fulfilling the high-level objectives, thus finding elements that aim at satisfying the intermediate level objectives will, in turn, help towards the realisation of the high-level objectives. Exhibit 5-2 below depicts the organizational table for gathering data. This table combines the intermediate level objectives, the Basic Cluster and the sub-criteria previously explained. The purpose is for the user to double check that information has been gathered for all 4 Main Criteria. The diagram directs the information to be gathered for each of the elements of the Basic Cluster- country, region and industry- according to the intermediate level objective. Due to the different nature of the data that needs to be gather, it is left to the user to identify which data collection technique is the most appropriate according to their needs. In the case of social related data, for example, interviews and questionnaires may be more appropriate, but also more time consuming and require more personnel mobility. The varying needs of each user is the rationale why no particular data collection technique is recommended or insisted upon in McPAF.

Exhibit 5-2: Data to be Collected

	Intermediate Objective 1.1	***Intermediate Objective 1.2***	***Intermediate Objective 2.1***	***Intermediate Objective 2.2***
Country	Job creation Benefits Social Acceptability Emissions goal Environmental goals and policies Economic incentives	Job creation Benefits Social Acceptability Emissions goal Environmental goals and policies Economic incentives	Job creation Benefits Social Acceptability Emissions goal Environmental goals and policies Economic incentives	Job creation Benefits Social Acceptability Emissions goal Environmental goals and policies Economic incentives
Regional	Job creation Benefits Social Acceptability Environmental goals	Job creation Benefits Social Acceptability	Job creation Benefits Social Acceptability	Job creation Benefits Social Acceptability
Industry 1	Efficiency Exergy Primary Energy Ratio Safety Reliability Maturity Emissions Land Use Noise CAPEX/OPEX Maintenance NPV Payback Period	Efficiency Exergy Primary Energy Ratio Safety Reliability Maturity Emissions Land Use Noise CAPEX/OPEX Maintenance NPV Payback Period	Efficiency Exergy Primary Energy Ratio Safety Reliability Maturity Emissions Land Use Noise CAPEX/OPEX Maintenance NPV Payback Period	Efficiency Exergy Primary Energy Ratio Safety Reliability Maturity Emissions Land Use Noise CAPEX/OPEX Maintenance NPV Payback Period
Industry 2	Efficiency Exergy Primary Energy Ratio Safety Reliability Maturity	Efficiency Exergy Primary Energy Ratio Safety Reliability Maturity	Efficiency Exergy Primary Energy Ratio Safety Reliability Maturity	Efficiency Exergy Primary Energy Ratio Safety Reliability Maturity

5.2.3 Identify Stakeholders and Key Players

The accurate identification of stakeholders ensures that all major viewpoints and issues are considered during the analysis, while the use of key players increases the manageability of the analysis process. By having key players, the number of individuals involved in the decision analysis process is reduced. As defined in Section 4.2.1.3, a stakeholder is an individual who has legitimate responsibility and/or an interest in the consequences of the decisions, while a key player is an individual who represent one or more major points of view on the issues at hand, and who can also make important and fruitful contributions to the process. The shown in Exhibit 5-3 is a check list with the purpose of helping to identify these individuals. In the first column, the checklist uses the Basic Cluster and TEES, to visualize all the items that should be considered. In the next column the possible participant is identified, which could be done by name, position or any other manner which the user deems fit.

Exhibit 5-3: Stakeholder and Key Player Identification Checklist

Basic Cluster/ Point of view	Possible participants	Legitimate Responsibility?	Interest in the consequences?	Can provide a useful/significant contribution?	Represents one or more major points of view?
Country		□	□	□	□
Regional		□	□	□	□
Industry 1		□	□	□	□
		□	□	□	□
Industry 2		□	□	□	□
Point of View 1		□	□	□	□
		□	□	□	□
		□	□	□	□
Point of View 2					

Built from the concepts expressed by Haralambopopulous, (2003) and Dogson (2009), the stakeholder and key player identification table provides the user a way to determine whether the proposed participant is a stakeholder, a key player or none of the above. The table requires the user to answer, for each possible participant, whether this person has legitimate responsibility, an interest in the consequences, whether they can provide a useful/significant contribution and if they represent at least one of the main points of view. If the answer is in the affirmative for either or both legitimate responsibility and interest in the consequences, then the participant should be considered a stakeholder. If, for the participant, the question regarding significant contribution is an affirmative, then the participant classifies as a key player. The last question, regarding the representation of a main point of view, is a security check aimed as means in which the user can ensure that indeed all the main points of view, TEES, have been identified.

The way in which the checklist works is that, first, the user will identify possible participants that represent each of the categories of the Basic Cluster- country, region and industry. Then, the user will identify possible participants that may represent each of the main points of view, TEES. As previously explained, for energy planning decisions, the minimum points of view to be taken into consideration are technical, economic, environmental and social, so the user will need to identify a possible participant that will represent each of these four points of view.

In order to identify these possible participants, the user will associate the TEES element with the relevant government agency, ministry, public or private entity. For example, for the country level a first choice as a representative would be the political leader of the country. For the environment point of view, the first choice would be the director, minister, or similar public official, of the country's environmental agency, ministry or similar governmental body. To select a representative of the region, a high ranking regional official for any of the TEES, should be considered. Other participants that must be considered are community leaders, scholars and experts in any of the fields included in the main criteria. Each of these possible participants would have to go through the evaluation of whether they have legitimate responsibility, interest in the consequences, can provide a significant contribution and represents one or more major points of view.

5.2.4 Determining Who Will be the DMs

The decision-makers will be selected from the general stakeholder group identified in Exhibit 5-4 and should not share the same interests or points of view. The reason for this is to guarantee across-the-board standpoints. Taking into consideration the Main Criteria identified the minimum number of decision-makers should be equal to four, safeguarding that each represents one of the main points of view. Exhibit 5-4 provides a decision-maker identification table. This table is to be used to write the names the chosen decision-makers and the point of view they represent. This visualization has the purpose of ensuring that all points of view are covered.

Exhibit 5-4: DM Identification

Point of View/Representative	DM
1	DM 1
2	DM 2
3	DM 3
4	DM 4

A challenged faced in any decision-making situation is the hierarchy rank of the individuals involved. Some of the participants may be influenced by the opinions expressed by the highest-ranking member of the group. Although not all DMs have the same level of responsibility regarding the project or their position within the group, if all the decision-makers are given the same importance—weight-- in the decision analysis process, the process will concentrate on analysing the preference for the criteria rather than being skewed by the weight of the decision-maker. Taking this into consideration, all decision-makers will bear the same weight in this framework. Their weight will be displayed as 1 over the total number of decision-makers. The minimum weight to be reflected will be ¼, as there are 4 decision-makers.

5.3 GENERATING ALTERNATIVES AND ESTABLISHING CRITERIA

5.3.1 Alternatives

The number of alternatives and criteria to be considered need to be kept at a reasonable amount as to not complicate the analysis process. To attain a practical and functional amount, this framework uses a SWOT analysis to differentiate between superior and inferior options, as proposed by Dogson (2009). An alternative for the SWOT analysis could have been a PEST analysis. However, the reason the PEST analysis was not chosen is because this method allows for the inclusion of political, economic, social and technological factors. As these factors are the same as the Main Criteria that will be used to evaluate the alternatives under a multi-criteria decision analysis method, it is not sensible to use it to differentiate between alternatives. Their use would be repetitive; the same points of view would be reviewed instead of new ones. On the other hand, a SWOT analysis allows the focus of the exercise to be on any risks, chances, advantages and disadvantages. This provides a different perspective than PESTE. SWOT also has the advantage that it is a relatively simple and straightforward approach that should not be too time consuming for the user. Exhibit 5-5 below provides a SWOT analysis template to be used to conduct the analysis. The use of different colours for each of the four items to be evaluated is done purposely to aid in better identifying each of these elements when executing the evaluation. This is consistent with the visual approach of McPAF.

Exhibit 5-5: SWOT Analysis

Alternative 1

Strength	Weakness
Opportunities	Threats

Alternative 2

Strength	Weakness
Opportunities	Threats

Alternative 3

Strength	Weakness
Opportunities	Threats

Alternative 4

Strength	Weakness
Opportunities	Threats

5.3.2 Criteria

As explained in section 5.2.2 above, for energy planning decision situations the literature has identified four main clusters of criteria- economic, environment, technical and social- as well as some sub-criteria under each of the clusters. Although Table 5-1 is a good starting point it is not, however, an extensive list; more main criteria can and should be added, according to what the needs of the process may be. Still, all possible criteria, including that identified by the literature and summarized in Table 5-1, should be evaluated for its suitability. Exhibit 5-6 is a checklist for the principles of criteria selection explained in section 4.2.2 and was constructed following the concepts indicated by Dogson (2009) and Wang, et als (2003). As it was mentioned in Chapter 4, no mathematical methods are used in McPAF to help sort and select the criteria in order to keep the framework as simple as possible for the user and, thus, facilitate its application. Although a mathematical approach may, arguably, be more objective, the survey evaluation included in this framework is comprehensive enough to allow for the effective distillation of the criteria to be used.

Exhibit 5-6: Principles for criteria selection checklist

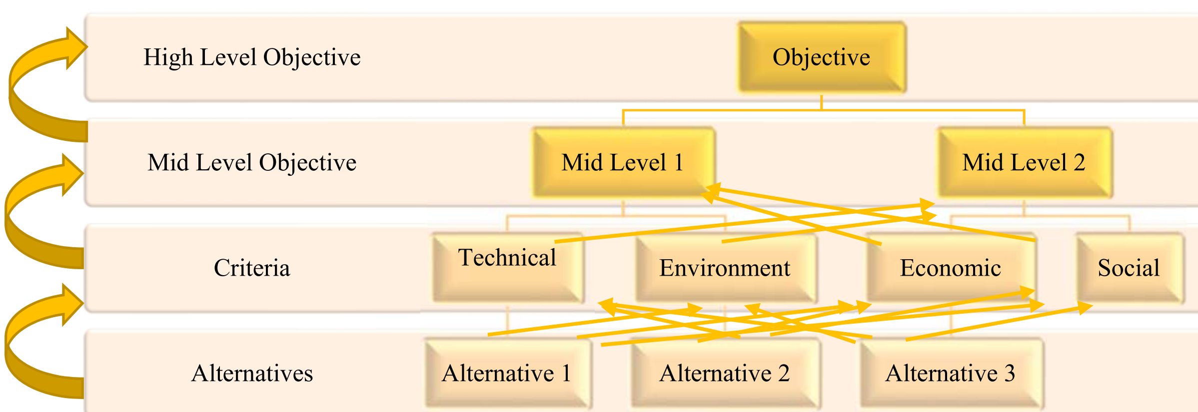
Most used criteria in the literature	**C**	**R**	**I**	**DC**	**SP**	**Con**	**M**	**Comp**	**S**	**IOT**	**Is the data available?**
Technical											
Efficiency	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Exergy	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Primary Energy Ratio	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Safety	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Reliability	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Maturity	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Environment											
CO_2 Emissions	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
NO_x Emissions	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Land use	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Noise	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Particles Emissions	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
SO_2 Emissions	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Economic											
CAPEX	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
OPEX	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Maintenance	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Cost of fuel	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
NPV	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Payback period	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Social											
Job creation	☐	☐	☐	☐	☐		☐	☐ ☐	☐	☐	☐
Benefits	☐	☐	☐	☐	☐		☐	☐ ☐	☐	☐	☐
Social Acceptability	☐	☐	☐	☐	☐		☐	☐ ☐	☐	☐	☐

C	Completeness
R	Redundancy
I	Independency
DC	Double counting
SP	Systemic principle
Con	Consistency
M	Measurability
Comp	Comparability
S	Size
IOT	Impact occurring over time

Using the checklist, any criteria that is considered redundant, cannot be measured, lacks independency or is not consistent with the defined objectives should be eliminated. Once the criteria are selected, if any criterion requires the use of qualitative data for its raw values then the user should convert it to a unit that can be measured. For this conversion, this framework will use the Saaty scale.

After all the potential criteria has been evaluated using the checklist and the suitable ones have been are identified, the alternatives, criteria, problem and objectives should be put together to confirm their cohesiveness. Exhibit 5-7, is a check for this cohesiveness. The exhibit is a graphic that has to be filled by the user. It puts together the various elements of MCDA as a complete unit. As the purpose is to corroborate the cohesiveness, it is not necessary for the user to include all the criteria and sub-criteria selected, however, as a minimum, the main criteria must be included. It is emphasized that visual representations are useful in safeguarding that the selected criteria and alternatives are suitable to fulfil the intermediate objectives and, consequently, the high-level objectives.

Exhibit 5-7: Check for Agreement between Alternatives, Criteria, and Objectives



The user must remember that each main criteria group must include the same amount of sub-criteria for the evaluation. For this reason, it may be useful to include the sub-criteria in the template provided in Exhibit 5-7. If there is no uniformity in the number of sub-criteria for each main criterion, then the selection of the sub-criteria to be used for the evaluation will be done based on the weight of the sub-criteria. For example, if one main criterion has four sub-criteria but the other main criteria have five, then four would be the maximum number of sub-criteria to be considered under each main criterion. The four sub-criteria with the most weight will be used for the evaluation of the alternatives. The method selected to calculate the weight of the criteria will be explained in Section 5.5 below. Once again, any criteria that is evaluated using qualitative terms must be converted to ordinal terms for calculation purposes. For this conversion, this framework will use the Saaty preference scale. The reason for selecting this specific scale is that, in addition to the simplicity of the scale to understand and use, the scale has also been vastly used in the literature for the evaluation of components of decision analysis.

5.4 CONSTRUCTION OF THE EVALUATION MATRIX

Once all the criteria and alternatives have been identified, the user can create the evaluation matrix. The matrix will include the criteria in columns, the alternatives in rows and the weights under each criterion. Based on the ideas expressed by Dogson (2009), this framework will not have only one matrix but rather, this framework will have various sub matrixes that will group the sub-criteria under the corresponding main criteria. Exhibit 5-8 below provides the Evaluation Matrix to be used in McPAF. This evaluation matrix is composed of one matrix that contains the main criteria, another matrix that contains the economic sub-criteria, one matrix that contains the environmental sub-criteria and so forth. Grouping the criteria is done to facilitate the calculation of the criteria weight after eliciting the decision-maker's preferences.

5.5 ASSIGN WEIGHT TO CRITERIA

This framework is based on the concept of aggregating the preference of more than one decision-maker to obtain a group preference. To achieve this, McPAF will use the SIMOS method to elicit the preference from the decision-makers and the AIP method to aggregate the result of the calculations. Both methods were explained in depth in section 4.2.1.4 above.

The first step in the weight elicitation process is to arrange the criteria and sub-criteria in hierarchal order according to existing public policies. This means that, if for example, the high-level objective is to reduce CO_2 emissions, then the sub-criterion for CO_2 emissions will have the greater weight within the environment criteria cluster, and the environment criterion will have the biggest weight compared to the other main criteria. For the rest of the criteria, the weight will be elicited from the decision-makers through the use of the SIMOS method.

Exhibit 5-8: Evaluation Matrix

	Technical	Environment	Economic	Social
Weight				
Alternative 1				
Alternative 2				
Alternative 3				
Alternative 4				

Technical

	Efficiency	Exergy	Primary Energy Ratio	Safety	Reliability	Maturity
Weight						
Alternative 1						
Alternative 2						
Alternative 3						
Alternative 4						

Environment

	CO_2 Emissions	NOx Emissions	Land Use	Noise	Particles Emissions	SO_2 Emissions
Weight						
Alternative 1						
Alternative 2						
Alternative 3						
Alternative 4						

Economic

	CAPEX	OPEX	Maintenance	Cost of fuel	NPV	Payback period
Weight						
Alternative 1						
Alternative 2						
Alternative 3						
Alternative 4						

Social

	Job Creation	Benefits	Social Acceptability
Weight			
Alternative 1			
Alternative 2			
Alternative 3			
Alternative 4			

The SIMOS method was selected over mathematical- and arguably more objective-weight elicitation methods because it is a user-friendly approach that allows to, somewhat, incorporate fuzziness in the preference of the decision-maker while at the same time allowing for side by side comparison between all the sub-criteria. Particular interest is brought on visualization in McPAF, and of all the methods discussed in Chapter 4 for weight elicitation, this was found to bring a good balance between visualization (in the side by side comparison), integration of fuzziness and mathematical calculations.

SIMOS also has the advantage that it can be executed virtually or onsite. This means that, if the decision-makers cannot be together in one place at one time, the preference of the decision-maker can still be elicited with a version of SIMOS prepared in an electronic format (such as a worksheet or a presentation). This is a great advantage as it allows for the process to continue forward without delays caused due to planning or logistic reasons. Exhibit 5-9 below illustrates how a SIMOS method can be constructed in a worksheet format, with the instructions to provide preferences.

McPAF will use a modified version of SIMOS based on an Excel workbook, shown in Exhibit 5-9. Each decision-maker will receive a workbook. This workbook contains a worksheet for each sub-criteria cluster and one for the Main Criteria. None of the worksheets include the criterion that had been previously identified as the most important from the objectives or government publications— referred herein as 1C--, if any has been identified as such. After the various workbooks have been collected, the user must incorporate the corresponding 1C into each of the worksheets in the space labelled “most important” and include it in the calculations. Within the worksheet, the decision-maker is asked to indicate his or her preference by placing the criteria in the corresponding column, as indicated in Exhibit 5-9, Weight Elicitation Instructions. The column indicates where the most important criterion and least important ones should be placed. The second modification done in the use of SIMOS, is to limit the number of blank cards allowed in the exercise. Since the original SIMOS method consists of the use of actual cards, red and white, the difference of importance between the criteria was physically limited. As this exercise is done in an electronic manner, a worksheet, there is no physical limit and thus a limitation must be included in the instructions. In Exhibit 5-9 the number of blank spaces- blank cards in the analogue method- was limited to two.

Exhibit 5-9: Weight Elicitation: Instructions

Instructions:

Please copy/paste the cells A9 to A13 into Column D, from least important to most important.
If you consider two or more cells to be of the same importance, place them together by adding a column to the right.
Blank spaces can be left between the cells. The blank spaces signify the difference in importance between criteria. You may leave from zero up to two blank spaces between criteria.

Original:

			Place Criteria Here
	1	**Least Important**	
	2		
Criteria for purchasing a car:	3		
Price	4		
Colour	5		
Brand	6		
Style	7		
Petrol Consumption	8		
	9		
	10		
	11		
	12		
	13	**Most Important**	

Example 1

			Place Criteria Here
	1	**Least Important**	**Colour**
	2		**Style**
Criteria for purchasing a car:	3		**Brand**
	4		**Petrol Consumption**
	5	**Most Important**	**Price**
	6		
	7		
	8		
	9		
	10		
	11		
	12		
	13		

As mentioned before, the minimum number of worksheets to be used in McPAF is five: one for each sub-criteria cluster and one for the Main Criteria. Exhibit 5-10, below, shows how the worksheets for weight elicitation by Decision-maker looks like. These exhibits are used in the case study developed in Chapter 6.

Exhibit 5-10: Weight Elicitation: DM 1

<u>Technology</u>

1 **<u>Least Important</u>**
2
3
4
5
6
7
8
9
1
0
1
1
1
2
1
3 **<u>Most Important</u>**

Environmental

1 **<u>Least Important</u>**
2
3
4
5
6
7
8
9
10
11
12
13 **<u>Most Important</u>**

<u>Economic</u>

1 **<u>Least Important</u>**
2
3
4
5
6
7
8
9
1
0
1
1
1
2
1
3 **<u>Most Important</u>**

<u>Social</u>

1 **<u>Least Important</u>**
2
3
4
5
6
7
8
9
10
11
12
13 **<u>Most Important</u>**

<u>Main Criteria</u>

1 **<u>Least Important</u>**
2
3
4
5
6 **<u>Most Important</u>**

Once the worksheets shown in Exhibit 5-10 are collected for all decision-makers, their preferences are combined and put in separate worksheets, shown in Exhibit 5-11, labelled Weight Elicitation by Criteria Cluster Aggregating all DM, below. This means that, for example, there will be one worksheet for the economic cluster that will contain the preferences expressed by all the decision-makers regarding the economic sub-criteria, while another worksheet will handle the environment cluster and sub-criteria, and so forth. Within each worksheet, the SIMOS method is used to calculate the weight of each sub-criterion according to each decision-maker.

The individual weights per sub-criterion are then aggregated using the AIP method. This calculation is performed in the template shown in Exhibit 5-12. To illustrate the minimum elements that must be included in the template Exhibit 5-12 already has the Main Criteria and sub-criteria identified on Table 5-1. The first global weight to be obtained with the AIP method is that of the Main Criteria, as these results will be needed to calculate the global weight of the sub-criteria. This is the first table within Exhibit 5-12. Once the weights of all Main Criteria are obtained from the use of the SIMOS method for each decision-maker, this weight is multiplied by the weight of each decision-maker, which in McPAF is equal to one over the total number of decision-makers. As a minimum, the weight must be ¼ for each decision-maker, given that there are four main points of view that need to be represented throughout the process. The results of the multiplication are included in the column labelled “aggregate result” for each of the rows. These aggregate results are then added together to obtain a total aggregate result. Each of the aggregate results is then divided by the total aggregate result, to obtain the global weight for each criterion.

After the global weight of the Main Criteria has been assigned, the next step is to obtain the global weight of each sub-criterion. The process is very similar: the weight obtained from the use of the SIMOS method in Exhibit 5-11 is multiplied by the weight of the decision-maker, the products are added together to obtain the total aggregate result, the individual aggregate results for each sub-criterion are then divided by the total aggregate results of all sub-criteria of that particular cluster, obtaining the “weight” of the sub-criteria in that particular cluster. The global weight for the sub-criteria is obtained in the next column—“sub-criteria global weight”-- by multiplying the “weight” of each sub-criterion by the global weight of the Main Criteria it belongs to. As a check, the addition of all sub-criteria global weights should be equal to 100%.

Exhibit 5-11: Weight Elicitation by Criteria Cluster Aggregating all DM using the SIMOS Method

DM1

DM's Weight 1/4

Ranking	Main Criteria	Number of cards	Weight (w)	Average Weight)	Relative Weight	Test
1	MC 1					
2	MC 2					
3	MC 3					
4	MC 4					

DM2

DM's Weight 1/4

Ranking	Main Criteria	Number of cards	Weight (w)	Average Weight)	Relative Weight	Test
1	MC 1					
2						
3						
4	MC 2					
5	MC 3					
6	MC 4					

DM3

DM's Weight 1/4

Ranking	Main Criteria	Number of cards	Weight (w)	Average Weight)	Relative Weight	Test
1	MC1/MC 2					
2	MC 3					
3	MC 4					

DM4

DM's Weight 1/4

Ranking	Main Criteria	Number of cards	Weight (w)	Average Weight)	Relative Weight	Test
1	MC 1					
2						
3						
4	MC 2					
5	MC 3					
6	MC 4					

Exhibit 5-12: Aggregation of Multiple DM's Weights using the AIP Method

	Aggregate result %	Weight %
Technology		
Environment		
Economic		
Social		
Total		

Technology

	Aggregate result %	Weight %	Sub-criteria global weight %
Primary Energy Ratio			
Maturity			
Exergy			
Safety			
Reliability			
Efficiency			

Environment

	Aggregate result %	Weight %	Sub-criteria global weight %
Land Use			
Noise			
Nox Emissions			
SO2 Emissions			
CO2 Emissions			
Particle Emission			

Economic

	Aggregate result %	Weight %	Sub-criteria global weight %
CAPEX			
NPV			
OPEX			
Payback Period			
Maintenance			
Cost of fuel			

Social

	Aggregate result %	Weight %	Sub-criteria global weight %
Job Creation			
Benefits			
Social Acceptability			

The AIP technique was chosen for this framework because, as the purpose of the decision analysis is to have an assemblage of independent individuals providing their points of views, AIP method is the better suited than the AIJ method explained in section 4.2.2. Within this framework, the arithmetic means approach is used as there is no need to embody how many more times one criteria is preferred over another. On the contrary, what is sought is a non-fuzzy solution.

5.6 SELECTING THE APPROPRIATE METHOD

With the problem structured, at this point the next step is to select the appropriate method. McPAF is based on the concepts expressed by Kurka (2013) and pre-selects methods based on the literature reviewed. A summary of some of the most applied methods in decision analysis related to energy planning, according to the literature reviewed, are indicated in Table 5-2 below.

Table 5-2: MCA Methods Applied in the Energy Sector

Situation	Method
Energy Alternatives	Preference Ranking Organization Method for Enrichment Evaluation *(PROMETHEE)*
Energy Planning	Preference Ranking Organization Method for Enrichment Evaluation *(PROMETHEE)* Elimination and Choice Translating Reality *(ELECTRE)* Analytical Hierarchy Process *(AHP)* Strength, Weakness, Opportunity and Threats analysis *(SWOT)* Weighed Sum Methodology *(WSM)* Weighted Product Method *(WPM)* Technique for Order Preference by Similarity to Ideal Solutions *(TOPSIS)*
Energy Adoption	Fixed-Effect Vector Decomposition
Shale Gas Development	*TIAMS*
Evaluation of technical options	Simple Additive Weight Model
Energy Policy	Multi Attribute Utility Theory *(MAUT)*
Environmental Impact Assessment	Multi Attribute Utility Theory *(MAUT)*
Resource Allocation	Analytical Hierarchy Process *(AHP)*
Project Planning	Analytical Hierarchy Process *(AHP)*
Sustainability Assessment	Analysis and Synthesis of Index at Information Deficiency (*ASPID)* General Sustainability Index

(Wang, Jing, Zhang, & Zhao, 2009) (Pohekar & Ramachandran, 2004) (Kurka & Blackwood, 2013)

If the decision situation to be analysed is not included in Table 5-2, the approach to be used to revise the literature is based on Velasquez and Hester's (2013) suggestion. The research approach proposed by the authors include searching electronic search engines and specialized scholar search engines with the term "multi-criteria decision analysis" and words from the problem. For example, to research MCDA methods used for shale gas planning, the search words to be used would be "multi-criteria decision analysis + shale gas".

The research of suitable methods is only one part, the second part is their selection. The selection of the appropriate method proposition is based Kurka & Blackwood (2013) and Greening (2004): to preselect MCA methods from either Table 5-2 or those identified in the literature and assess them against the considerations stated in Table 4-6. The comparison matrix is included in Exhibit 5-13 below. The methods pre-selected in this Exhibit are used of example purses only.

Exhibit 5-13: Considerations for the Selection of the Appropriate MCA Method

	AHP	MAUT	PROMETHEE	ELECTRE	WSM
How many DMs involved?					
Are all appropriate stakeholders engaged? How much is their involvement?					
How does the DM prefer to have the data presented?					
What kind of result is the DM looking for?					
Can data be easily obtained?					
Is the DM looking for compensations?					
Method meets main assumptions?					
Software needed?					
Can the method support many alternatives and criteria?					
How does the model quantify the importance of the criteria or their weights?					
How does the model deal with uncertainty?					
Can the decision be re-evaluated using new data?					
Is the model transparent and easy to explain?					
Is the method easy to use?					
Does the method provide for sensitivity analysis?					

McPAF uses at two MCA methods for the evaluation of the alternatives. The purpose of running the analysis through at least two MCA methods is because evaluating the alternatives against the criteria with more than one method and analysing the similarities or differences in the results will provide more information for the decision-makers. Nevertheless, running the evaluation through numerous methods would prove counterproductive, as it is time consuming and could further confuse the decision-maker instead of aiding. This is the reason why this framework will only select two methods.

For further aid, Table 5-3 below shows some examples of different MCA methods that have been used for decision analysis involving renewable energy decisions specifically and the area in which they were applied.

Table 5-3: MCA Methods Applied in the Renewable Energy Industry

Scope	Methods
Scenarios	AHP
	WSM
	WPM
	PROMETHEE
	ELECTRE
	TOPSIS
	VIKOR
	SIMOS
Alternative Power Generation	PROMETHEE
Usage appraisal of National Energy Scenarios	SIMOS PROMETHEE
Energy planning	MAUT
	AHP
	PROMETHEE
	ELECTRE
Resource allocation	AHP
Project planning	AHP
	PROMETHEE
	ELECTRE

(San Cristobal Mateo, 2012) (Kurka & Blackwood, 2013) (Pohekar & Ramachandran, 2004)

5.7 ANALYSIS AND RANKING OF ALTERNATIVES

Once the methods have been selected, the evaluation is run with the alternatives, criteria and weights previously identified. Up to this point McPAF has been created specifically considering the user to be a non-expert in decision analysis methods and thus, it has aimed at being user friendly and easy to operate. Nevertheless, from this point forward it is strongly encouraged to employ the skills and understanding of an expert in decision analysis methods as these require mathematical formulations that may require a more refined skill.

5.8 SENSITIVITY ANALYSIS AND RECOMMENDATIONS

Once the models are run, a sensitivity analysis must be done. A sensitivity analysis may include changes in the weights or the criteria used to evaluate the alternatives. This framework will approach the sensitivity analysis by changing some criteria with the criteria that had the next highest weight per cluster. This approach was chosen after considering how time consuming the weight elicitation process is, which makes it difficult to make a second weight elicitation process to obtain different weights to run the analysis. Another option contemplated was to randomly apply new weights to the criteria for the sensitivity analysis, but the challenges of explaining to the decision-maker the reasoning why of the random weight applications was considered and determined to be an unnecessary obstacle. The selection of the next highest weight is considered as a more transparent option and easier to explain to the decision-makers.

If a change, or changes, in the government or the current administration are expected before the complete implementation of the answer sought through this decision analysis, these changes in the administration may alter the ranking of the criteria or the preferences of the new decision-maker/makers. As such, these changes must be included in the sensitivity analysis.

5.9 CONCLUSIONS

This chapter follows the development of the Multi-criteria Preference Aggregation Framework (McPAF). The purpose of this model is to work out some of the challenges that have been associated with multi-criteria decision analysis and which were explained in the previous chapters, as well as to have a step by step process on how to focus a decision analysis process to the energy field. These challenges include how to structure the problem, identify the objectives, decide which and how to collect the data, determine who are the stakeholders, the key players, and the decision-makers, how to select suitable criteria and alternatives, how to select the appropriate methods, and how to elicit weight preferences from the participants as well as how these preferences can be totalled. In addition, this model integrates a level of fuzziness in the weight elicitation process, as to allow for the decision-maker to express how much more one criterion is preferred over another. This framework allows for better organization of the decision analysis in energy. It is applicable to sustainable energy as the organization of the framework ensures all main points of view will be considered, leaving no blind spots. The framework takes into consideration issues such as demand, production, social and environmental aspects. Within these issues, the current and future needs of the population are considered, making it appropriate for sustainable energy.

The model does not introduce a new method, yet it combines several elements that were already existing in the literature-- for example, the aggregate individual preference method to total weight preferences of various decision-makers, the SIMOS method to elicit the weight preferences of each of the decision-makers, the concept of the Basic Cluster and Main Criteria for data collection, the suggestion of using SWOT analysis to assess the alternatives amongst themselves and the guidelines to be used to determine the suitability of the criteria— in a manner that enhances the use of multi-criteria decision analysis methods by addressing one by one the challenges associated and providing a solution for each. McPAF has some new elements, such as the concept of visualization between problem, objectives, criteria and alternatives and the matrix for the organization of data to be collected. Different matrixes were developed for this framework, identified as Exhibits, with the purpose of facilitating organization and visualization for the user. The concept of visualization was highlighted on this framework because it is both, a security check in every step of the process and is also helpful for easier explanation of the analysis and results. Due to shortage of time, McPAF does not consider

Although McPAF is not made from scratch, but rather combines known and new elements, it still provides a valuable contribution. The development of McPAF is similar to the preparation of a food dish. In a food dish, the chef uses already existing produce- for instance carrots, turnips, onions, celery, leek, barley, peas, lamb and pepper-, follow a set of instructions or recipe-for instance heat all the ingredients in a saucepan until boiling, reduce the heat and simmer gently for 3 hours- and the result, the combination of the produce after following the recipe, is something new on its own- in this case scotch broth. This analogy is very suitable to describe McPAF and its contribution to the literature: it takes existing elements (produce)- such as multi-criteria decision methods, ideas on how to gather data, select criteria, alternatives, stakeholder and decision-makers, concepts on how to elicit weight preferences and how to aggregate the preferences of various decision-makers- provides a set of instructions that explain step by step the process to be followed (recipe) and the result, McPAF, is a new product that combines all the different elements (food dish). Although the various elements had existed, the manner in which these elements were combined to resolute the challenges faced when using multi-criteria decision analysis methods, while providing emphasis on analysing situations which involve energy field or planning, had not been done. This framework provides theoretical advancement of the organization for decision analysis, leaving no blind spots. This is a superior framework for decision analysis which includes cost benefit analysis instead of complementing it and presents a newness of structure. It is a generalizable framework that was developed in the context of sustainable energy, yet its components can be changed, added or discarded. It is not an ad hoc model.

6 SIMULATION: SCOTLAND´S ENERGY POLICY

6.1 INTRODUCTION

Chapters 3 and 4 discussed the basics of MCDA: its uses, steps, available models and suitability in the energy field. Chapter 5 developed the McPAF framework, which provided a methodology for how to tackle some of the most common problems when using MCDA methods, such as how to define the problem, how to aggregate the priorities of the different decision-makers, the need to have more than one decision-maker, the case for why all decision-makers should be given the same weight, how to select criteria, how to select the appropriate multi-criteria decision analysis method, as well as how to identify the suitable alternatives, while maintaining focus solely on the energy field. This chapter provides a Simulation where McPAF is put to the test.

The Simulation is based on Scotland's action on energy plan. In January 2017 the Scottish government published a communication titled "Scottish Energy Strategy: The future of energy in Scotland." In it, the Scottish Government set out their vision for the energy system in Scotland until 2050. Accompanying this strategy, the Government also launched a public consultation process to seek the populace's view on the country's future energy system as well as how the Government should go about to achieve it. The Simulation in this chapter was prepared using the information provided in the strategy, as well as publicly published information regarding the position of the Scottish Government on energy.

The Simulation, however, is not an analysis of the Scottish Government's goals or agenda. Rather, the information published by the Scottish Government was used as an example to highlight how McPAF would work for a similar situation that required decision analysis. For instance, the objectives discussed below were taken from various publications by the Scottish government, rather than requesting clarification directly with the decision-makers, as would have been the case if the study was specifically designed to analyse a decision to be taken by the Scottish government. The values used to run the methods in this Simulation are mock ups, used for illustration purposes only and at best approximations of what the actual numbers may be. Consequently, it is stressed and emphasized that the values used in this Simulation should not be taken as accurate or complete.

This Chapter will explain the use of the Simulation step by step, following the process established in Chapter 5. The weight input required for the elicitation of weights was provided by colleagues who volunteered and used the SIMOS method; no actual stakeholders or potential decision-makers were contacted. Other inputs required were assumed; these assumptions are explained throughout the sections. Section 6.2 provides the explanations of the Simulation, including the assumptions, the reason behind the selections and the explanation of the method to elicit the preferences. These explanations are cross referenced with the samples provided in Section 6.3, which offer the numeric results of the Simulation. The samples were separated from the explanation as having them together would interrupt conceptualization of the Simulation via the use of the templates previously discussed in Chapter 5.

This Simulation creates a clear picture as of final product: the food dish; it is the application of the combination of the different elements, with its recipe, to obtain an analysis. Although this method is a compilation of techniques and ideas that were already circulating, the contribution is that, in the manner in which McPAF is arranged helps to streamline the process and overcome the challenges associated with MCDA methods. The value in using MCDA methods relies in the comprehensive overview of the problem it provides, allowing to analyse the problem from a real-world perspective, instead of analysing it in a vacuum. The Simulation will show how McPAF is a coherent reorganization of known elements that simplify their understanding and use, making it more efficient for those that seek an analysis of a situation.

6.2 SIMULATION EXPLANATIONS

6.2.1 Defining/Structuring the problem

After following the steps previously discussed, the problem was defined enough to be able to be structured in a question form: “which are the renewable energy alternatives that would best fulfil the Scottish government’s goal of moving towards a low carbon economy?” How the problem was defined to this term is further explained in the following subsections.

6.2.1.1 Determine the Objectives

As McPAF is focused on energy related decision situations, various government publications that discussed energy related issues in Scotland were reviewed, particularly publications regarding the energy future of Scotland. Although this was the methodology implemented to identify the objectives in this Simulation, however, the objectives in a real case scenario must be confirmed directly with the parties pursuing the analysis. Since this simulation is a hypothetical example, which purpose was not to perform an actual evaluation of an energy planning decision situation for Scotland, no such consultation was done.

During the research the theme of the Scottish government's desire to advance the implementation of a low carbon economy in the short term appeared. This theme was further researched in order to identify specific high-level objectives and intermediate level objectives. The high-level objective was identified as "move towards a low carbon economy." The intermediate objectives were determined to be: i) accelerate the implementation of renewable energy, ii) generate an equivalent of 100% electricity demand from renewable sources and iii) generate an equivalent of at least 11% renewable heat. Once the objectives were identified, the problem was structured as a question, indicated in section 6.2.1. Simulation 6-1 provides a visual representation as to how the problem, the high-level objectives, and the intermediate objectives are interrelated. This representation is based on the template provided in Exhibit 5-1.

6.2.1.2 Data Collection

The data was collected following the Basic Cluster and Main Criteria approach introduced in Chapter 5. From the official publications researched, and taking into consideration the high-level and intermediate objectives, the industry was identified as renewable energy technologies. No specific technology was distinguished, at this time, as the publications did not communicate a predilection for any.

The data collection was organized referring to the intermediate level objectives, as shown in Simulation 6-2. No actual data was gathered for this case study however, Simulation 6-2 itemizes example of data that should be gathered; for example, under the first objective, accelerate the implementation of renewable energy, for the country and region clusters a component of the environment criteria to be obtained should be average emissions for the renewable industry. Likewise, CAPEX and OPEX for the renewable industry, integration cost for regional and cost of alternative fuels, are components of the economic criteria that must be obtained for the second objective: generating an equivalent of 100% electricity demand from renewable sources. The diagram contains additional information to be gathered, as a manner to show that the data collection process should not be limited to the Main Criteria and corresponding sub-criteria, but that the user is free to add other information deemed suitable.

As an actual field study is not included in the scope of this Simulation, no interviews, questionnaires or surveys were used; instead the information used to run this Simulation was obtained from different publications. As the information was not obtained from first hand experimentation and data gathering, this thesis cannot certify the veracity of the data, which is used is only for illustration purposes. McPAF does not recommend any particular data gathering method; this is left for the user to decide.

6.2.1.3 Identify the Stakeholders

The identification of stakeholders was performed via a desktop study of government officials and their functions. The first potential participants to be identified were those who could represent the interests defined in the Basic Cluster, followed by those potential participants who could represent each of the four main points of view: technology, environment, economic and social. These participants were identified from the different ministries in the Scottish Government. Simulation 6-3 provides a sample of how the template provided in Exhibit 5-3 would be filled as the scope of this Simulation does not include an actual evaluation of the possible participants.

6.2.1.4 Determine Who Will be the DMs

Four decision-makers were identified from the group of stakeholders, each representing one four the Main Criteria. This to maintain the integrity of the evaluation of all points of view. Their weight was distributed equally, with each having a weight equal to ¼. The decision-makers are identified in Simulation 6-4.

6.2.2 Generating Alternatives and Establishing Criteria

6.2.2.1 Alternatives

The alternatives were also identified from the reviewed publications, particularly those technologies mentioned in the 2020 Routemap for Renewable Energy in Scotland. (Govt, 2015). At this point, McPAF would use a SWOT analysis to further select the suitable options. As an actual SWOT analysis was outside of the scope of this research, the SWOT analysis for the offshore wind alternative was duplicated from that published in the Offshore Wind Industrial Strategy Business and Government Action (Government, 2013), while for the other technologies the information was obtained from the 2020 Routemap publication. Simulation 6-5 shows the results of the SWOT analysis. Taking into consideration the strengths, weaknesses, opportunities and threats of each of the technologies studied, three were selected: onshore wind, wave and tidal and hydropower. The reason these three technologies were selected was because, out of the group evaluated, these three revealed to possess more strengths and opportunities than weaknesses or threats. The opposite was found for the other alternatives, as the strengths in each were less than the number of threats or weaknesses found.

6.2.2.2 Criteria

As specific, tangible data was not gathered for the Simulation, given its scope, Simulation 6-6 is a model of how the principles for criteria selection would be applied. This Simulation assumes that all the criteria included in Simulation 6-6 complies with the checklist. To keep with the size principle, given that the social criteria only contains 3 sub-criteria while the other Main Criteria have five or more, the sub-criteria that obtains the three top weights after eliciting the decision-maker's preferences will be used.

The problem, objectives, criteria and alternatives are put together in Simulation 6-7 to corroborate their cohesiveness.

6.2.3 Evaluation Matrix

Simulation 6-8 shows the full evaluation matrix, which is composed of four sub-matrixes: one to evaluate the technical sub-criteria, another to evaluate the environment sub-criteria, a third sub matrix to evaluate the economic sub-criteria and, last, a fourth matrix that evaluates the social sub-criteria. Weights are not included in Simulation 6-8 as they will be calculated in the next step.

6.2.4 Assigning weight to the criteria

The weight elicitation process was the most complex for this Simulation. Four non-expert volunteers were asked to indicate their preferences. Logistical reasons, including physical location of the volunteers as well as their scheduled, meant that the elicitation process had to be done virtually instead of physically- meaning that the elicitation would have to be obtained via electronic methods as there was no possibility of having all the volunteers together at the same time in the same place. The use of a virtual substitute, in this case an Excel workbook, turned out to be very time consuming. The first challenge presented was following up on the answers; it became difficult to obtain replies in general and to obtain them in a timely manner. There were four original volunteers, from which three had to be replaced due to not receiving reply after various follow ups. These three new volunteers still required some following up to be able to obtain their preferences. The timeframe allocated for this task was severely delayed due to this need of following up. The second challenge confronted was that the volunteers that did offer their preferences found the instructions in the worksheet to be confusing and difficult to follow. This required a one on one approach with each of the volunteers, which in turn delayed the time allocated for the task even more. The purpose of saving time was not achieved with the use of the electronic alternative.

The virtual option for weight elicitation had two approaches. The first was creating a version of the SIMOS method using a presentation template (Power Point). In the presentation, an equivalent of white and red cards was design for the criteria and the difference in importance, respectively. A first slide gave the instructions followed by five slides, one comparing the sub-criteria for each main criterion and one comparing the main criteria amongst themselves. This model was used by only one of the volunteers. After receiving feedback given by this volunteer, the suggestions were accepted, and the approach was changed. The feedback from the volunteer is transcribed below:

> *'Slide 6-Needs a slide explaining the white cards- this is a bit confusing- why is optional to place the white cards in between? Why do it/not do it?*
>
> *Slide 7 - probably needs a prompt that explanation for white cards is on the next slide*
>
> *Don't know why the exercise of white cards - wouldn't this decision be made in two seconds giving a number to each category?*
>
> *White cards - If you do a value between 1-10 (or 10 spaces) then you wouldn't need the white cards, they can leave a space if they consider each category to have more/less importance?*

Idea: You can do this with a Google Survey

Method

Cutting/pasting is difficult as it places it behind figure and then you have to re-format it - make sure you click on the frame where you want the cards, and click Format - Send to Back so that it remains there if I want to change cards.

White cards - Probably would be best to replicate or do something to have the cards be put on previous slide. Or include them'

Suggestion: Perhaps Excel spreadsheet illustrating cells as empty 'cards'

Is there a maximum of white cards? [sic]

Explaining - white cards can be used to distance each criteria [sic] when needed.

Person should tell you which is their [sic] maximum range they are using (ex. [sic] 20 as most important, etc.)

In model of cards it [sic] would be measured according to distance.'

After receiving this feedback, the electronic template was changed from the use of a presentation to a workbook. A workbook approach was considered to be easier for the volunteers, as it allowed for the copy/paste of the criteria in the corresponding column. Another change was that the number of white cards was limited to two per criterion. This meant that, if there were five criteria to evaluate, there would be a maximum of eight white cards to be used to differentiate between the importance of the criteria. The third change was that the instructions were revised for clarity. All of these changes are reflected in in Simulation 6-9.

While this new workbook approach was easier for the volunteer, nevertheless the revised instructions alone proved to be insufficient and the volunteers still required more clarifications. An unexpected situation encountered was that, even though it was explained that the purpose of the exercise was to elicit their preferences, the volunteers were concerned with whether the answers provided were the correct ones, in which cases they were reminded of the purpose of the exercise and that, due to this, there were no right or wrong answers. Simulations 6-10 through 6-13 display the preferences as elicited from the volunteers.

Once the preferences were collected, the worksheet provided the greatest advantage for the user, as Excel made it easier to run the calculations. Simulations 6-10 through 6-13 show how the instructions prove insufficient, as the volunteers did not understand that the least and most important criteria should have been placed next to the label indicating each. This requires further revision of the instructions. Still, the use of this electronic template proved convenient for both the volunteer and the user, as it facilitated the copy/paste of the order of the preferences as expressed by the volunteers, then it facilitated inserting the missing values (e.g. values corresponding to the number of cards column and weight (w) column). Last, the system was able to run the calculations with the formulas previously entered for the average weight and the relative weight.

Simulations 6-14 through 6-17 show the weight calculation using the SIMOS method for each sub-criterion. Simulation 6-18 shows the weight calculation for each Main Criterion. The resulting values were then used to find the global weight using the AIP method. The values were inserted in the template shown in Simulation 6-19. As a security check, the resulting weights were added to ensure the final aggregation was equal to 1. The global weight of each criterion and the security check is included in Table 6-1 below.

As discussed in Section 6.2.2.2 above, in the Simulation not all of the Main Criteria have the same number of sub-criteria. Following the size principle for the selection of criteria, this Simulation used the top three weights as obtained from the application of the AIP method in Simulation 6-19. Sub-criteria is capped at three as it was the amount of sub-criteria identified for the Social Main Criteria. In Simulation 6-20, the three top sub-criteria for each of the Main Criteria is highlighted. Their weight and sub-criteria global weight were then re calculated to represent the new value. The change of the value comes because, as only three criteria would be used, instead of the five or six, the total aggregate result was different. For example, for the technology criterion the original values and weights are shown in Table 6-2 below, and the sum of the aggregate result equals one. However, as the maturity, safety, and reliability sub-criteria will no longer be used for the analysis of the decision situation. Table 6-3 shows the recalculation, where the total aggregate result takes into consideration only three criteria, which in turn changes the weight of the sub criteria. Notice that in Table 6-2, Primary Energy Ratio had a sub-criteria global weight of 18% while in Table 6-3 it increases to 28%.

Table 6-1: Weight Values Security Check

Criterion	Weight
Technology	
Primary Energy Ratio	7%
Maturity	3%
Exergy	7%
Safety	6%
Reliability	6%
Efficiency	12%
Environment	
Land Use	2%
Noise	2%
Nox Emmissions	6%
SO2 Emissions	6%
CO2 Emissions	8%
Particle Emission	8%
Economic	
CAPEX	4%
NPV	2%
OPEX	3%
Payback Period	3%
Maintenance	2%
Cost of fuel	2%
Social	
Job Creation	5%
Benefits	3%
Social Acceptability	2%
Test:	**100%**

Table 6-2: Original Aggregate Result and Weight: Technology

	Aggregate Result	Weight
Primary Energy Ratio	18%	18%
Maturity	7%	7%
Exergy	18%	18%
Safety	14%	14%
Reliability	15%	15%
Efficiency	28%	28%
	1.00	100%

Table 6-3: Re Calculated Aggregate result and Weight- Technology

	Aggregate Result	Weight
Primary Energy Ratio	18.094%	28%
Exergy	18.095%	28%
Efficiency	28%	44%
	64%	100%

The second round of security checks is performed for Simulation 6-20, which confirms the new total aggregate weight values. The results are shown shown in Table 6-4 below, where the new global sub-criteria weight is shown under the “weight” column and sums up to 100%.

As can be seen, the only exception to the selection of a sub-criterion according to their weight was in the environment criteria with the SO_2 sub-criterion. This sub-criterion was discarded as an evaluation criterion because the data was not available. This lack of data was expressed in Simulation 6-6. In its place the sub-criterion with the next highest weight, NOx was chosen.

Table 6-4: Security Check for Simulation 6-20

Criteria	Weight
Technology	
Primary Energy Ratio	11%
Exergy	11%
Efficiency	18%
Environment	
NOx Emissions	9%
CO2 Emissions	11%
Particle Emission	12%
Economic	
CAPEX	7%
OPEX	5%
Payback Period	5%
Social	
Job Creation	5%
Benefits	3%
Social Acceptability	2%
Test:	**100%**

6.2.5 Selecting the Appropriate Method

Following Table 5.3, the methods chosen for pre-selection are: AHP, MAUT, PROMETHE, ELECTRE and WSM. The first four methods were pre-selected as they are used in energy planning scenarios and project planning, while WSM was pre-selected because it is a method that has been used for evaluating scenarios and does not entail extensive calculations. These pre-selected methods were analysed against the considerations stated in Exhibit 5-14. The results are included in Simulation 6-21. With the inclusion of the SIMOS and AIP method, the problems of aggregating the preferences of various stakeholders and how to quantify the importance of the criteria and the weight were solved. This meant that neither of these issues was taken into consideration for the selection of one method over another. The identification of the main points of view, the key players and the decision-makers also solves question whether the appropriate stakeholders are engaged, reason for which this item is also no longer a consideration for the selection of the appropriate method. As this exercise is a simulation, the question of how the decision-maker prefers the data to be presented was left blank, as was the question of whether the DM is looking for compensations. The use of the SIMOS method, to an extent, helps in deal with uncertainty as it allows for the decision-maker to express variations in the degree of preferences.

After the evaluation, both PROMETHEE and ELECTRE proved to have the disadvantage that specialized software was needed and that the model was difficult to explain, especially the preference, veto and indifference thresholds. The disadvantage found for AHP was the other methods provided for complete mathematic input, while AHP obtains its inputs from the results of the pairwise comparison performed by the decision-makers. Based on the experience of how time consuming the weight elicitation part was, the AHP approached was also discarded. Still, even if the use of the SIMOS method becomes too time consuming for the users, it is not recommended to instead to use AHP's pairwise comparison concept to elicit weight preferences as it will fall into the cycle of using an MCDA approach to solve challenges within an MCDA method. As a result, the methods selected were MAUT and WSM. These methods were found to be transparent, easy to explain and did not require specialized software.

6.2.6 Analysing and Ranking of the a\Alternatives

The assessment of the alternatives against the criteria was done using the MAUT and WMS methods. One raw scale was prepared and populated with simulated information that mixes qualitative and quantitative responses. In particular, social criterion was populated based on the Saaty Scale. Both processes share the raw scale. Because the inputs of the raw scale reflected different values, these were normalized using the max-min method.

Simulation 6-22 shows the analysis done under the MAUT method. In this simulation the highest ranked alternative was Onshore Wind, followed by Hydropower and Wave and Tidal. Two graphs were added to the analysis. The global utility graph shows the difference in the ranking result among the three alternatives, while the weighted utility score graph illustrate the impact of each sub-criterion in the total result per alternative.

Simulation 6-23 shows the analysis under the WSM method. In this simulation, however, the highest ranked alternative was Wave and Tidal, followed by Hydropower and Onshore Wind. The analysis also includes the global and weighted graphs. The first and third ranking were different with each method, yet the hydropower alternative ranked in second place for each of the decision analysis methods. Although the WSM method was originally constructed to be used only with data that contained the same measurement unit, it was complimented with a normalization method to be able to accommodate different measurement units.

The results obtained from the calculations, specifically the first ranked alternative, should not be interpreted as the solution to the decision analysis situation. In other words, neither onshore wind nor wave and tidal answer the problem: which are the renewable energy alternatives that would best fulfil the Scottish government's goal of moving towards a low carbon economy. Rather, what the results provide is an analysis for the decision-makers to take into consideration to make their determinations. The solution to the problem is to be provided by the decision-makers, not by the method used.

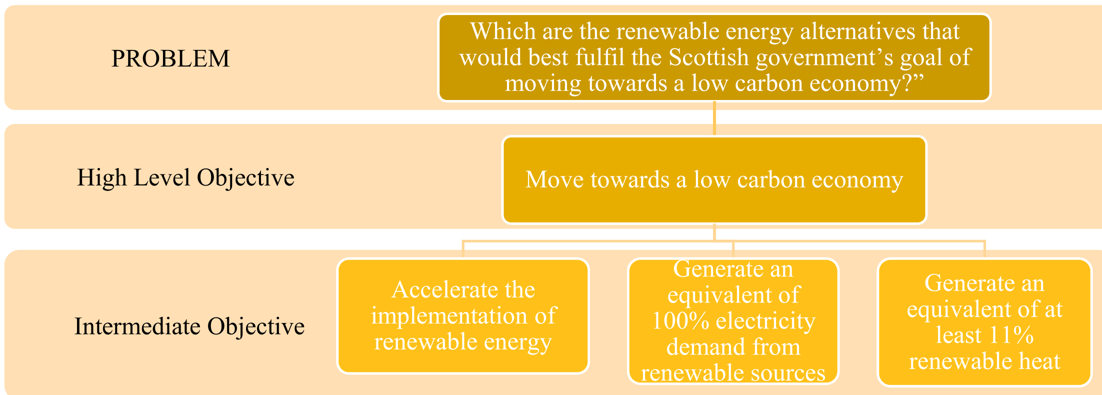
6.2.7 Sensitivity Analysis and Recommendations

The sensitivity analysis was performed by changing some of the sub-criteria to be evaluated. Technology and Environment were randomly selected to have one sub-criterion changed each. For Technology, primary energy ratio was substituted for Efficiency, while in Environment NOx Emission was substituted for Land Use. The new global weight was calculated, and the results are shown in Simulation 6-24. It should be clarified that the randomness was in the selection of which criterion to be substituted, not which value it would be substituted for, in concordance with Section 5.8. The new values were added to the raw scale, which was then normalized following the min-max method. The new calculations and the results are shown in Simulation 6-25 for the MAUT method and 6-26 for the WSM method. With the changes in weight, the results in the sensitivity analysis for both methods were the same, with wave and tidal ranking first, followed by onshore wind and hydropower. Although it has been stressed several times throughout this thesis, once again attention is drawn to the fact that the results of the analysis do not indicate the decision to be made, but rather only provide an analysis of how the different alternatives measure against the selected criteria.

6.3 Simulation Exercise

6.3.1 Defining and Structuring the Problem

Simulation 6-1: Problem and Objectives



Simulation 6-2: Data to be Collected

Intermediate Objectives:	**Accelerate the implementation of renewable energy**	**Generate an equivalent of 100% electricity demand from renewable sources**	**Generate an equivalent of at least 11% renewable heat**
Country	• Feasibility studies • Interconnection possibilities • Workforce Skills • Available Workforce • Environmental impact • Emissions goals • Carbon Footprint	• Demand • Supply • Social Acceptance of Renewable Technologies • Cost of alternative fuels	• Demand and Supply of main heat provider (e.g. gas) • Alternative fuels • Cost of alternative fuels • Environmental impact
Regional	• Feasibility studies • Demand and Supply • Weather patterns • Job creation • Social benefits • Emissions goals • Carbon Footprint	• Case Studies • Demand-Supply • Integration cost • Cost of workforce reallocation • Emissions • Carbon Footprint	• Comparative cost analysis • Emissions • Carbon Footprint • Social Impact • Social Acceptance • Environmental impact
Renewable	• CAPEX, OPEX, Maintenance, NPV, Payback Period • Success Rate • Incentives needed • Average job creation • Average social benefits • Average emissions • Average carbon footprint	• Case Studies • Back up alternatives • Integration with the electrical grid • Average emissions • Average carbon footprint	• Average environmental impact • Suitable technologies • Average Carbon Footprint

Simulation 6-3: Stakeholder and Key Player Identification

Points of view	**Possible participants**	**Legitimate Responsibility?**	**Interest in the consequences?**	**Can provide a useful/significant contribution?**	**Represents one or more major points of view?**
Country	First Minister	YES	YES	YES	NO
Regional	Representative for the EU		X	X	NO
Renewable Energy Technologies	Minister for Business, Innovation and Energy	YES			YES
Technical	Cabinet Secretary for the Rural Economy and Connectivity				
Economic	Cabinet Secretary for Finance and the Constitution				
	Cabinet Secretary for the Rural Economy and Connectivity				
	Cabinet Secretary for Economy, Jobs and Fair Work				
Environmental	Cabinet Secretary for Environment, Climate Change and Land Reform				YES
Social	Cabinet Secretary for Health and Sport				
	Cabinet Secretary for Environment, Climate Change and Land Reform				
	Cabinet Secretary for Communities, Social Security and Equalities				
	Cabinet Secretary for Economy, Jobs and Fair Work				
	Minister for Community Safety and Legal Affairs				YES
	Minister for Employability and Training				

Simulation 6-4: DM Identification

Point of View/Representative	DM
Economic	Cabinet Secretary for Finance and the Constitution
Social	Minister for Community Safety and Legal Affairs
Technical	Minister for Business, Innovation and Energy
Environmental	Cabinet Secretary for Environment, Climate Change and Land Reform

6.3.2 Generating alternatives and selecting criteria

Simulation 6-5: SWOT Analysis

Onshore Wind

STRENGTH	WEAKNESS
5,015MW generating capacity £82.50/MWh	Closure of the Renewables Obligation Uncertainty surrounding remaining subsidies No appropriate in National Parks or National Scenic Areas which represents a fifth of the country Higher protection in areas outwith National Parks and National Scenic Areas, which cover a tenth of the country
OPPORTUNITIES	**THREATS**
Opportunity to reduce cost allows it to compete with nuclear and thermal Repowering of onshore wind farms.	Investment depends on clear, well-defined structure of support Public interest in accurate mapping of onshore wind farms. Public information is available for projects over 1MW, but not so much for projects under 1MW when they are located in private property.

(Govt, 2015)

Solar PV

STRENGTH	WEAKNESS
Could achieve grid parity in the UK Cost reduction	Climate Renewable Obligation closed for larger solar projects
OPPORTUNITIES	**THREATS**
Allow under-represented urban communities to access energy ownership and benefits. Community and Renewable Energy Scheme (CARES) funding	Ensuring timely and affordable grid access Increasing innovation required to reduce costs Enabling financial predictability Building community and industry confidence

(Govt, 2015)

Bioenergy and Energy from Waste

STRENGTH	WEAKNESS
Supporting the use of biomass for CHP or heat-only plants is larger than 15MW	Ensuring resources are not used more efficiently elsewhere 15MW cap on support for electricity only biomass plants.
OPPORTUNITIES	**THREATS**
Study looking at potential feedstock crops for anaerobic digestion.	Lack of resources due to more efficient use elsewhere

(Govt, 2015)

Hydropower

STRENGTH	WEAKNESS
Fifth of Scotland's renewable output.	20% reduction in the Hydro feed-in-tarrifs (FIT) rate apply after December 2014.
OPPORTUNITIES	**THREATS**
More community developed and owned hydro scheme as the Callander Community Hydro Ltd has been successful.	Reducing levels of support for hydro power through FIT. Comprehensive review of the FIT

(Govt, 2015)

Offshore Wind

STRENGTH	WEAKNESS
Large wing resources and favourable locations with substantial potential for export of power Expertise in Offshore engineering, platform deployment, and marine operations transferable to offshore wind Strong R & D capability in renewables with increasing competence in demonstration and early deployment Expertise in advanced manufacturing and materials applicable to offshore wind Regulatory and price support framework enabling deployment of low-carbon energy generating technologies, including offshore wind, with cross party support	Testing and technology deployment is low which hinders the move to larger turbines and fully utilising R&D capability High energy cost of offshore wind in comparison with other renewable sources Foreign investment is limited to date as overseas investors are often unaware of benefits of investing or locating their activities in the UK Industry collaboration and SME activity is often limited Low involvement of UK supply chain as it is estimated only 30% of content in UK offshore wind sites on average is sourced from UK suppliers Waterside manufacturing infrastructure insufficient to fully meet sector's needs and new investment is not materialising.
OPPORTUNITIES	**THREATS**
Large economic benefits by 2020 offshore wind could deliver up to £7bn GVA (excluding exports) and boos total UK jobs by over 30,000 FTE Growing demand for renewable energy to meet climate change targets, security of supply and increasing demand for energy, both domestically and abroad Offshore wind cost reduction via technology, supply chain and finance. The Crown Estate cost reduction pathways study (2012) showed that 28% reduction in levelised cost to £100/MWh (2011 prices) was achievable for 2020. TINA study (2012) estimated that levelised costs of offshore wind energy could go down by 60% by 2050. Synergies with other industries could be realised as offshore wind relies on products and services from other sectors e.g. professional services, manufacturing and transport.	High competition for the location of top tier supply chain companies given turbines, foundations and electrical components can be manufactured from many locations on the North Sea coast line. Access to finance could affect speed of deployment and ability of UK supply chains to scale up quickly due to perceived risks by financiers. Cost of energy mat not reduce significantly if build rates are low. Availability of highly skilled workforce- offshore wind, like the wider energy industry, faces engineering and managerial skills gaps, competition for talent and ageing workforce. High market concentration & lack of varied competition in the supply chain-over 90% of turbines are supplied by two manufacturers but no turbine manufacturers currently located in the UK.

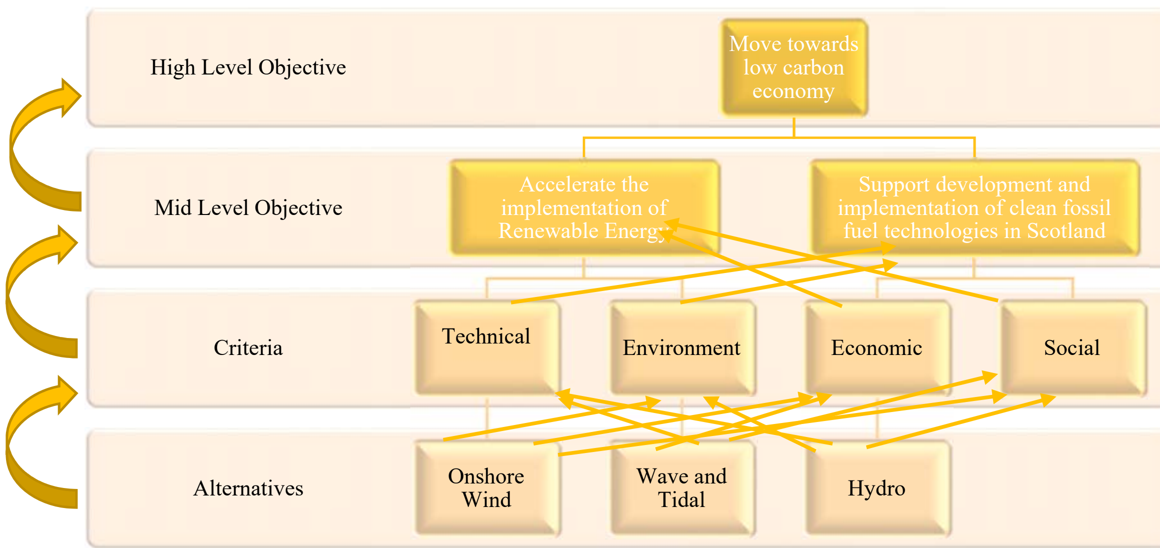
(Government, 2013)

Simulation 6-6: Principles for criteria selection checklist

Most used criteria in the literature	**C**	**R**	**I**	**DC**	**SP**	**Con**	**M**	**Comp**	**S**	**IOT**	**Is the data available?**
Technical									N		
Efficiency	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Y
Exergy	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	N
Primary Energy Ratio	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Y
Safety	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Y
Reliability	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Y
Maturity	☐	☐	☐	☐	☐	☐	☐	☐		Y	Y
Environment									N		
CO_2 Emissions	☐	N	☐	☐	☐	☐	☐	☐	☐	Y	Y
NO_x Emissions	☐	N	☐	☐	☐	☐	☐	☐	☐	Y	Y
Land use	☐	N	☐	☐	☐	☐	☐	☐	☐	N	Y
Noise	☐	N	☐	☐	☐	☐	☐	☐	☐	Y	N
Particles Emissions	☐	Y	☐	☐	☐	☐	☐	☐	☐	Y	Y
SO_2 Emissions	☐	N	☐	☐	☐	☐	☐	☐	☐	Y	N
Economic									N		
CAPEX	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Y
OPEX	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Y
Maintenance	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Y
Cost of fuel	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	N/A
NPV	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	N
Payback period	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	N
Social									N		
Job creation	Y	N	Y	N	Y	Y	U	Y	☐	Y	Y
Benefits	☐	☐	☐	☐	☐	☐	☐	N	☐	☐	Y
Social Acceptability	☐	☐	☐	☐	☐	☐	D	N	☐	☐	N

C	Completeness
R	Redundancy
I	Independency
DC	Double counting
SP	Systemic principle
Con	Consistency
M	Measurability
Comp	Comparability
S	Size
IOT	Impact occurring over time

Simulation 6-7: Checklist of agreement between alternatives, criteria and objectives



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6.3.3 Construction of the evaluation matrix

Simulation 6-8: Evaluation Matrix

Technical

	Efficiency	Exergy	Primary Energy Ratio	Safety	Reliability	Maturity
Onshore Wind						
Wave and Tidal						
Hydropower						

Environment

	CO_2 Emissions	NOx Emissions	Land Use	Noise	Particles Emissions	SO_2 Emissions
Onshore Wind						
Wave and Tidal						
Hydropower						

Economic

	CAPEX	OPEX	Maintenance	Cost of fuel	NPV	Payback period
Onshore Wind						
Wave and Tidal						
Hydropower						

Social

	Job Creation	Benefits	Social Acceptability
Onshore Wind			
Wave and Tidal			
Hydropower			

6.3.4 Assign weight to the criteria

Simulation 6-9: Weight elicitation- Instructions

Instructions:

Please copy/paste the cells A9 to A13 into Column D, from least important to most important.
If you consider two or more cells to be of the same importance, place them together by adding a column to the right.

Blank spaces can be left between the cells. The blank spaces signify the difference in importance between criteria. You may leave from zero up to two blank spaces between criteria.

Original:

			Place Criteria Here
	1	**Least Important**	
	2		
Criteria for purchasing a car:	3		
Price	4		
Color	5		
Brand	6		
Style	7		
Petrol Consumption	8		
	9		
	10		
	11		
	12		
	13	**Most Important**	

First Example:

		Place Criteria Here
1	**Least Important**	**Colour**
2		**Style**
3		**Brand**
4		**Petrol Consumption**
5	**Most Important**	**Price**
6		
7		
8		

Second Example:

		Place Criteria Here
1	**Least Important**	**Colour**
2		
3		
4		**Style**
5		
6		
7		**Brand/ Petrol Consumption**
8		
9		
10		
11		
12		
13	**Most Important**	**Price**

Simulation 6-10: Weight elicitation- DM 1

Technology

1	**Least Important**	
2		
3		
4		
5		
6		
7		
8		
9		**Primary Energy Ratio**
10		**Maturity**
11		**Exergy**
12		**Safety**
13	**Most Important**	**Reliability**

Environmental

1	**Least Important**	
2		
3		
4		
5		
6		
7		
8		
9		**Land Use**
10		**Noise**
11		**NOx Emissions**
12		**SO2 Emissions**
13	**Most Important**	**CO2 Emissions**

Economic

1	**Least Important**	
2		
3		
4		
5		
6		
7		
8		**OPEX**
9		**NPV**
10		**Cost of fuel**
11		**Maintenance**
12		**CAPEX**
13	**Most Important**	**Payback Period**

Social

1	**Least Important**	
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		**Social Acceptability**
12		**Benefits**
13	**Most Important**	**Job Creation**

Main Criteria		
1	**Least Important**	
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		
12		**Social**
13	**Most Important**	**Economic**

Simulation 6-11: Weight elicitation- DM 2

Technology

1	**Least Important**	
2		
3		
4		
5		
6		**Maturity**
7		
8		**Reliability**
9		
10		**Safety**
11		**Exergy**
12		**Primary Energy Ratio**
13	**Most Important**	
1	**Least Important**	

Environmental

1	**Least Important**	
2		
3		
4		
5		**Noise**
6		
7		**Land Use**
8		
9		
10		**NOx Emissions**
11		**SO2 Emissions**
12		**CO2 Emissions**
13	**Most Important**	

Economic

1	**Least Important**	
2		
3		
4		
5		**Payback Period**
6		
7		**Maintenance**
8		
9		**Cost of fuel**
10		**OPEX**
11		**CAPEX**
12		**NPV**
13	**Most Important**	

Social

1	**Least Important**	
2		
3		
4		
5		
6		
7		**Social Acceptability**
8		
9		
10		**Benefits**
11		**Job Creation**
12		
13	**Most Important**	

Main Criteria

1	**Least Important**	
2		
3		
4		
5		
6		
7		
8		
9		**Social**
10		
11		
12	**Most Important**	**Economic**

Simulation 6-12: Weight elicitation- DM 3

Technology

Rank		Criteria
1	**Least Important**	
2		
3		
4		
5		Maturity
6		
7		
8		
9		Safety
10		
11		Primary Energy Ratio
12		
13	**Most Important**	Reliability; Exergy

Environmental

Rank		Criteria
1	**Least Important**	
2		
3		Noise
4		
5		
6		Land Use
7		
8		
9		
10		
11		SO2 Emissions
12		CO2 Emissions; NOx Emissions
13	**Most Important**	

Economic

Rank		Criteria
1	**Least Important**	Cost of fuel
2		
3		
4		
5		
6		
7		
8		Maintenance
9		
10		NPV
11		
12		CAPEX; OPEX
13	**Most Important**	Payback Period

Social

Rank		Criteria
1	**Least Important**	
2		
3		
4		
5		Benefits
6		
7		
8		
9		
10		Job Creation
11		Social Acceptability
12		
13	**Most Important**	

Main Criteria

Rank		Criteria
1	**Least Important**	
2		
3		
4		
5		
6		
7		
8		
9	**Most Important**	Social; Economic

Simulation 6-13: Weight elicitation- DM 4

	Technology	Environmental	Economic	Social
1 Least Important			NPV	
2			Maintenance	
3		SO2 Emissions		
4				
5			Cost of fuel	
6		NOx Emissions		
7	Reliability	CO2 Emissions		
8	Safety		Payback Period	
9	Maturity		OPEX	Social Acceptability
10	Exergy	Noise		Benefits
11				
12				
13 Most Important	Primary Energy Ratio	Land Use	CAPEX	Job Creation

Main Criteria

1 Least Important	
2	
3	
4	Social
5	
6	
7	Economic
8	
9	
10	
11	
12 Most Important	

Simulation 6-14: Weight Elicitation by DM using the SIMOS Method- Technology

DM 1's Weight
1/4

Ranking	sub-criteria	No. of cards	Weight (w)	Average Weight)	Relative Weight	Test
1	**Primary Energy Ratio**	1	1	1	5%	5%
2	**Maturity**	1	2	2	10%	10%
3	**Exergy**	1	3	3	14%	14%
4	**Safety**	1	4	4	19%	19%
5	**Reliability**	1	5	5	24%	24%
6	**Efficiency**	1	6	6	29%	29%
			21			100 %

DM 2's Weight 1/4

Ranking	sub-criteria	Number of cards	Weight (w)	Average Weight	Relative Weight	Test
1	**Maturity**	1	1	1	3%	3%
2		1	2	2		
3	**Reliability**	1	3	3	10%	10%
4		1	4	4		
5	**Safety**	1	5	5	17%	17%
6	**Exergy**	1	6	6	20%	20%
7	**Primary Energy Ratio**	1	7	7	23%	23%
8	**Efficiency**	1	8	8	27%	27%
			30			100%

DM 3's Weight 1/4

Ranking	sub-criteria	No of cards	Weight (w)	Average Weight	Relative Weight	Test
1	**Maturity**	1	1	1	2%	2%
2	White Card	1	2	2		0%
3	White Card	1	3	3		0%
4	White Card	1	4	4		0%
5	**Safety**	1	5	5	12%	12%
6	White Card	1	6	6		0%
7	**Primary Energy Ratio**	1	7	7	16%	16%
8	White Card	1	8	8		0%
9	**Reliability/Exergy**	2	9, 10	9.5	22%	44%
10	**Efficiency**	1	11	11	26%	26%
			43			100 %

Simulation 6-15: Weight Elicitation by DM using the SIMOS Method- Environmental

DM1

DM's Weight 1/4

Ranking	sub-criteria	No. of cards	Weight (w)	Average Weight)	Relative Weight	Test
1	**Land Use**	1	1	1	5%	5%
2	**Noise**	1	2	2	10%	10%
3	**Nox Emissions**	1	3	3	15%	15%
4	**SO2 Emissions**	1	4	4	20%	20%
5	**CO2 Emissions**	1	5	5	25%	25%
6	**Particle Emission**	1	5	5	25%	25%
			20			100%

DM2

DM's Weight **1/4**

Ranking	sub-criteria	No. of cards	Weight (w)	Average Weight	Relative Weight	Test
1	**Noise**	1	1	1	3%	3%
2		1	2	2		
3	**Land Use**	1	3	3	9%	9%
4		1	4	4		
5		1	5	5		
6	**Nox Emissions**	1	6	6	18%	18%
7	**SO2 Emissions**	1	7	7	21%	21%
8	**CO2 Emissions**	1	8	8	24%	24%
9	**Particle Emission**	1	9	9	26%	26%
			34			100 %

DM3

DM's Weight 1/4

Ranking	sub-criteria	No. of cards	Weight (w)	Average Weight)	Relative Weight	Test
1	**Noise**	1	1	1	2%	2%
2	White Card	1	2	2		
3	White Card	1	3	3		
4	**Land Use**	1	4	4	9%	9%
5	White Card	1	5	5		
6	White Card	1	6	6		
7	White Card	1	7	7		
8	White Card	1	8	8		
9	**SO2 Emissions**	1	9	9	19%	19%
10	**CO2 Emissions/ NOx Emissions**	2	10, 11	11	22%	45%
11	**Particle Emission**	1	12	12	26%	26%
			47			100 %

DM4

DM's Weight	**1/4**					
Ranking	**sub-criteria**	**No. of cards**	**Weight (w)**	**Average Weight)**	**Relative Weight**	**Test**
1	**SO2 Emissions**	1	1	1	2%	2%
2		1	2	2		
3		1	3	3		
4	**NOx Emissions**	1	4	4	10%	10%
5	**CO2 Emissions**	1	5	5	12%	12%
6		1	6	6		
7		1	7	7		
8	**Noise**	1	8	8	20%	20%
9		1	9	9		
10		1	10	10		
11	**Land Use**	1	11	11	27%	27%
12	**Particle Emission**	1	12	12	29%	29%
			41			100%

Simulation 6-16: Weight Elicitation by DM using the SIMOS Method- Economic

DM1

DM's Weight 1/4

Ranking	sub-criteria	Number of cards	Weight (w)	Average Weight)	Relative Weight	Test
1	OPEX	1	1	1	5%	5%
2	NPV	1	2	2	10%	10%
3	Cost of fuel	1	3	3	14%	14%
4	Maintenance	1	4	4	19%	19%
5	CAPEX	1	5	5	24%	24%
6	Payback Period	1	6	6	29%	29%
			21			100%

DM2

DM's Weight 1/4

Ranking	sub-criteria	Number of cards	Weight (w)	Average Weight	Relative Weight	Test
1	Payback Period	1	1	1	3%	3%
2		1	2	2		
3	Maintenance	1	3	3	10%	10%
4		1	4	4		
5	Cost of fuel	1	5	5	17%	17%
6	OPEX	1	6	6	20%	20%
7	CAPEX	1	7	7	23%	23%
8	NPV	1	8	8	27%	27%
			30			100%

DM3

DM's Weight 1/4

Ranking	sub-criteria	Number of cards	Weight (w)	Average Weight	Relative Weight	Test
1	**Cost of fuel**	1	1	1	2%	2%
2	White Card	1	2	2		
3	White Card	1	3	3		
4	White Card	1	4	4		
5	White Card	1	5	5		
6	White Card	1	6	6		
7	White Card	1	7	7		
8	**Maintenance**	1	8	8	14%	14%
9	White Card	1	9	9		
10	**NPV**	1	10	10	17%	17%
11	White Card	1	11	11		
12	**CAPEX/ OPEX**	2	12, 13	12.5	22%	43%
13	**Payback Period**	1	14	14	24%	24%
			58			100%

DM4

DM's Weight 1/4

Ranking	sub-criteria	Number of cards	Weight (w)	Average Weight)	Relative Weight	Test
1	**NPV**	1	1	1	3%	3%
2	**Maintenance**	1	2	2	5%	5%
3		1	3	3		0%
4		1	4	4		0%
5	**Cost of fuel**	1	5	5	13%	13%
6		1	6	6		0%
7		1	7	7		0%
8	**Payback Period**	1	8	8	21%	21%
9	**OPEX**	1	9	9	24%	24%
10		1	10	10		0%
11		1	11	11		0%
12		1	12	12		0%
13	**CAPEX**	1	13	13	34%	34%
			38			100%

Simulation 6-17: Weight Elicitation by DM using the SIMOS Method-Social

DM1

DM's Weight 1/4

Ranking	sub-criteria	Number of cards	Weight (w)	Average Weight)	Relative Weight	Test
1	Social Acceptability	1	1	1	17%	17%
2	Benefits	1	2	2	33%	33%
3	Job Creation	1	3	3	50%	50%
			6			100%

DM2

DM's Weight 1/4

Ranking	sub-criteria	Number of cards	Weight (w)	Average Weight	Relative Weight	Test
1	Social Acceptability	1	1	1	10%	10%
2		1	2	2	20%	
3		1	3	3	30%	
4	Benefits	1	4	4	40%	40%
5	Job Creation	1	5	5	50%	50%
			10			100%

DM3

DM's Weight 1/4

Ranking	sub-criteria	Number of cards	Weight (w)	Average Weight	Relative Weight	Test
1	Benefits	1	1	1	7%	7%
2	White Card	1	2	2		0%
3	White Card	1	3	3		0%
4	White Card	1	4	4		0%
5	White Card	1	5	5		0%
6	Job Creation	1	6	6	43%	43%
	Social Acceptability	1	7	7	50%	50%
			14			100%

DM4

DM's Weight 1/4

Ranking	sub-criteria	Number of cards	Weight (w)	Average Weight)	Relative Weight	Test
1	**Social Acceptability**	1	1	1	13%	13%
2	**Benefits**	1	2	2	25%	25%
3		1	3	3		0%
4		1	4	4		0%
5	**Job Creation**	1	5	5	63%	63%
			8			100%

Simulation 6-18: Weight Elicitation by DM using the SIMOS Method-Main Criteria

DM1

DM's Weight 1/4

Ranking	Main Criteria	Number of cards	Weight (w)	Average Weight)	Relative Weight	Test
1	Social	1	1	1	10%	10%
2	Economic	1	2	2	20%	20%
3	Environment	1	3	3	30%	30%
4	Technology	1	4	4	40%	40%
			10			1

DM2

DM's Weight 1/4

Ranking	Main Criteria	Number of cards	Weight (w)	Average Weight)	Relative Weight	Test
1	Social	1	1	1	6%	6%
2		1	2	2		0%
3		1	3	3		0%
4	Economic	1	4	4	25%	25%
5	Environment	1	5	5	31%	31%
6	Technology	1	6	6	38%	38%
			16			100%

DM3

DM's Weight 1/4

Ranking	Main Criteria	Number of cards	Weight (w)	Average Weight	Relative Weight	Test
1	Social/ Economic	2	1, 2	1.5	15%	30%
2	Environment	1	3	3	30%	30%
3	Technology	1	4	4	40%	40%
			10			100%

DM4

DM's Weight 1/4

Ranking	Main Criteria	Number of cards	Weight (w)	Average Weight)	Relative Weight	Test
1	Social	1	1	1	6%	6%
2		1	2	2		
3		1	3	3		
4	Economic	1	4	4	25%	25%
5	Environment	1	5	5	31%	31%
6	Technology	1	6	6	38%	38%
			16			100%

Simulation 6-19: Aggregation of Multiple DM's weights using the AIP method

	Aggregate result	Weight
Technology	39%	41%
Environment	31%	32%
Economic	16%	17%
Social	9%	10%
	0.95	1.00

Technology

	Aggr result	Weight	Sub-criteria global weight
Primary Energy Ratio	18%	18%	7%
Maturity	7%	7%	3%
Exergy	18%	18%	7%
Safety	14%	14%	6%
Reliability	15%	15%	6%
Efficiency	28%	28%	12%
	1.00	100%	41%

Environment

	Agg result	Weight	Sub-criteria global weight
Land Use	3%	7%	2%
Noise	3%	6%	2%
Nox Emissions	9%	19%	6%
SO2 Emissions	10%	20%	6%
CO2 Emissions	12%	24%	8%
Particle Emission	13%	25%	8%
	50%	100%	32%

Economic

	Agg result	Weight	Sub-criteria global weight
CAPEX	26%	26%	4%
NPV	14%	14%	2%
OPEX	17%	17%	3%
Payback Period	19%	19%	3%
Maintenance	12%	12%	2%
Cost of fuel	11%	11%	2%
	1.00	1.00	17%

Social

	Agg result	Weight	Sub-criteria global weight
Job Creation	51%	51%	5%
Benefits	26%	26%	3%
Social Acceptability	22%	22%	2%
	1.00	1.00	10%

Simulation 6-20: Criteria selection according to weight

Technology

	Aggregate result	Weight	Sub-criteria global weight
Primary Energy Ratio	18.094%	28%	11%
Maturity	7%		
Exergy	18.095%	28%	11%
Safety	14%		
Reliability	15%		
Efficiency	28%	44%	18%
	64%	100%	41%

Environment

	Aggregate result	Weight	Sub-criteria global weight
Land Use	3%		
Noise	3%		
NOx Emissions	9%	28%	8.90%
SO2 Emissions	9.79%		
CO2 Emissions	12%	35%	11%
Particle Emission	13%	37%	12%
	34%	100%	32%

Economic

	Aggregate result	Weight	Sub-criteria global weight
CAPEX	26%	41%	7%
NPV	14%		
OPEX	17%	28%	5%
Payback Period	19%	31%	5%
Maintenance	12%		
Cost of fuel	11%		
	62%	1.00	17%

Social

	Aggregate result	Weight	Sub-criteria global weight
Job Creation	51%	51%	5%
Benefits	26%	26%	3%
Social Acceptability	22%	22%	2%
	1.00	1.00	10%

6.3.5 Selection of the Appropriate method

Simulation 6-21: Considerations for the selection of the appropriate MCA method

	AHP	MAUT	PROMETHEE	ELECTRE	WSM
How many DMs involved?	4	4	4	4	4
Are all appropriate stakeholders engaged? How much is their involvement?	Yes, through the selection of key players and decision-makers	Yes, through the selection of key players and decision-makers	Yes, through the selection of key players and decision-makers	Yes, through the selection of key players and decision-makers	Yes, through the selection of key players and decision-makers
How does the DM prefer to have the data presented?					
What kind of result is the DM looking for?	Less objective as the calculation is a result of comparison.	Provides more objectivity as the results is obtained from mathematical calculations	Provides more objectivity as the results is obtained from mathematical calculations	Provides more objectivity as the results is obtained from mathematical calculations	Provides more objectivity as the results is obtained from mathematical calculations
Can data be easily obtained?	Yes	Yes	No	No	yes
Is the DM looking for compensations?					
Method meets main assumptions?	Yes	Yes	Yes	Yes	Yes
Software needed?	No	No	Yes	Yes	No
Can the method support many alternatives and criteria?	Yes	Yes	Yes	Yes	Yes
How does the model quantify the importance of the criteria or their weights?	All models will use the SIMOS and AIP methods	All models will use the SIMOS and AIP methods	All models will use the SIMOS and AIP methods	All models will use the SIMOS and AIP methods	All models will use the SIMOS and AIP methods
How does the model deal with uncertainty?	Regarding the criteria, this is somewhat captured with the use of the SIMOS method	Regarding the criteria, this is somewhat captured with the use of the SIMOS method	Regarding the criteria, this is somewhat captured with the use of the SIMOS method	Regarding the criteria, this is somewhat captured with the use of the SIMOS method	Regarding the criteria, this is somewhat captured with the use of the SIMOS method
Can the decision be re-evaluated using new data?	Yes	Yes	Yes	Yes	Yes
Is the model transparent and easy to explain?	Yes	Yes	Difficult to explain	Difficult to Explain	Yes
Is the method easy to use?	Yes	Yes	No	No	Yes
Does the method provide for sensitivity analysis?	Yes	Yes	Yes	Yes	Yes

6.3.6 Analysis and ranking of the alternatives

Simulation 6-22: MAUT

Raw Scale

	Technical			Environment			Economic			Social		
	Efficiency	Exergy	Primary Energy Ratio	CO_2 Emission	NOx Emission	Particles Emission	CAPEX USDm/MW	OPEX USD/MW/yr	Payback period (yrs)	Job Creation	Benefits USDm/MW	Social Acceptability
Weight	**18%**	**11%**	**11%**	**11%**	**9%**	**12%**	**7%**	**5%**	**5%**	**5%**	**3%**	**2%**
Onshore Wind	70%	48.70 %	1.44%	11	12	0.1	1.52	28,750.00	8	11	0.304	5
Wave and Tidal	90%	62%	0.89%	17	17	0.1	9.03	130,000.00	7.5	21	1.806	9
Hydropower	95%	66%	6.79%	24	24	0.5	3.915	73,500.00	6.2	15	0.783	9

Normalize Scale: Maximize Criterion

	Technical			Environment			Economic			Social		
	Efficiency	Exergy	Primary Energy Ratio	CO_2 Emission	NOx Emission	Particles Emissions	CAPEX	OPEX	Payback period	Job Creation	Benefits	Social Acceptability
Onshore Wind	0.000	0.000	0.093	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000
Wave and Tidal	0.800	0.795	0.000	0.462	0.417	0.000	1.000	1.000	0.722	1.000	1.000	1.000
Hydropower	1.000	1.000	1.000	1.000	1.000	1.000	0.319	0.442	0.000	0.400	0.319	1.000

Normalized Scale: Minimize Criterion

	Technical			Environment			Economic			Social		
	Efficiency	Exergy	Primary Energy Ratio	CO_2 Emissions	NOx Emissions	Particles Emissions	CAPEX	OPEX	Payback period	Job Creation	Benefits	Social Acceptability
Onshore Wind	1.000	1.000	0.907	1.000	1.000	1.000	1.000	1.000	0.000	1.000	1.000	1.000
Wave and Tidal	0.200	0.205	1.000	0.538	0.583	1.000	0.000	0.000	0.278	0.000	0.000	0.000
Hydropower	0.000	0.000	0.000	0.000	0.000	0.000	0.681	0.558	1.000	0.600	0.681	0.000

Normalized matrix

	Technical			Environment			Economic			Social		
	Efficiency	Exergy	Primary Energy Ratio	CO_2 Emissions	NOx Emissions	Particles Emissions	CAPEX	OPEX	Payback period	Job Creation	Benefits	Social Acceptability
	max	max	max	min	min	min	min	min	max	max	max	max
Onshore Wind	0.000	0.000	0.093	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.000	0.000
Wave and Tidal	0.800	0.795	0.000	0.538	0.583	1.000	0.000	0.000	0.722	1.000	1.000	1.000
Hydropower	1.000	1.000	1.000	0.000	0.000	0.000	0.681	0.558	0.000	0.400	0.319	1.000

Marginal Utility

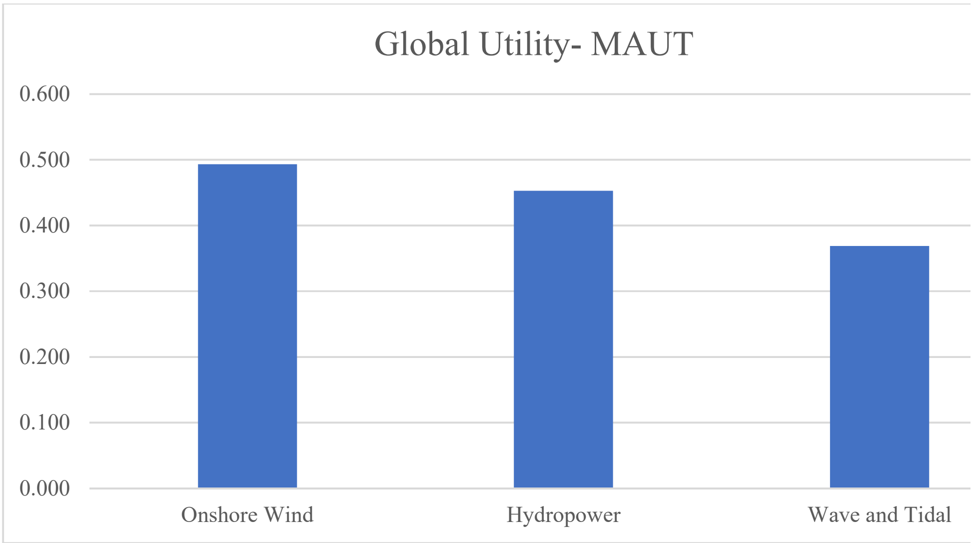
	Technical			Environment			Economic			Social		
	Efficiency	Exergy	Primary Energy Ratio	CO_2 Emissions	NOx Emissions	Particles Emissions	CAPEX	OPEX	Payback period	Job Creation	Benefits	Social Acceptability
Onshore Wind	0.000	0.000	0.000	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.000	0.000
Wave and Tidal	0.389	0.380	0.000	0.098	0.128	1.000	0.000	0.000	0.266	1.000	1.000	1.000
Hydropower	1.000	1.000	1.000	0.000	0.000	0.000	0.216	0.110	0.000	0.038	0.019	1.000

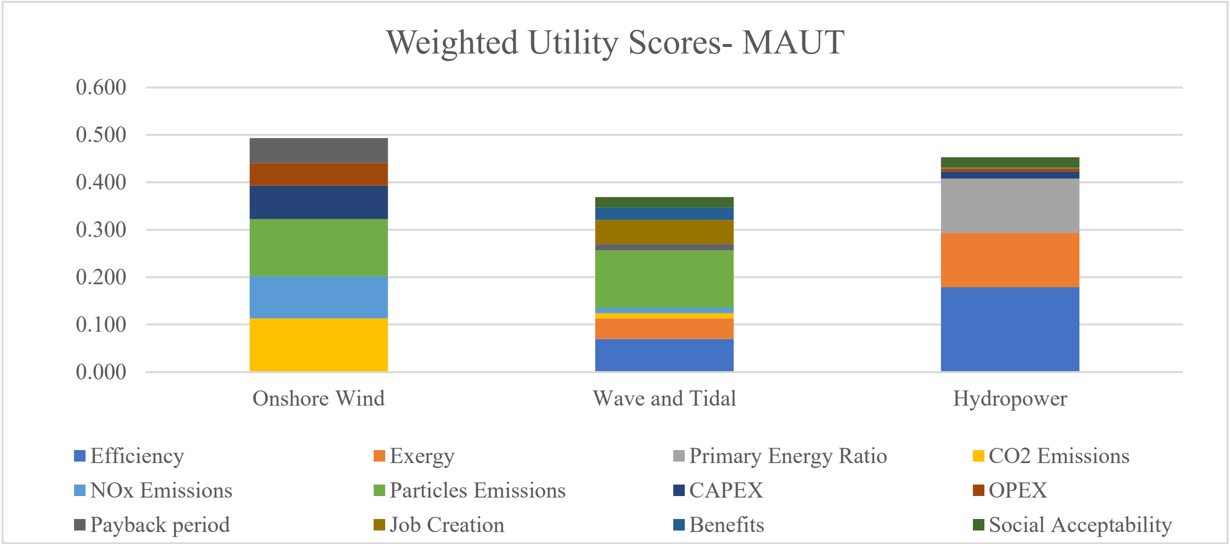
Analysis and Result

	Technical			Environment			Economic			Social			
	Efficiency	Exergy	Primary Energy Ratio	CO_2 Emissions	NOx Emissions	Particles Emissions	CAPEX	OPEX	Payback period	Job Creation	Benefits	Social Accept	Result
	18%	11%	11%	11%	9%	12%	7%	5%	5%	5%	3%	2%	
Onshore Wind	0.000	0.000	0.000	0.113	0.089	0.120	0.070	0.048	0.053	0.000	0.000	0.000	0.493
Wave and Tidal	0.070	0.044	0.000	0.011	0.011	0.120	0.000	0.000	0.014	0.051	0.026	0.022	0.369
Hydropower	0.179	0.115	0.115	0.000	0.000	0.000	0.015	0.005	0.000	0.002	0.000	0.022	0.453

Ranking

1	0.493	Onshore Wind
2	0.453	Hydropower
3	0.369	Wave and Tidal


Global Utility- MAUT
0.600
0.500
0.400
0.300
0.200
0.100
0.000
Onshore Wind
Hydropower
Wave and Tidal


Weighted Utility Scores- MAUT
0.600
0.500
0.400
0.300
0.200
0.100
0.000
Onshore Wind
Wave and Tidal
Hydropower
Efficiency
Exergy
Primary Energy Ratio
CO2 Emissions
NOx Emissions
Particles Emissions
CAPEX
OPEX
Payback period
Job Creation
Benefits
Social Acceptability

Simulation 6-23: WSM

Raw Scale

	Technical			Environment			Economic			Social		
	Efficiency	Exergy	Primary Energy Ratio	CO_2 Emissions	NOx Emissions	Particles Emissions	CAPEX USDm/MW	OPEX USD/MW/yr	Payback period (yrs)	Job Creation	Benefits USDm/MW	Social Acceptability
	18%	**11%**	**11%**	**11%**	**9%**	**12%**	**7%**	**5%**	**5%**	**5%**	**3%**	**2%**
Onshore Wind	70%	48.70 %	1.44%	11	12	0.1	1.52	28,750.00	8	11	0.304	5
Wave and Tidal	90%	62%	0.89%	17	17	0.1	9.03	130,000.00	7.5	21	1.806	9
Hydropower	95%	66%	6.79%	24	24	0.5	3.915	73,500.00	6.2	15	0.783	9

Normalize Scale: Maximize Criterion

	Technical			Environment			Economic			Social		
	Efficiency	Exergy	Primary Energy Ratio	CO_2 Emissions	NOx Emissions	Particles Emissions	CAPEX	OPEX	Payback period	Job Creation	Benefits	Social Acceptability
Onshore Wind	0.000	0.000	0.093	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000
Wave and Tidal	0.800	0.795	0.000	0.462	0.417	0.000	1.000	1.000	0.722	1.000	1.000	1.000
Hydropower	1.000	1.000	1.000	1.000	1.000	1.000	0.319	0.442	0.000	0.400	0.319	1.000

Normalized Scale: Minimize Criterion

	Technical			Environment			Economic			Social		
	Efficiency	Exergy	Primary Energy Ratio	CO_2 Emissions	NOx Emissions	Particles Emissions	CAPEX	OPEX	Payback period	Job Creation	Benefits	Social Acceptability
Onshore Wind	1.000	1.000	0.907	1.000	1.000	1.000	1.000	1.000	0.000	1.000	1.000	1.000
Wave and Tidal	0.200	0.205	1.000	0.538	0.583	1.000	0.000	0.000	0.278	0.000	0.000	0.000
Hydropower	0.000	0.000	0.000	0.000	0.000	0.000	0.681	0.558	1.000	0.600	0.681	0.000

Normalized matrix

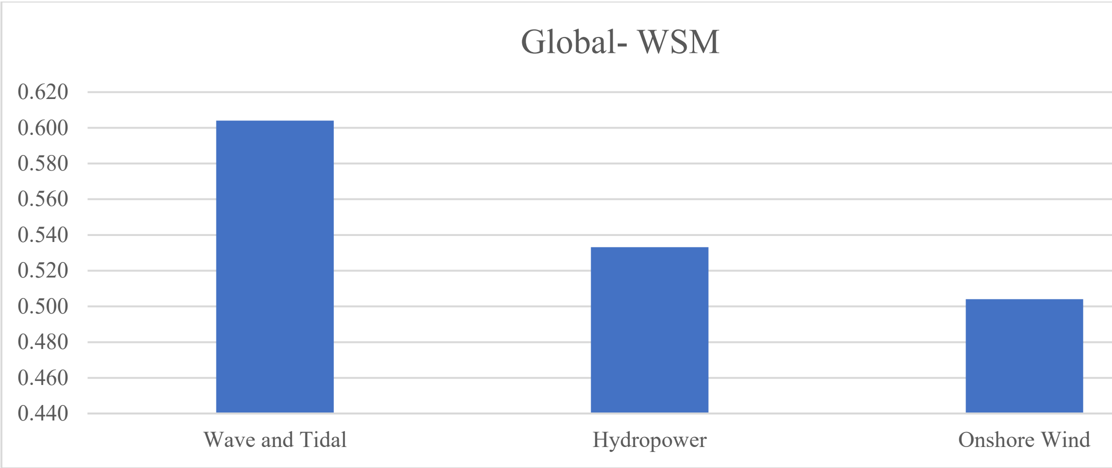
	Technical			Environment			Economic			Social		
	Efficiency	Exergy	Primary Energy Ratio	CO_2 Emissions	NOx Emissions	Particles Emissions	CAPEX	OPEX	Payback period	Job Creation	Benefits	Social Acceptability
	18%	11%	11%	11%	9%	12%	7%	5%	5%	5%	3%	2%
Onshore Wind	0.000	0.000	0.093	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.000	0.000
Wave and Tidal	0.800	0.795	0.000	0.538	0.583	1.000	0.000	0.000	0.722	1.000	1.000	1.000
Hydropower	1.000	1.000	1.000	0.000	0.000	0.000	0.681	0.558	0.000	0.400	0.319	1.000

Analysis and Result

	Technical			Environment			Economic			Social			
	Efficiency	Exergy	Primary Energy Ratio	CO_2 Emissions	NOx Emissions	Particles Emissions	CAPEX	OPEX	Payback period	Job Creation	Benefits	Social Acceptability	Result
Onshore Wind	0.000	0.000	0.011	0.113	0.089	0.120	0.070	0.048	0.053	0.000	0.000	0.000	0.504
Wave and Tidal	0.143	0.091	0.000	0.061	0.052	0.120	0.000	0.000	0.038	0.051	0.026	0.022	0.604
Hydropower	0.179	0.115	0.115	0.000	0.000	0.000	0.048	0.027	0.000	0.020	0.008	0.022	0.533

Ranking

1	0.604	Wave and Tidal
2	0.533	Hydropower
3	0.504	Onshore Wind


Global- WSM
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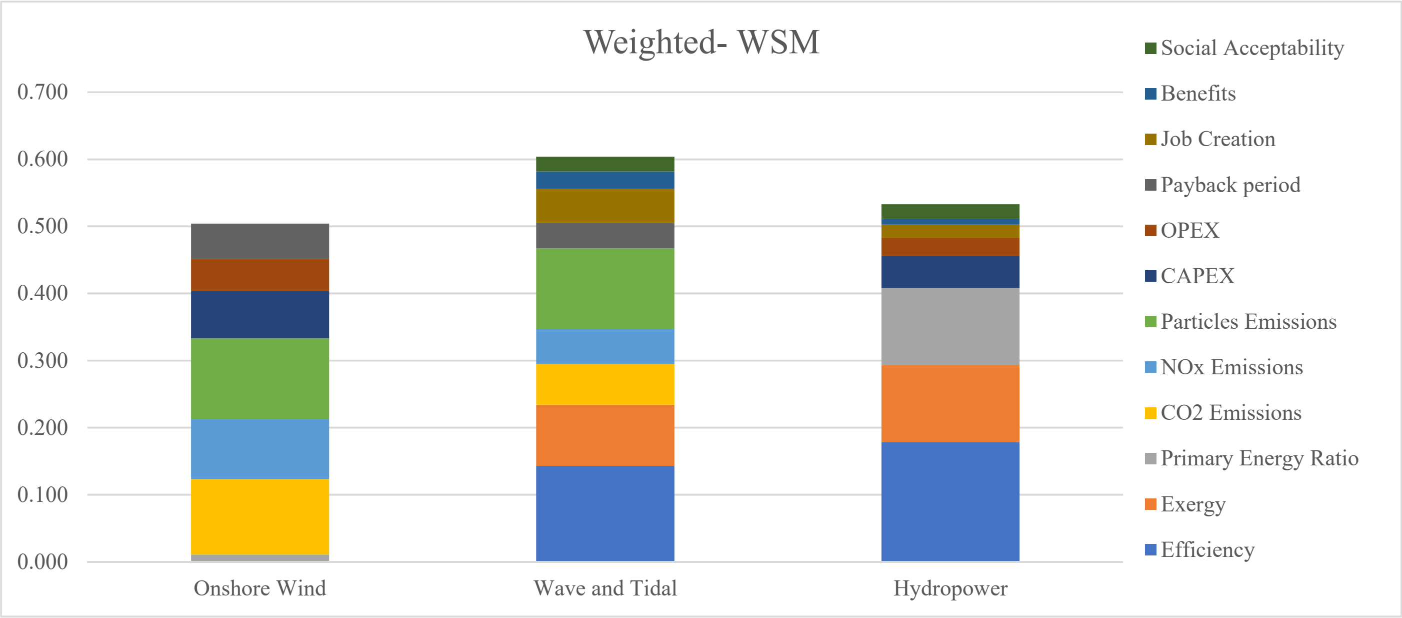
0.600
0.580
0.560
0.540
0.520
0.500
0.480
0.460
0.440
Wave and Tidal
Hydropower
Onshore Wind


Weighted- WSM
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
Onshore Wind
Wave and Tidal
Hydropower
Social Acceptability
Benefits
Job Creation
Payback period
OPEX
CAPEX
Particles Emissions
NOx Emissions
CO2 Emissions
Primary Energy Ratio
Exergy
Efficiency

6.3.7 Sensitivity Analysis and Recommendations

Simulation 6-24: Sensitivity Weight Change

Technology

	Aggregate result	Weight	Sub-criteria global weight
Primary Energy Ratio	18.094%		0%
Maturity	7%		
Exergy	18.095%	30%	12%
Safety	14%		
Reliability	15%	24%	10%
Efficiency	28%	46%	19%
	61%	100%	41%

Environment

	Aggregate result	Weight	Sub-criteria global weight
Land Use	3%	12%	4%
Noise	3%		
NOx Emissions	9.34%		
SO2 Emissions	9.79%		
CO2 Emissions	12%	43%	14%
Particle Emission	13%	45%	15%
	0.28	100%	32%

Economic

	Aggregate result	Weight	Sub-criteria global weight
CAPEX	26%	41%	7%
NPV	14%		
OPEX	17%	28%	5%
Payback Period	19%	31%	5%
Maintenance	12%		
Cost of fuel	11%		
	0.62	1.00	17%

Social

	Aggregate result	Weight	Sub-criteria global weight
Job Creation	51%	51%	5%
Benefits	26%	26%	3%
Social Acceptability	22%	22%	2%
	100%	100%	10%

Simulation 6-25: Sensitivity MAUT

Raw Scale

	Technical			Environment			Economic			Social		
	Efficiency	Exergy	**Reliability**	CO_2 Emissions	**Land Use**	Particles Emissions	CAPEX USDm/MW	OPEX USD/MW/yr	Payback period (yrs)	Job Creation	Benefits USDm/MW	Social Acceptability
	19%	**12%**	**10%**	**14%**	**4%**	**15%**	**7%**	**5%**	**5%**	**5%**	**3%**	**2%**
Onshore Wind	70%	48.70 %	3.00	11	8	0.1	1.52	28,750.00	8	11	0.304	5
Wave and Tidal	90%	62%	9.00	17	0	0.1	9.03	130,000.00	7.5	21	1.806	9
Hydropower	95%	66%	5.00	24	60	0.5	3.915	73,500.00	6.2	15	0.783	9

Normalize Scale: Maximize Criterion

	Technical			Environment			Economic			Social		
	Efficiency	Exergy	**Reliability**	CO_2 Emissions	**Land Use**	Particles Emissions	CAPEX	OPEX	Payback period	Job Creation	Benefits	Social Acceptability
Onshore Wind	0.000	0.000	0.000	0.000	0.133	0.000	0.000	0.000	1.000	0.000	0.000	0.000
Wave and Tidal	0.800	0.795	1.000	0.462	0.000	0.000	1.000	1.000	0.722	1.000	1.000	1.000
Hydropower	1.000	1.000	0.333	1.000	1.000	1.000	0.319	0.442	0.000	0.400	0.319	1.000

Normalized Scale: Minimize Criterion

	Technical			Environment			Economic			Social		
	Efficiency	Exergy	**Reliability**	CO_2 Emissions	**Land Use**	Particles Emissions	CAPEX USDm/MW	OPEX USD/MW/yr	Payback period (yrs)	Job Creation	Benefits USDm/MW	Social Acceptability
Onshore Wind	1.000	1.000	1.000	1.000	0.867	1.000	1.000	1.000	0.000	1.000	1.000	1.000
Wave and Tidal	0.200	0.205	0.000	0.538	1.000	1.000	0.000	0.000	0.278	0.000	0.000	0.000
Hydropower	0.000	0.000	0.667	0.000	0.000	0.000	0.681	0.558	1.000	0.600	0.681	0.000

Normalized matrix

	Technical			Environment			Economic			Social		
	Efficiency	Exergy	**Reliability**	CO_2 Emissions	**Land Use**	Particles Emissions	CAPEX	OPEX	Payback period	Job Creation	Benefits	Social Acceptability
	max	max	max	min	min	min	min	min	max	max	max	max
Onshore Wind	0.000	0.000	0.000	1.000	0.867	1.000	1.000	1.000	1.000	0.000	0.000	0.000
Wave and Tidal	0.800	0.795	1.000	0.538	1.000	1.000	0.000	0.000	0.722	1.000	1.000	1.000
Hydropower	1.000	1.000	0.333	0.000	0.000	0.000	0.681	0.558	0.000	0.400	0.319	1.000

Marginal Utility

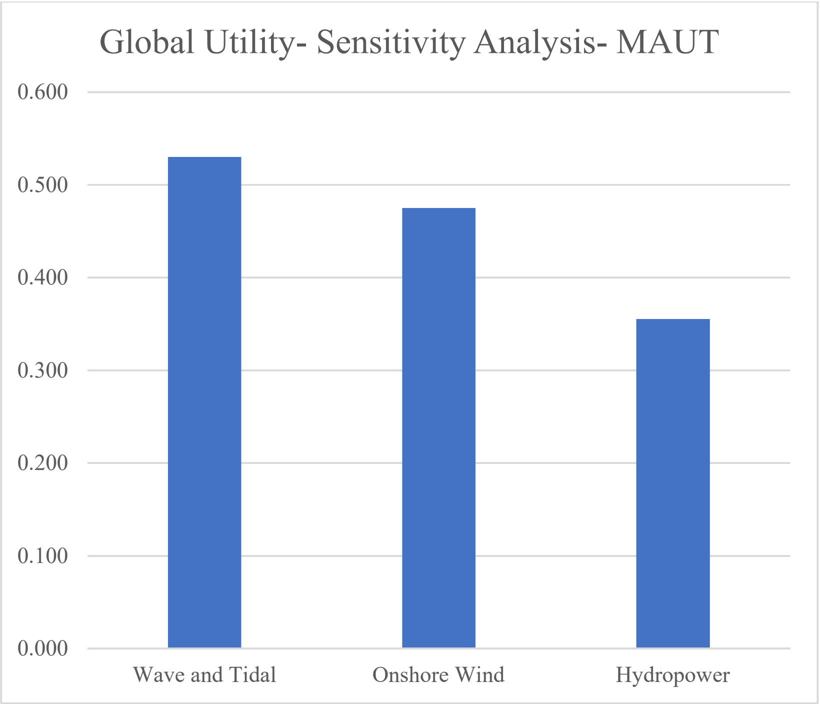
	Technical			Environment			Economic			Social		
	Efficiency	Exergy	**<u>Reliability</u>**	CO_2 Emissions	**<u>Land Use</u>**	Particles Emissions	CAPEX	OPEX	Payback period	Job Creation	Benefits	Social Acceptability
Onshore Wind	0.000	0.000	0.000	1.000	0.534	1.000	1.000	1.000	1.000	0.000	0.000	0.000
Wave and Tidal	0.389	0.380	1.000	0.098	1.000	1.000	0.000	0.000	0.266	1.000	1.000	1.000
Hydropower	1.000	1.000	0.022	0.000	0.000	0.000	0.216	0.110	0.000	0.038	0.019	1.000

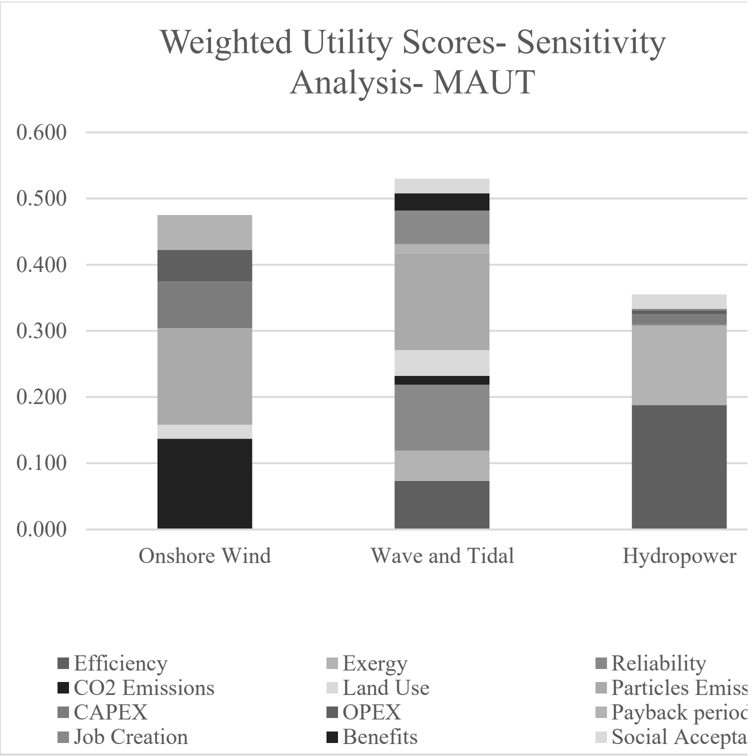
Analysis and Result

	Technical			Environment			Economic			Social			
	Efficiency	Exergy	**<u>Reliability</u>**	CO_2 Emissions	**<u>Land Use</u>**	Particles Emissions	CAPEX	OPEX	Payback period	Job Creation	Benefits	Social Acceptability	Result
	19%	**12%**	**10%**	**14%**	**4%**	**15%**	**7%**	**5%**	**5%**	**5%**	**3%**	**2%**	
Onshore Wind	0.000	0.000	0.000	0.137	0.021	0.146	0.070	0.048	0.053	0.000	0.000	0.000	0.475
Wave and Tidal	0.073	0.046	0.100	0.013	0.039	0.146	0.000	0.000	0.014	0.051	0.026	0.022	0.530
Hydropower	0.188	0.120	0.002	0.000	0.000	0.000	0.015	0.005	0.000	0.002	0.000	0.022	0.355

Ranking

1	0.530	Wave and Tidal
2	0.475	Onshore Wind
3	0.355	Hydropower


Global Utility- Sensitivity Analysis- MAUT
0.600
0.500
0.400
0.300
0.200
0.100
0.000
Wave and Tidal
Onshore Wind
Hydropower


Weighted Utility Scores- Sensitivity Analysis- MAUT
0.600
0.500
0.400
0.300
0.200
0.100
0.000
Onshore Wind
Wave and Tidal
Hydropower
Efficiency
Exergy
Reliability
CO2 Emissions
Land Use
Particles Emiss
CAPEX
OPEX
Payback period
Job Creation
Benefits
Social Accepta

Simulation 6-26: Sensitivity -WSM

Raw Scale

	Technical			Environment			Economic			Social		
	Efficiency	Exergy	**Reliability**	CO_2 Emissions	**Land Use**	Particles Emissions	CAPEX USDm/MW	OPEX USD/MW/yr	Payback period (yrs)	Job Creation	Benefits USDm/MW	Social Acceptability
	19%	**12%**	**10%**	**14%**	**4%**	**15%**	**7%**	**5%**	**5%**	**5%**	**3%**	**2%**
Onshore Wind	70%	48.70 %	3.00	11	8	0.1	1.52	28,750.00	8	11	0.304	5
Wave and Tidal	90%	62%	9.00	17	0	0.1	9.03	130,000.00	7.5	21	1.806	9
Hydropower	95%	66%	5.00	24	60	0.5	3.915	73,500.00	6.2	15	0.783	9

Normalize Scale: Maximize Criterion

	Technical			Environment			Economic			Social		
	Efficiency	Exergy	**Reliability**	CO_2 Emissions	**Land Use**	Particles Emissions	CAPEX USDm/MW	OPEX USD/MW/yr	Payback period (yrs)	Job Creation	Benefits USDm/MW	Social Acceptability
Onshore Wind	0.000	0.000	0.000	0.000	0.133	0.000	0.000	0.000	1.000	0.000	0.000	0.000
Wave and Tidal	0.800	0.795	1.000	0.462	0.000	0.000	1.000	1.000	0.722	1.000	1.000	1.000
Hydropower	1.000	1.000	0.333	1.000	1.000	1.000	0.319	0.442	0.000	0.400	0.319	1.000

Normalized Scale: Minimize Criterion

	Technical			Environment			Economic			Social		
	Efficiency	Exergy	**Reliability**	CO_2 Emissions	**Land Use**	Particles Emissions	CAPEX	OPEX	Payback period	Job Creation	Benefits	Social Acceptability
Onshore Wind	1.000	1.000	1.000	1.000	0.867	1.000	1.000	1.000	0.000	1.000	1.000	1.000
Wave and Tidal	0.200	0.205	0.000	0.538	1.000	1.000	0.000	0.000	0.278	0.000	0.000	0.000
Hydropower	0.000	0.000	0.667	0.000	0.000	0.000	0.681	0.558	1.000	0.600	0.681	0.000

Normalized matrix

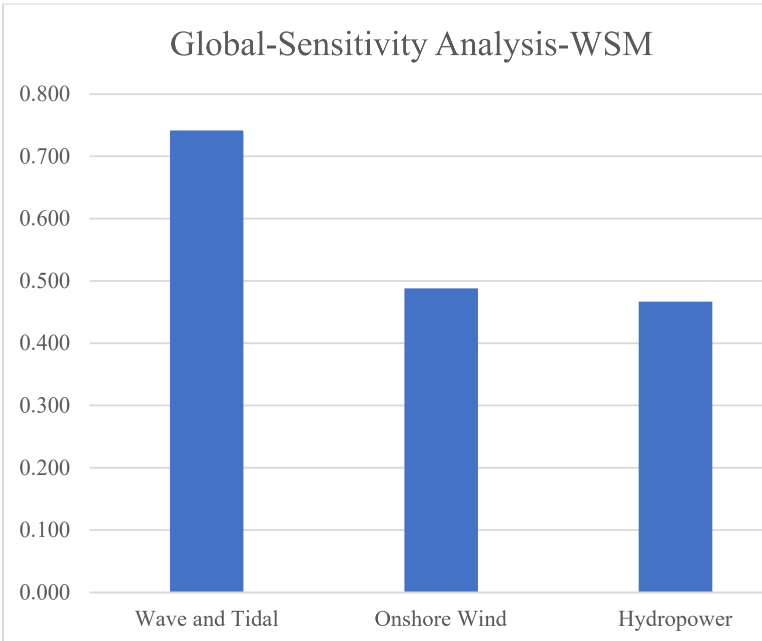
	Technical			Environment			Economic			Social		
	Efficiency	Exergy	**Reliability**	CO_2 Emissions	**Land Use**	Particles Emissions	CAPEX	OPEX	Payback period	Job Creation	Benefits	Social Acceptability
	19%	12%	10%	14%	4%	15%	7%	5%	5%	5%	3%	2%
Onshore Wind	0.000	0.000	0.000	1.000	0.867	1.000	1.000	1.000	1.000	0.000	0.000	0.000
Wave and Tidal	0.800	0.795	1.000	0.538	1.000	1.000	0.000	0.000	0.722	1.000	1.000	1.000
Hydropower	1.000	1.000	0.333	0.000	0.000	0.000	0.681	0.558	0.000	0.400	0.319	1.000

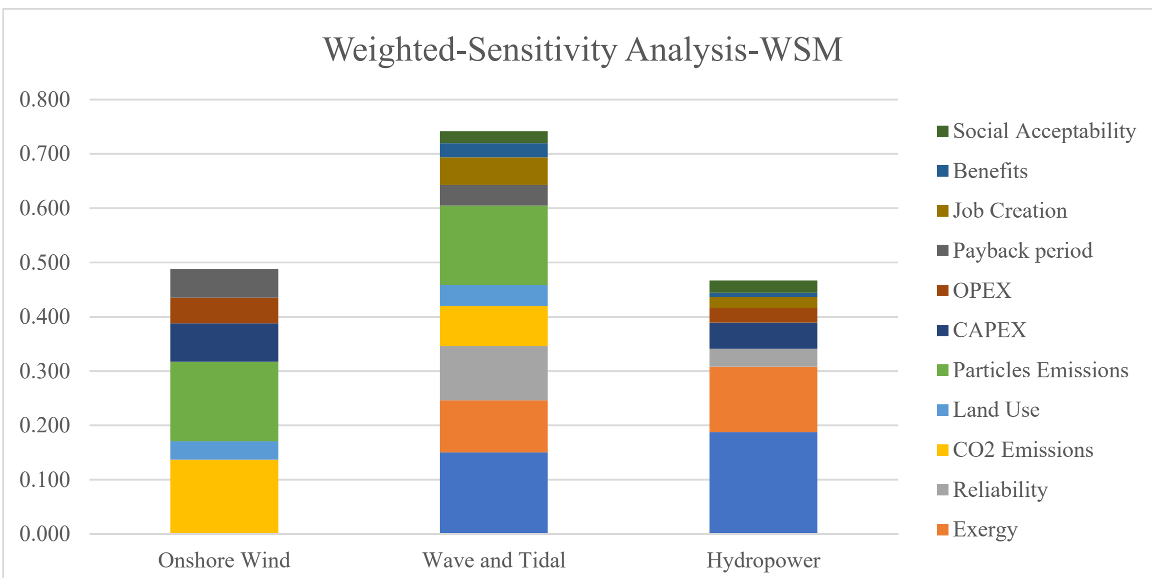
Analysis and Result

	Technical			Environment			Economic			Social			
	Efficiency	Exergy	**Reliability**	CO_2 Emissions	**Land Use**	Particles Emissions	CAPEX	OPEX	Payback period	Job Creation	Benefits	Social Acceptability	Result
Onshore Wind	0.000	0.000	0.000	0.137	0.034	0.146	0.070	0.048	0.053	0.000	0.000	0.000	0.488
Wave and Tidal	0.150	0.096	0.100	0.074	0.039	0.146	0.000	0.000	0.038	0.051	0.026	0.022	0.742
Hydropower	0.188	0.120	0.033	0.000	0.000	0.000	0.048	0.027	0.000	0.020	0.008	0.022	0.467

Ranking

1	0.742	Wave and Tidal
2	0.488	Onshore Wind
3	0.467	Hydropower


Global-Sensitivity Analysis-WSM
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
Wave and Tidal
Onshore Wind
Hydropower


Weighted-Sensitivity Analysis-WSM
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
Onshore Wind
Wave and Tidal
Hydropower
Social Acceptability
Benefits
Job Creation
Payback period
OPEX
CAPEX
Particles Emissions
Land Use
CO2 Emissions
Reliability
Exergy

6.4 CONCLUSION

In this chapter the McPAF method was put to the test. Due to lack of time the case study could only be run once and a statistical analysis of multiple runs could not be performed. The method provided a logical, reasonable and simple manner in which to approach and resolve the challenges presented when using MCDA methods. McPAF was able to provide a simple solution to the selection of criteria, determining the suitable alternatives and the selection of decision-makers. It also showed how it is possible to aggregate the preferences of the decision-makers to obtain a global result.

Within the process, the reason for using two MCDA methods became quite apparent. In the result of the Simulation, the first and last ranked alternatives varied between the MAUT and the WSM methods. Yet, when the sensitivity analysis was run both methods provided the same ranking of the alternatives. These outcomes provide additional information to the user and the decision-makers, which should be evaluated prior to taking the decision; for example, they could revaluate their criteria preference in regards to the results and the objectives. As stated, the results do not reflect the decision that should be taken, but rather how the analysis fared; what was the result of the assessment of the alternatives against the criteria.

7 CONCLUSION AND RECOMMENDATIONS FOR FURTHER RESEARCH

The question this researched aimed at answering was 'How can sustainable energy planning decisions be comprehensively analysed?' To provide the answer, this research proposed the creation of a framework that would provide a step-by-step description of how to obtain the analysis sought. As part of the design, the framework would have to be broad and provide for the inclusion of various points of view. Taking this into consideration, the selected approach was to base the framework on multi-criteria decision analysis methods. As multi-criteria decision analysis methods was further studied, some challenges inherent to the methods were discovered. As a result, the framework would need to provide a manner in which to address the construction of the problem, the identification of the stakeholders, decision-makers and key players; how to select suitable criteria, alternatives and the appropriate method; and finally how to aggregate the preference of various decision-makers.

The ultimate purpose of McPAF is to assess alternatives. It can be used for policy models if the policy requires the assessment of pre-determined alternatives; thus if there are no alternatives to assess, McPAF is not the right tool to be used to implement or evaluate policy models. Due to shortage of time this thesis did not considered problems identified in integrative policy models.

The research was divided in seven chapters. Chapter 1 provided background information on the subject to be discussed and the reason why it was selected. It also stated the question the thesis aims at answering in conjunction with the objectives, the analytical method used, the manner in which the thesis would be structured, the current situation and the importance of the research. Chapter 2 provided a rundown of the literature used during this research. It included both, literature that was cited and that which provided motivation for the selection of the topic. The content of the chapter was summaries of the articles referenced with an explanation of how they were used through the research. In some instances where the reference was not used, the chapter included an explanation as to why it was determined that the article was not suitable to be used. The gap identified after the literature review was the lack of a structure that provides the user with a guide on how to face the characteristic challenges inbuilt in multi-criteria decision analysis methods.

Chapter 3 entered more deeply into the discipline of decision analysis. It explained the history of the development of the discipline, as well as its use in the energy field. The chapter introduced the concept of multi objective and multi-criteria methods. Within the multi-criteria, the branches of value measurement models, models for goal, aspiration and reference level and outranking models were discussed. The basic steps of a MCA model can be summarized as: defining and structuring a problem, generating alternatives or options, selecting the appropriate criteria or attributes, construction of an evaluation matrix, assigning weight to the criteria, selecting the appropriate MCA method, analysis and ranking of the alternatives and sensitivity analysis and recommendations. This chapter also discussed some of the most popular MCDM, including MAUT, AHP, WSM, ELECTRE and PROMETHEE.

Chapter 4 provided a detailed explanation of each step of the general multi-criteria decision analysis framework. It determined that, the user has to determine the objectives, collect the necessary data, identify the stakeholders and the key players, and select the decision-makers from within the pool of stakeholders. Objectives can be high level, or intermediate objectives. The stakeholders were defined as those who have either a legitimate responsibility and-or an interest in the consequences of the decision, while key players are those individuals who participate in the decision analysis process, who can make important and fruitful contributions and who represent the stakeholders. The concept of the aggregation of preferences was first introduced in this chapter, including the aggregating individual judgement and the aggregating individual priorities techniques. In regards to the selection of alternatives, the use of the SWOT and PEST analyses was presented. For the selection of criteria, technique discussed include Delphi method, LMS, min-max deviation and the correlation coefficient. For the elicitation of preferences, the chapter discussed the following methods: equal weights, SMART, SWING SIMOS, pair-wise comparison, AHP, approximate method, eigenvalue method, geometric mean, entropy method, TOPSIS, vertical and horizontal method and combination methods. Concerning the selection of suitable methods, the techniques proposed to achieve this include analysing the problem, the considerations to be reflected upon and pre-selection of potential methods.

Chapter 5 followed the development of the Multi-criteria Preference Aggregation Framework (McPAF). This framework provided a step by step progression for focusing a decision analysis process to the energy field. McPAF provided one way to work through each of the challenges associated with multi-criteria decision analysis, explained in the previous chapters. The challenges tackled included how to structure the problem, how to identify the objectives, how to decide which data is suitable, how to determine who are the stakeholders, the key players, and the decision-makers, how to select suitable criteria and alternatives, how to select the appropriate methods, and how to elicit weight preferences from the participants as well as how to aggregate these preferences. As an extra layer the model moderately integrated a level of fuzziness in the weight elicitation process to allow the decision-maker to express how much more one criterion is preferred over another. The intent of the framework was never to be a new decision analysis method, but rather the consequence or outcome of combining several already existing elements. Examples of these already existing elements include: the aggregate individual preference method to find a total weight preferences of various decision-makers, the SIMOS method to elicit the weight preferences of each of the decision-makers, the concept of the Basic Cluster and Main Criteria for data collection, the suggestion of using SWOT analysis to assess the alternatives amongst themselves and the guidelines to be used to determine the suitability of the criteria. Some other elements were novel, for instance the concept of visualization between problem, objectives, criteria and alternatives and the matrix for the organization of data to be collected. In line with this visualization concept, different matrixes were developed for this framework, to facilitate organization and visualization for the user. Visualization was emphasized in this framework because it is both, a security check in every step of the process and is also helpful for easier explanation of the analysis and results.

Chapter 6 saw the framework in action. It is a logical, reasonable and simple manner in which to approach and resolve the challenges presented when using MCDA methods, including the selection of criteria, determining the suitable alternatives and the selection of decision-makers. It also showed how it is possible to aggregate the preferences of the decision-makers to obtain a global result. The framework suggested using two MCDA methods for comparison between the results. As the case study showed, the first results were completely different but when the sensitivity analysis was run, the same results were yielded.

McPAF combines known and new elements to further facilitate the use of multi-criteria decision analysis methods by providing solutions to the challenges faced when using this type of methods. Further research for this thesis could be an evaluation of how some of the alternatives discarded in this research to tackle the challenges faced in decision analysis methods would fare compared to the ones proposed. The study could be divided into simple approaches and more complex ones, to include deep mathematical calculations. With this approach, two types of audiences could be assisted, the experts and non-experts. Another future research could be the impact of legal conventions on sustainability or sustainable energy, which was not included due to shortage of time.

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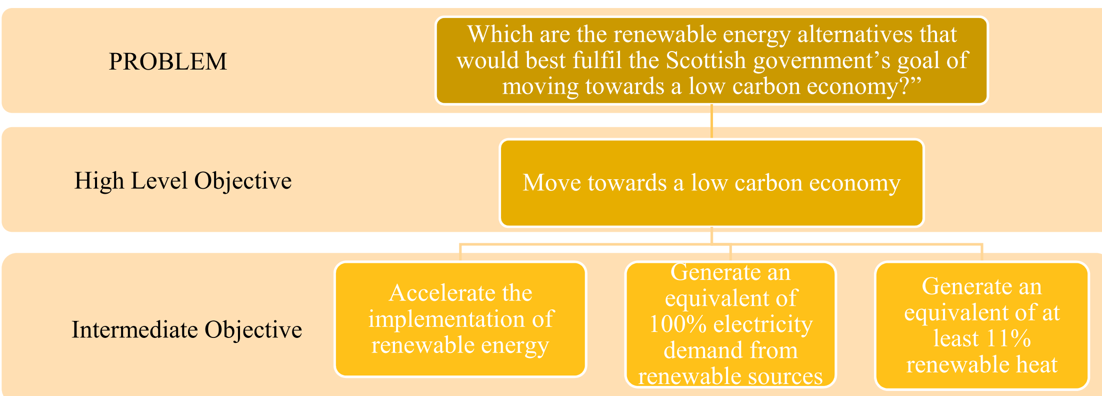
8 ANNEX TO SIMULATION

8.1 DETERMINE THE OBJECTIVES

During the research the theme of the Scottish government's desire to advance the implementation of a low carbon economy in the short term appeared. This theme was further researched in order to identify specific high-level objectives and intermediate level objectives. The high-level objective was identified as "move towards a low carbon economy." The intermediate objectives were determined to be: i) accelerate the implementation of renewable energy, ii) generate an equivalent of 100% electricity demand from renewable sources and iii) generate an equivalent of at least 11% renewable heat.

Simulation 8-1: Problem and Objectives



8.2 Data Collection

The data was collected following the Basic Cluster and Main Criteria approach introduced in Chapter 5. From the official publications researched, and taking into consideration the high-level and intermediate objectives, the industry was identified as renewable energy technologies. No specific technology was distinguished, at this time, as the publications did not communicate a predilection for any. The data collection was organized referring to the intermediate level objectives.

Simulation 8-2: Data to be Collected

Intermediate Objectives:	**Accelerate the implementation of renewable energy**	**Generate an equivalent of 100% electricity demand from renewable sources**	**Generate an equivalent of at least 11% renewable heat**
Country	• Feasibility studies • Interconnection possibilities • Workforce Skills • Available Workforce • Environmental impact • Emissions goals • Carbon Footprint	• Demand • Supply • Social Acceptance of Renewable Technologies • Cost of alternative fuels	• Demand and Supply of main heat provider (e.g. gas) • Alternative fuels • Cost of alternative fuels • Environmental impact
Regional	• Feasibility studies • Demand and Supply • Weather patterns • Job creation • Social benefits • Emissions goals • Carbon Footprint	• Case Studies • Demand-Supply • Integration cost • Cost of workforce reallocation • Emissions • Carbon Footprint	• Comparative cost analysis • Emissions • Carbon Footprint • Social Impact • Social Acceptance • Environmental impact
Renewable	• CAPEX, OPEX, Maintenance, NPV, Payback Period • Success Rate • Incentives needed • Average job creation • Average social benefits • Average emissions • Average carbon footprint	• Case Studies • Back up alternatives • Integration with the electrical grid • Average emissions • Average carbon footprint	• Average environmental impact • Suitable technologies • Average Carbon Footprint

8.3 IDENTIFY THE STAKEHOLDERS

The first potential participants to be identified via a desktop study of government officials and their functions were those who could represent the interests defined in the Basic Cluster, followed by those potential participants who could represent each of the four main points of view. These participants were identified from the different ministries in the Scottish Government.

Simulation 8-3: Stakeholder and Key Player Identification

Points of view	**Possible participants**	**Legitimate Responsibility?**	**Interest in the consequences?**	**Can provide a useful/significant contribution?**	**Represents one or more major points of view?**
Country	First Minister	YES	YES	YES	NO
Regional	Representative for the EU		X	X	NO
Renewable Energy Technologies	Minister for Business, Innovation and Energy	YES			YES
Technical	Cabinet Secretary for the Rural Economy and Connectivity				
Economic	Cabinet Secretary for Finance and the Constitution				
	Cabinet Secretary for the Rural Economy and Connectivity				
	Cabinet Secretary for Economy, Jobs and Fair Work				
Environmental	Cabinet Secretary for Environment, Climate Change and Land Reform				YES
Social	Cabinet Secretary for Health and Sport				
	Cabinet Secretary for Environment, Climate Change and Land Reform				
	Cabinet Secretary for Communities, Social Security and Equalities				
	Cabinet Secretary for Economy, Jobs and Fair Work				
	Minister for Community Safety and Legal Affairs				YES
	Minister for Employability and Training				

8.4 Determine Who Will be the DMs

Four decision-makers were identified from the group of stakeholders, each representing one four the Main Criteria. This to maintain the integrity of the evaluation of all points of view. Their weight was distributed equally, with each having a weight equal to ¼.

Simulation 8-4: DM Identification

Point of View/Representative	DM
Economic	Cabinet Secretary for Finance and the Constitution
Social	Minister for Community Safety and Legal Affairs
Technical	Minister for Business, Innovation and Energy
Environmental	Cabinet Secretary for Environment, Climate Change and Land Reform

8.5 GENERATING ALTERNATIVES AND ESTABLISHING CRITERIA

8.5.1 Alternatives

The alternatives were also identified from the reviewed publications, particularly those technologies mentioned in the 2020 Routemap for Renewable Energy in Scotland. (Govt, 2015). At this point, McPAF would use a SWOT analysis to further select the suitable options. As an actual SWOT analysis was outside of the scope of this research, the SWOT analysis for the offshore wind alternative was duplicated from that published in the Offshore Wind Industrial Strategy Business and Government Action (Government, 2013), while for the other technologies the information was obtained from the 2020 Routemap publication. Simulation 6-5 shows the results of the SWOT analysis. Taking into consideration the strengths, weaknesses, opportunities and threats of each of the technologies studied, three were selected: onshore wind, wave and tidal and hydropower. The reason these three technologies were selected was because, out of the group evaluated, these three revealed to possess more strengths and opportunities than weaknesses or threats. The opposite was found for the other alternatives, as the strengths in each were less than the number of threats or weaknesses found.

Simulation 8-5: SWOT Analysis

Onshore Wind

STRENGTH	WEAKNESS
5,015MW generating capacity £82.50/MWh	Closure of the Renewables Obligation Uncertainty surrounding remaining subsidies No appropriate in National Parks or National Scenic Areas which represents a fifth of the country Higher protection in areas outwith National Parks and National Scenic Areas, which cover a tenth of the country
OPPORTUNITIES	**THREATS**
Opportunity to reduce cost allows it to compete with nuclear and thermal Repowering of onshore wind farms.	Investment depends on clear, well-defined structure of support Public interest in accurate mapping of onshore wind farms. Public information is available for projects over 1MW, but not so much for projects under 1MW when they are located in private property.

(Govt, 2015)

Solar PV

STRENGTH	WEAKNESS
Could achieve grid parity in the UK Cost reduction	Climate Renewable Obligation closed for larger solar projects
OPPORTUNITIES	**THREATS**
Allow under-represented urban communities to access energy ownership and benefits. Community and Renewable Energy Scheme (CARES) funding	Ensuring timely and affordable grid access Increasing innovation required to reduce costs Enabling financial predictability Building community and industry confidence

(Govt, 2015)

Bioenergy and Energy from Waste

STRENGTH	WEAKNESS
Supporting the use of biomass for CHP or heat-only plants is larger than 15MW	Ensuring resources are not used more efficiently elsewhere 15MW cap on support for electricity only biomass plants.
OPPORTUNITIES	**THREATS**
Study looking at potential feedstock crops for anaerobic digestion.	Lack of resources due to more efficient use elsewhere

(Govt, 2015)

Hydropower

STRENGTH	WEAKNESS
Fifth of Scotland's renewable output.	20% reduction in the Hydro feed-in-tarrifs (FIT) rate apply after December 2014.
OPPORTUNITIES	**THREATS**
More community developed and owned hydro scheme as the Callander Community Hydro Ltd has been successful.	Reducing levels of support for hydro power through FIT. Comprehensive review of the FIT

(Govt, 2015)

Offshore Wind

STRENGTH	WEAKNESS
Large wing resources and favourable locations with substantial potential for export of power Expertise in Offshore engineering, platform deployment, and marine operations transferable to offshore wind Strong R & D capability in renewables with increasing competence in demonstration and early deployment Expertise in advanced manufacturing and materials applicable to offshore wind Regulatory and price support framework enabling deployment of low-carbon energy generating technologies, including offshore wind, with cross party support	Testing and technology deployment is low which hinders the move to larger turbines and fully utilising R&D capability High energy cost of offshore wind in comparison with other renewable sources Foreign investment is limited to date as overseas investors are often unaware of benefits of investing or locating their activities in the UK Industry collaboration and SME activity is often limited Low involvement of UK supply chain as it is estimated only 30% of content in UK offshore wind sites on average is sourced from UK suppliers Waterside manufacturing infrastructure insufficient to fully meet sector's needs and new investment is not materialising.
OPPORTUNITIES	**THREATS**
Large economic benefits by 2020 offshore wind could deliver up to £7bn GVA (excluding exports) and boos total UK jobs by over 30,000 FTE Growing demand for renewable energy to meet climate change targets, security of supply and increasing demand for energy, both domestically and abroad Offshore wind cost reduction via technology, supply chain and finance. The Crown Estate cost reduction pathways study (2012) showed that 28% reduction in levelised cost to £100/MWh (2011 prices) was achievable for 2020. TINA study (2012) estimated that levelised costs of offshore wind energy could go down by 60% by 2050. Synergies with other industries could be realised as offshore wind relies on products and services from other sectors e.g. professional services, manufacturing and transport.	High competition for the location of top tier supply chain companies given turbines, foundations and electrical components can be manufactured from many locations on the North Sea coast line. Access to finance could affect speed of deployment and ability of UK supply chains to scale up quickly due to perceived risks by financiers. Cost of energy mat not reduce significantly if build rates are low. Availability of highly skilled workforce- offshore wind, like the wider energy industry, faces engineering and managerial skills gaps, competition for talent and ageing workforce. High market concentration & lack of varied competition in the supply chain-over 90% of turbines are supplied by two manufacturers but no turbine manufacturers currently located in the UK.

(Government, 2013)

8.5.2 Criteria

Simulation 8-6: Principles for criteria selection checklist

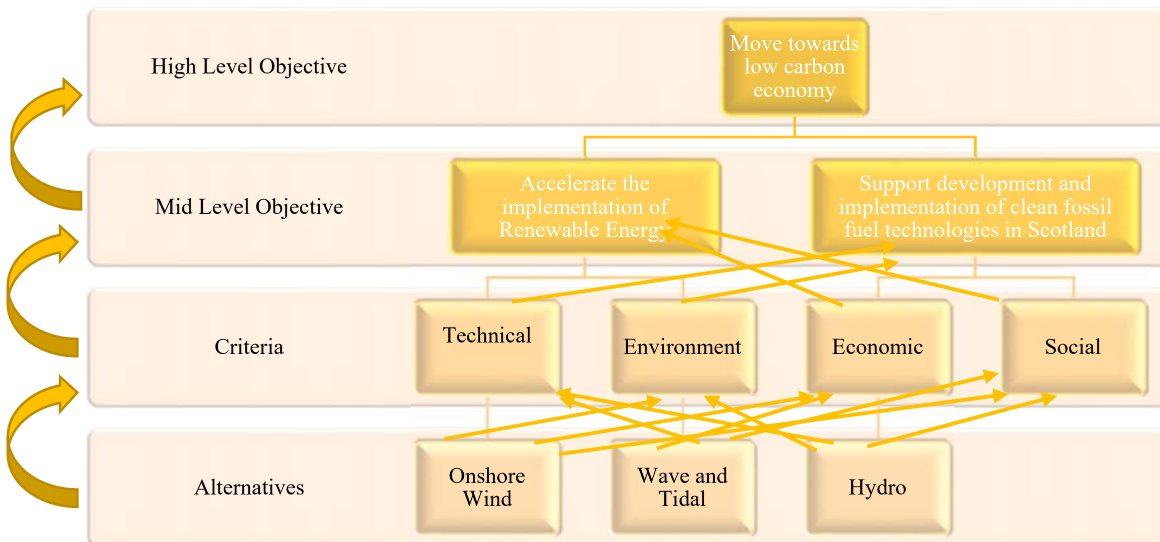
Most used criteria in the literature	C	R	I	DC	SP	Con	M	Comp	S	IOT	Is the data available?
Technical									N		
Efficiency	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Y
Exergy	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	N
Primary Energy Ratio	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Y
Safety	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Y
Reliability	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Y
Maturity	☐	☐	☐	☐	☐	☐	☐	☐		Y	Y
Environment									N		
CO_2 Emissions	☐	N	☐	☐	☐	☐	☐	☐	☐	Y	Y
NO_x Emissions	☐	N	☐	☐	☐	☐	☐	☐	☐	Y	Y
Land use	☐	N	☐	☐	☐	☐	☐	☐	☐	N	Y
Noise	☐	N	☐	☐	☐	☐	☐	☐	☐	Y	N
Particles Emissions	☐	Y	☐	☐	☐	☐	☐	☐	☐	Y	Y
SO_2 Emissions	☐	N	☐	☐	☐	☐	☐	☐	☐	Y	N
Economic									N		
CAPEX	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Y
OPEX	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Y
Maintenance	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Y
Cost of fuel	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	N/A
NPV	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	N
Payback period	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	N
Social									N		
Job creation	Y	N	Y	N	Y	Y	U	Y	☐	Y	Y
Benefits	☐	☐	☐	☐	☐	☐	☐	N	☐	☐	Y
Social Acceptability	☐	☐	☐	☐	☐	☐	D	N	☐	☐	N

C	Completeness
R	Redundancy
I	Independency
DC	Double counting
SP	Systemic principle
Con	Consistency
M	Measurability
Comp	Comparability
S	Size
IOT	Impact occurring over time

As specific, tangible data was not gathered for the Simulation, given its scope, Simulation 6-6 is a model of how the principles for criteria selection would be applied. This Simulation assumes that all the criteria included in Simulation 6-6 complies with the checklist. To keep with the size principle, given that the social criteria only contains 3 sub-criteria while the other Main Criteria have five or more, the sub-criteria that obtains the three top weights after eliciting the decision-maker's preferences will be used.

The problem, objectives, criteria and alternatives are put together in Simulation 6-7 to corroborate their cohesiveness.

Simulation 8-7: Checklist of agreement between alternatives, criteria and objectives



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8.6 Evaluation Matrix

Simulation 6-8 shows the full evaluation matrix, which is composed of four sub-matrixes: one to evaluate the technical sub-criteria, another to evaluate the environment sub-criteria, a third sub matrix to evaluate the economic sub-criteria and, last, a fourth matrix that evaluates the social sub-criteria. Weights are not included in Simulation 6-8 as they will be calculated in the next step.

Simulation 8-8: Evaluation Matrix

Technical

	Efficiency	Exergy	Primary Energy Ratio	Safety	Reliability	Maturity
Onshore Wind						
Wave and Tidal						
Hydropower						

Environment

	CO_2 Emissions	NOx Emissions	Land Use	Noise	Particles Emissions	SO_2 Emissions
Onshore Wind						
Wave and Tidal						
Hydropower						

Economic

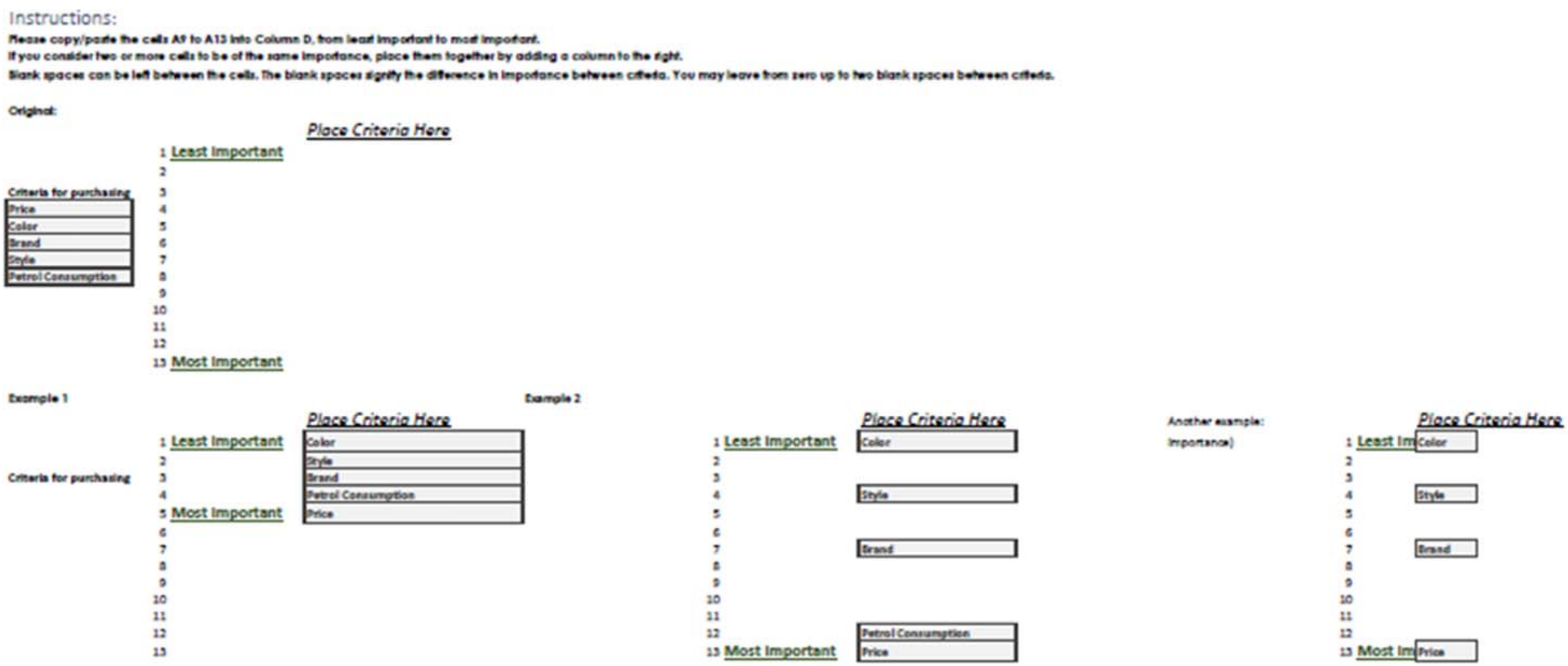
	CAPEX	OPEX	Maintenance	Cost of fuel	NPV	Payback period
Onshore Wind						
Wave and Tidal						
Hydropower						

Social

	Job Creation	Benefits	Social Acceptability
Onshore Wind			
Wave and Tidal			
Hydropower			

8.7 ASSIGNING WEIGHT TO THE CRITERIA

A workbook approach was considered to be easier for the volunteers, as it allowed for the copy/paste of the criteria in the corresponding column. Another change was that the number of white cards was limited to two per criterion. This meant that, if there were five criteria to evaluate, there would be a maximum of eight white cards to be used to differentiate between the importance of the criteria. The third change was that the instructions were revised for clarity. All of these changes are reflected in in Simulation 6-9.



Simulations 6-10 through 6-13 display the preferences as elicited from the volunteers.

Simulation 8-9: Weight elicitation- DM 1

Technology

1	**Least Important**	
2		
3		
4		
5		
6		
7		
8		
9		**Primary Energy Ratio**
10		**Maturity**
11		**Exergy**
12		**Safety**
13	**Most Important**	**Reliability**

Environmental

1	**Least Important**	
2		
3		
4		
5		
6		
7		
8		
9		**Land Use**
10		**Noise**
11		**NOx Emissions**
12		**SO2 Emissions**
13	**Most Important**	**CO2 Emissions**

Economic

1	**Least Important**	
2		
3		
4		
5		
6		
7		
8		**OPEX**
9		**NPV**
10		**Cost of fuel**
11		**Maintenance**
12		**CAPEX**
13	**Most Important**	**Payback Period**

Social

1	**Least Important**	
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		**Social Acceptability**
12		**Benefits**
13	**Most Important**	**Job Creation**

Main Criteria

Rank		
1	**Least Important**	
2		
3		
4		
5		
6		
7		
8		
9		
10		

11		
12		**Social**
13	**<u>Most Important</u>**	**Economic**

Simulation 8-10: Weight elicitation- DM 2

Technology

1	Least Important	
2		
3		
4		
5		
6		Maturity
7		
8		Reliability
9		
10		Safety
11		Exergy
12		Primary Energy Ratio
13	Most Important	
1	Least Important	

Environmental

1	Least Important	
2		
3		
4		
5		Noise
6		
7		Land Use
8		
9		
10		NOx Emissions
11		SO2 Emissions
12		CO2 Emissions
13	Most Important	

Economic

1	Least Important	
2		
3		
4		
5		Payback Period
6		
7		Maintenance
8		
9		Cost of fuel
10		OPEX
11		CAPEX
12		NPV
13	Most Important	

Social

1	Least Important	
2		
3		
4		
5		
6		
7		Social Acceptability
8		
9		
10		Benefits
11		Job Creation
12		
13	Most Important	

Main Criteria

1	Least Important	
2		
3		
4		
5		
6		
7		
8		
9		Social
10		
11		
12	Most Important	Economic

Simulation 8-11: Weight elicitation- DM 3

Technology

Rank	Criteria
1	**Least Important**
2	
3	
4	
5	Maturity
6	
7	
8	
9	Safety
10	
11	Primary Energy Ratio
12	
13	**Most Important** — Reliability, Exergy

Environmental

Rank	Criteria
1	**Least Important**
2	
3	Noise
4	
5	
6	Land Use
7	
8	
9	
10	
11	SO2 Emissions
12	CO2 Emissions, NOx Emissions
13	**Most Important**

Economic

Rank	Criteria
1	**Least Important** — Cost of fuel
2	
3	
4	
5	
6	
7	
8	Maintenance
9	
10	NPV
11	
12	CAPEX, OPEX
13	**Most Important** — Payback Period

Social

Rank	Criteria
1	**Least Important**
2	
3	
4	
5	Benefits
6	
7	
8	
9	
10	Job Creation
11	Social Acceptability
12	
13	**Most Important**

Main Criteria

Rank	Criteria
1	**Least Important**
2	
3	
4	
5	
6	
7	

8			
9	**Most Important**	**Social**	**Economic**

Simulation 8-12: Weight elicitation- DM 4

Technology

1	**Least Important**	
2		
3		
4		
5		
6		
7		**Reliability**
8		**Safety**
9		**Maturity**
10		**Exergy**
11		
12		
13	**Most Important**	**Primary Energy Ratio**

Environmental

1	**Least Important**	
2		
3		**SO2 Emissions**
4		
5		
6		**NOx Emissions**
7		**CO2 Emissions**
8		
9		
10		**Noise**
11		
12		
13	**Most Important**	**Land Use**

Economic

1	**Least Important**	**NPV**
2		**Maintenance**
3		
4		
5		**Cost of fuel**
6		
7		
8		**Payback Period**
9		**OPEX**
10		
11		
12		
13	**Most Important**	**CAPEX**

Social

1	**Least Important**	
2		
3		
4		
5		
6		
7		
8		
9		**Social Acceptability**
10		**Benefits**
11		
12		
13	**Most Important**	**Job Creation**

Main Criteria

1	**Least Important**	
2		
3		
4		**Social**
5		
6		
7		**Economic**
8		
9		
10		
11		
12	**Most Important**	

Simulations 6-14 through 6-17 show the weight calculation using the SIMOS method for each sub-criterion

Simulation 8-13: Weight Elicitation by DM using the SIMOS Method- Technology

DM1

DM's Weight 1/4

Ranking	sub Criteria	Number of cards	Weight (w)	Average Weight)	Relative Weight	Test
1	Primary Energy Ratio	1	1	1	5%	5%
2	Maturity	1	2	2	10%	10%
3	Exergy	1	3	3	14%	14%
4	Safety	1	4	4	19%	19%
5	Reliability	1	5	5	24%	24%
6	Efficiency	1	6	6	29%	29%
			21			100%

DM2

DM 2's Weight 1/4

Ranking	sub Criteria	Number of cards	Weight (w)	Average Weight)	Relative Weight	Test
1	Maturity	1	1	1	3%	3%
2		1	2	2		
3	Reliability	1	3	3	10%	10%
4		1	4	4		
5	Safety	1	5	5	17%	17%
6	Exergy	1	6	6	20%	20%
7	Primary Energy Ratio	1	7	7	23%	23%
8	Efficiency	1	8	8	27%	27%
				30		

DM3

DM 3's Weight 1/4

Ranking	sub Criteria	Number of cards	Weight (w)	Average Weight)	Relative Weight	Test
1	Maturity	1	1	1	2%	2%
2	White Card	1	2	2		0%
3	White Card	1	3	3		0%
4	White Card	1	4	4		0%
5	Safety	1	5	5	12%	12%
6	White Card	1	6	6		0%

7	Primary Energy Ratio	1	7	7	16%	16%
8	White Card	1	8	8		0%
9	Reliability/Exergy	2	9, 10	9.5	22%	44%
10	Efficiency	1	11	11	26%	26%
			43			100%

DM4

DM 4's Weight 1/4

Ranking	sub Criteria	Number of cards	Weight (w)	Average Weight)	Relative Weight	Test
1	Reliability	1	1	1	4%	4%
2	Safety	1	2	2	8%	8%
3	Maturity	1	3	3	12%	12%
4	Exergy	1	4	4	16%	16%
5		1	5	5		0%
6		1	6	6		0%
7	Primary Energy Ratio	1	7	7	28%	28%
8	Efficiency	1	8	8	32%	32%
			25			100%

Simulation 8-14: Weight Elicitation by DM using the SIMOS Method- Environmental

DM1

DM's Weight 1/4

Ranking	**sub-criteria**	**No. of cards**	**Weight (w)**	**Average Weight)**	**Relative Weight**	**Test**
1	**Land Use**	1	1	1	5%	5%
2	**Noise**	1	2	2	10%	10%
3	**Nox Emissions**	1	3	3	15%	15%
4	**SO2 Emissions**	1	4	4	20%	20%
5	**CO2 Emissions**	1	5	5	25%	25%
6	**Particle Emission**	1	5	5	25%	25%
			20			100%

DM2

DM's Weight **1/4**

Ranking	**sub-criteria**	**No. of cards**	**Weight (w)**	**Average Weight**	**Relative Weight**	**Test**
1	**Noise**	1	1	1	3%	3%
2		1	2	2		
3	**Land Use**	1	3	3	9%	9%
4		1	4	4		
5		1	5	5		
6	**Nox Emissions**	1	6	6	18%	18%
7	**SO2 Emissions**	1	7	7	21%	21%
8	**CO2 Emissions**	1	8	8	24%	24%
9	**Particle Emission**	1	9	9	26%	26%
			34			100%

DM3

DM's Weight 1/4

Ranking	**sub-criteria**	**No. of cards**	**Weight (w)**	**Average Weight)**	**Relative Weight**	**Test**
1	**Noise**	1	1	1	2%	2%
2	White Card	1	2	2		
3	White Card	1	3	3		
4	**Land Use**	1	4	4	9%	9%
5	White Card	1	5	5		
6	White Card	1	6	6		
7	White Card	1	7	7		
8	White Card	1	8	8		
9	**SO2 Emissions**	1	9	9	19%	19%
10	**CO2 Emissions/ NOx Emissions**	2	10, 11	11	22%	45%
11	**Particle Emission**	1	12	12	26%	26%
			47			100%

DM4

DM's Weight **1/4**

Ranking	sub-criteria	No. of cards	Weight (w)	Average Weight)	Relative Weight	Test
1	**SO2 Emissions**	1	1	1	2%	2%
2		1	2	2		
3		1	3	3		
4	**NOx Emissions**	1	4	4	10%	10%
5	**CO2 Emissions**	1	5	5	12%	12%
6		1	6	6		
7		1	7	7		
8	**Noise**	1	8	8	20%	20%
9		1	9	9		
10		1	10	10		
11	**Land Use**	1	11	11	27%	27%
12	**Particle Emission**	1	12	12	29%	29%
			41			100%

Simulation 8-15: Weight Elicitation by DM using the SIMOS Method- Economic

DM1

DM's Weight 1/4

Ranking	sub-criteria	Number of cards	Weight (w)	Average Weight)	Relative Weight	Test
1	OPEX	1	1	1	5%	5%
2	NPV	1	2	2	10%	10%
3	Cost of fuel	1	3	3	14%	14%
4	Maintenance	1	4	4	19%	19%
5	CAPEX	1	5	5	24%	24%
6	Payback Period	1	6	6	29%	29%
			21			100%

DM2

DM's Weight 1/4

Ranking	sub-criteria	Number of cards	Weight (w)	Average Weight	Relative Weight	Test
1	Payback Period	1	1	1	3%	3%
2		1	2	2		
3	Maintenance	1	3	3	10%	10%
4		1	4	4		
5	Cost of fuel	1	5	5	17%	17%
6	OPEX	1	6	6	20%	20%
7	CAPEX	1	7	7	23%	23%
8	NPV	1	8	8	27%	27%
			30			100%

DM3

DM's Weight 1/4

Ranking	sub-criteria	Number of cards	Weight (w)	Average Weight	Relative Weight	Test
1	**Cost of fuel**	1	1	1	2%	2%
2	White Card	1	2	2		
3	White Card	1	3	3		
4	White Card	1	4	4		
5	White Card	1	5	5		
6	White Card	1	6	6		
7	White Card	1	7	7		
8	**Maintenance**	1	8	8	14%	14%
9	White Card	1	9	9		
10	**NPV**	1	10	10	17%	17%
11	White Card	1	11	11		
12	**CAPEX/ OPEX**	2	12, 13	12.5	22%	43%
13	**Payback Period**	1	14	14	24%	24%
			58			100%

DM4

DM's Weight 1/4

Ranking	sub-criteria	Number of cards	Weight (w)	Average Weight)	Relative Weight	Test
1	**NPV**	1	1	1	3%	3%
2	**Maintenance**	1	2	2	5%	5%
3		1	3	3		0%
4		1	4	4		0%
5	**Cost of fuel**	1	5	5	13%	13%
6		1	6	6		0%
7		1	7	7		0%
8	**Payback Period**	1	8	8	21%	21%
9	**OPEX**	1	9	9	24%	24%
10		1	10	10		0%
11		1	11	11		0%
12		1	12	12		0%
13	**CAPEX**	1	13	13	34%	34%
			38			100%

Simulation 8-16: Weight Elicitation by DM using the SIMOS Method-Social

DM1

DM's Weight 1/4

Ranking	sub-criteria	Number of cards	Weight (w)	Average Weight)	Relative Weight	Test
1	**Social Acceptability**	1	1	1	17%	17%
2	**Benefits**	1	2	2	33%	33%
3	**Job Creation**	1	3	3	50%	50%
			6			100%

DM2

DM's Weight 1/4

Ranking	sub-criteria	Number of cards	Weight (w)	Average Weight	Relative Weight	Test
1	**Social Acceptability**	1	1	1	10%	10%
2		1	2	2	20%	
3		1	3	3	30%	
4	**Benefits**	1	4	4	40%	40%
5	**Job Creation**	1	5	5	50%	50%
			10			100%

DM3

DM's Weight 1/4

Ranking	sub-criteria	Number of cards	Weight (w)	Average Weight	Relative Weight	Test
1	**Benefits**	1	1	1	7%	7%
2	White Card	1	2	2		0%
3	White Card	1	3	3		0%
4	White Card	1	4	4		0%
5	White Card	1	5	5		0%
6	**Job Creation**	1	6	6	43%	43%
	Social Acceptability	1	7	7	50%	50%
			14			100%

DM4

DM's Weight 1/4

Ranking	sub-criteria	Number of cards	Weight (w)	Average Weight)	Relative Weight	Test
1	**Social Acceptability**	1	1	1	13%	13%
2	**Benefits**	1	2	2	25%	25%
3		1	3	3		0%
4		1	4	4		0%
5	**Job Creation**	1	5	5	63%	63%
			8			100%

Simulation 6-18 shows the weight calculation for each Main Criterion.

Simulation 8-17: Weight Elicitation by DM using the SIMOS Method-Main Criteria

DM1

DM's Weight 1/4

Ranking	Main Criteria	Number of cards	Weight (w)	Average Weight)	Relative Weight	Test
1	Social	1	1	1	10%	10%
2	Economic	1	2	2	20%	20%
3	Environment	1	3	3	30%	30%
4	Technology	1	4	4	40%	40%
			10			1

DM2

DM's Weight 1/4

Ranking	Main Criteria	Number of cards	Weight (w)	Average Weight)	Relative Weight	Test
1	Social	1	1	1	6%	6%
2		1	2	2		0%
3		1	3	3		0%
4	Economic	1	4	4	25%	25%
5	Environment	1	5	5	31%	31%
6	Technology	1	6	6	38%	38%
			16			100%

DM3

DM's Weight 1/4

Ranking	Main Criteria	Number of cards	Weight (w)	Average Weight	Relative Weight	Test
1	Social/ Economic	2	1, 2	1.5	15%	30%
2	Environment	1	3	3	30%	30%
3	Technology	1	4	4	40%	40%
			10			100%

DM4

DM's Weight 1/4

Ranking	Main Criteria	Number of cards	Weight (w)	Average Weight)	Relative Weight	Test
1	Social	1	1	1	6%	6%
2		1	2	2		
3		1	3	3		
4	Economic	1	4	4	25%	25%
5	Environment	1	5	5	31%	31%

6	**Technology**	1	6	6	38%	38%
			16			100%

The values obtained as a result of using the SIMOS method were then used to find the global weight using the AIP method, as shown in Simulation 6-19. As a security check, the resulting weights were added to ensure the final aggregation was equal to 1.

Simulation 8-18: Aggregation of Multiple DM's weights using the AIP method

	Aggregate result	Weight
Technology	39%	41%
Environment	31%	32%
Economic	16%	17%
Social	9%	10%
	0.95	1.00

Technology

	Aggr result	Weight	Sub-criteria global weight
Primary Energy Ratio	18%	18%	7%
Maturity	7%	7%	3%
Exergy	18%	18%	7%
Safety	14%	14%	6%
Reliability	15%	15%	6%
Efficiency	28%	28%	12%
	1.00	100%	41%

Environment

	Agg result	Weight	Sub-criteria global weight
Land Use	3%	7%	2%
Noise	3%	6%	2%
Nox Emissions	9%	19%	6%
SO2 Emissions	10%	20%	6%
CO2 Emissions	12%	24%	8%
Particle Emission	13%	25%	8%
	50%	100%	32%

Economic

	Agg result	Weight	Sub-criteria global weight
CAPEX	26%	26%	4%
NPV	14%	14%	2%
OPEX	17%	17%	3%
Payback Period	19%	19%	3%
Maintenance	12%	12%	2%
Cost of fuel	11%	11%	2%

Social

	Agg result	Weight	Sub-criteria global weight
Job Creation	51%	51%	5%
Benefits	26%	26%	3%
Social Acceptability	22%	22%	2%
	1.00	1.00	10%

	1.00	1.00	17%

Following the size principle for the selection of criteria, this Simulation used the top three weights as obtained from the application of the AIP method in Simulation 6-19, shown in Simulation 6-20.

Simulation 8-19: Criteria selection according to weight

Technology

	Aggregate result	Weight	Sub-criteria global weight
Primary Energy Ratio	18.094%	28%	11%
Maturity	7%		
Exergy	18.095%	28%	11%
Safety	14%		
Reliability	15%		
Efficiency	28%	44%	18%
	64%	100%	41%

Environment

	Aggregate result	Weight	Sub-criteria global weight
Land Use	3%		
Noise	3%		
NOx Emissions	9%	28%	8.90%
SO2 Emissions	9.79%		
CO2 Emissions	12%	35%	11%
Particle Emission	13%	37%	12%
	34%	100%	32%

Economic

	Aggregate result	Weight	Sub-criteria global weight
CAPEX	26%	41%	7%
NPV	14%		
OPEX	17%	28%	5%
Payback Period	19%	31%	5%
Maintenance	12%		
Cost of fuel	11%		
	62%	1.00	17%

Social

	Aggregate result	Weight	Sub-criteria global weight
Job Creation	51%	51%	5%
Benefits	26%	26%	3%
Social Acceptability	22%	22%	2%
	1.00	1.00	10%

8.8 SELECTING THE APPROPRIATE METHOD

These pre-selected methods were analysed against the considerations stated in Exhibit 5-14. The results are included in Simulation 6-21.

After the evaluation, both PROMETHEE and ELECTRE proved to have the disadvantage that specialized software was needed and that the model was difficult to explain, especially the preference, veto and indifference thresholds. The disadvantage found for AHP was the other methods provided for complete mathematic input, while AHP obtains its inputs from the results of the pairwise comparison performed by the decision-makers. Based on the experience of how time consuming the weight elicitation part was, the AHP approached was also discarded. Still, even if the use of the SIMOS method becomes too time consuming for the users, it is not recommended to instead to use AHP's pairwise comparison concept to elicit weight preferences as it will fall into the cycle of using an MCDA approach to solve challenges within an MCDA method. As a result, the methods selected were MAUT and WSM. These methods were found to be transparent, easy to explain and did not require specialized software.

Simulation 8-20: Considerations for the selection of the appropriate MCA method

	AHP	MAUT	PROMETHEE	ELECTRE	WSM
How many DMs involved?	4	4	4	4	4
Are all appropriate stakeholders engaged? How much is their involvement?	Yes, through the selection of key players and decision-makers	Yes, through the selection of key players and decision-makers	Yes, through the selection of key players and decision-makers	Yes, through the selection of key players and decision-makers	Yes, through the selection of key players and decision-makers
How does the DM prefer to have the data presented?					
What kind of result is the DM looking for?	Less objective as the calculation is a result of comparison.	Provides more objectivity as the results are obtained from mathematical calculations	Provides more objectivity as the results are obtained from mathematical calculations	Provides more objectivity as the results are obtained from mathematical calculations	Provides more objectivity as the results are obtained from mathematical calculations
Can data be easily obtained?	Yes	Yes	No	No	yes
Is the DM looking for compensations?					
Method meets main assumptions?	Yes	Yes	Yes	Yes	Yes
Software needed?	No	No	Yes	Yes	No
Can the method support many alternatives and criteria?	Yes	Yes	Yes	Yes	Yes
How does the model quantify the importance of the criteria or their weights?	All models will use the SIMOS and AIP methods	All models will use the SIMOS and AIP methods	All models will use the SIMOS and AIP methods	All models will use the SIMOS and AIP methods	All models will use the SIMOS and AIP methods
How does the model deal with uncertainty?	Regarding the criteria, this is somewhat captured with the use of the SIMOS method	Regarding the criteria, this is somewhat captured with the use of the SIMOS method	Regarding the criteria, this is somewhat captured with the use of the SIMOS method	Regarding the criteria, this is somewhat captured with the use of the SIMOS method	Regarding the criteria, this is somewhat captured with the use of the SIMOS method
Can the decision be re-evaluated using new data?	Yes	Yes	Yes	Yes	Yes
Is the model transparent and easy to explain?	Yes	Yes	Difficult to explain	Difficult to Explain	Yes
Is the method easy to use?	Yes	Yes	No	No	Yes

Does the method provide for sensitivity analysis?	Yes	Yes	Yes	Yes	Yes

8.9 ANALYSING AND RANKING OF THE A\ALTERNATIVES

The assessment of the alternatives against the criteria was done using the MAUT and WMS methods. One raw scale was prepared and populated with simulated information that mixes qualitative and quantitative responses. Because the inputs of the raw scale reflected different values, these were normalized using the max-min method. Simulation 6-22 shows the analysis done under the MAUT method. Simulation 6-23 shows the analysis under the WSM method

Simulation 8-21: MAUT

Raw Scale

	Technical			Environment			Economic			Social		
	Efficiency	Exergy	Primary Energy Ratio	CO_2 Emission	NOx Emission	Particles Emission	CAPEX USDm/MW	OPEX USD/MW/yr	Payback period (yrs)	Job Creation	Benefits USDm/MW	Social Acceptability
Weight	**18%**	**11%**	**11%**	**11%**	**9%**	**12%**	**7%**	**5%**	**5%**	**5%**	**3%**	**2%**
Onshore Wind	70%	48.70%	1.44%	11	12	0.1	1.52	28,750.00	8	11	0.304	5
Wave and Tidal	90%	62%	0.89%	17	17	0.1	9.03	130,000.00	7.5	21	1.806	9
Hydropower	95%	66%	6.79%	24	24	0.5	3.915	73,500.00	6.2	15	0.783	9

Normalize Scale: Maximize Criterion

	Technical			Environment			Economic			Social		
	Efficiency	Exergy	Primary Energy Ratio	CO_2 Emission	NOx Emission	Particles Emissions	CAPEX	OPEX	Payback period	Job Creation	Benefits	Social Acceptability
Onshore Wind	0.000	0.000	0.093	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000
Wave and Tidal	0.800	0.795	0.000	0.462	0.417	0.000	1.000	1.000	0.722	1.000	1.000	1.000
Hydropower	1.000	1.000	1.000	1.000	1.000	1.000	0.319	0.442	0.000	0.400	0.319	1.000

Normalized Scale: Minimize Criterion

	Technical			Environment			Economic			Social		
	Efficiency	Exergy	Primary Energy Ratio	CO_2 Emissions	NOx Emissions	Particles Emissions	CAPEX	OPEX	Payback period	Job Creation	Benefits	Social Acceptability
Onshore Wind	1.000	1.000	0.907	1.000	1.000	1.000	1.000	1.000	0.000	1.000	1.000	1.000

Wave and Tidal	0.200	0.205	1.000	0.538	0.583	1.000	0.000	0.000	0.278	0.000	0.000	0.000
Hydropower	0.000	0.000	0.000	0.000	0.000	0.000	0.681	0.558	1.000	0.600	0.681	0.000

Normalized matrix

	Technical			Environment			Economic			Social		
	Efficiency	Exergy	Primary Energy Ratio	CO_2 Emissions	NOx Emissions	Particles Emissions	CAPEX	OPEX	Payback period	Job Creation	Benefits	Social Acceptability
	max	max	max	min	min	min	min	min	max	max	max	max
Onshore Wind	0.000	0.000	0.093	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.000	0.000
Wave and Tidal	0.800	0.795	0.000	0.538	0.583	1.000	0.000	0.000	0.722	1.000	1.000	1.000
Hydropower	1.000	1.000	1.000	0.000	0.000	0.000	0.681	0.558	0.000	0.400	0.319	1.000

Marginal Utility

	Technical			Environment			Economic			Social		
	Efficiency	Exergy	Primary Energy Ratio	CO_2 Emissions	NOx Emissions	Particles Emissions	CAPEX	OPEX	Payback period	Job Creation	Benefits	Social Acceptability
Onshore Wind	0.000	0.000	0.000	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.000	0.000
Wave and Tidal	0.389	0.380	0.000	0.098	0.128	1.000	0.000	0.000	0.266	1.000	1.000	1.000
Hydropower	1.000	1.000	1.000	0.000	0.000	0.000	0.216	0.110	0.000	0.038	0.019	1.000

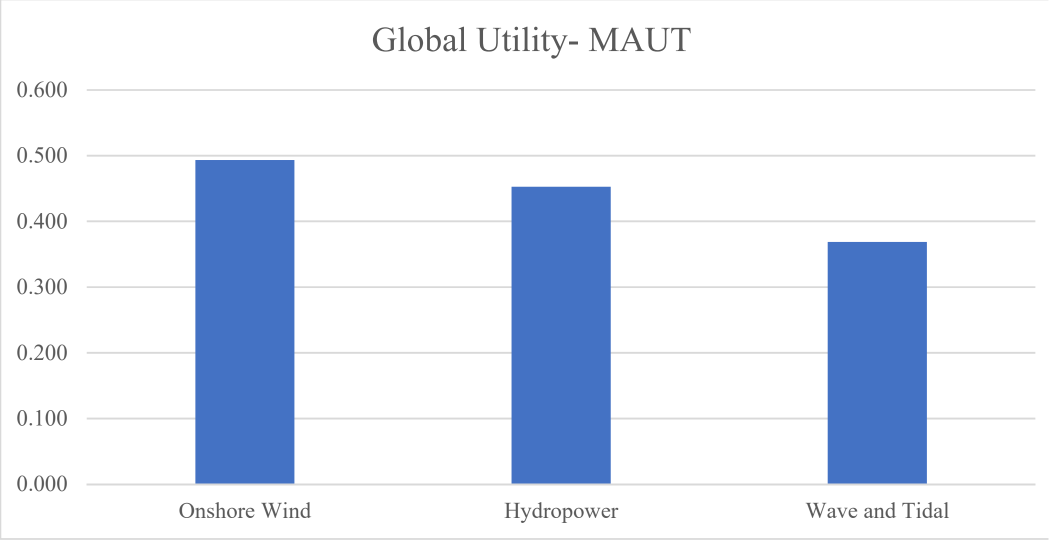
Analysis and Result

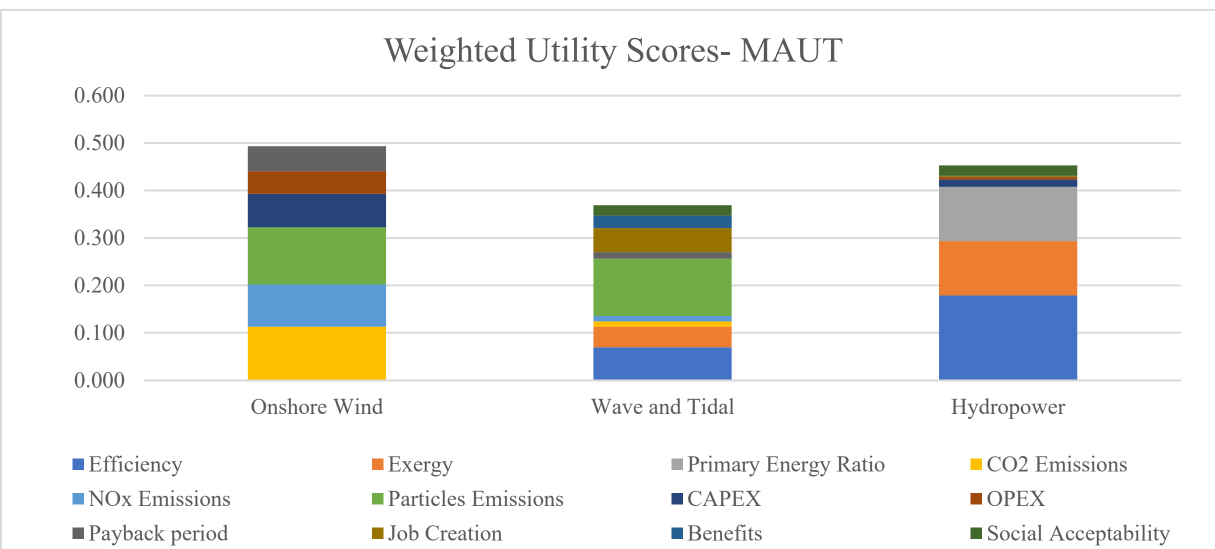
Technical			Environment			Economic			Social			
Efficiency	Exergy	Primary Energy Ratio	CO_2 Emissions	NOx Emissions	Particles Emissions	CAPEX	OPEX	Payback period	Job Creation	Benefits	Social Accept	Result
18%	11%	11%	11%	9%	12%	7%	5%	5%	5%	3%	2%	

Onshore Wind	0.000	0.000	0.000	0.113	0.089	0.120	0.070	0.048	0.053	0.000	0.000	0.000	0.493
Wave and Tidal	0.070	0.044	0.000	0.011	0.011	0.120	0.000	0.000	0.014	0.051	0.026	0.022	0.369
Hydropower	0.179	0.115	0.115	0.000	0.000	0.000	0.015	0.005	0.000	0.002	0.000	0.022	0.453

Ranking

1	0.493	Onshore Wind
2	0.453	Hydropower
3	0.369	Wave and Tidal




Weighted Utility Scores- MAUT
0.600
0.500
0.400
0.300
0.200
0.100
0.000
Onshore Wind
Wave and Tidal
Hydropower
Efficiency
Exergy
Primary Energy Ratio
CO2 Emissions
NOx Emissions
Particles Emissions
CAPEX
OPEX
Payback period
Job Creation
Benefits
Social Acceptability

Simulation 8-22: WSM

Raw Scale

	Technical			Environment			Economic			Social		
	Efficiency	Exergy	Primary Energy Ratio	CO_2 Emissions	NOx Emissions	Particles Emissions	CAPEX USDm/MW	OPEX USD/MW/yr	Payback period (yrs)	Job Creation	Benefits USDm/MW	Social Acceptability
	18%	**11%**	**11%**	**11%**	**9%**	**12%**	**7%**	**5%**	**5%**	**5%**	**3%**	**2%**
Onshore Wind	70%	48.70%	1.44%	11	12	0.1	1.52	28,750.00	8	11	0.304	5
Wave and Tidal	90%	62%	0.89%	17	17	0.1	9.03	130,000.00	7.5	21	1.806	9
Hydropower	95%	66%	6.79%	24	24	0.5	3.915	73,500.00	6.2	15	0.783	9

Normalize Scale: Maximize Criterion

	Technical			Environment			Economic			Social		
	Efficienc y	Exergy	Primary Energy Ratio	CO_2 Emissions	NOx Emissions	Particles Emissions	CAPEX	OPEX	Payback period	Job Creation	Benefits	Social Acceptabilit y
Onshore Wind	0.000	0.000	0.093	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000
Wave and Tidal	0.800	0.795	0.000	0.462	0.417	0.000	1.000	1.000	0.722	1.000	1.000	1.000
Hydropower	1.000	1.000	1.000	1.000	1.000	1.000	0.319	0.442	0.000	0.400	0.319	1.000

Normalized Scale: Minimize Criterion

	Technical			Environment			Economic			Social		
	Efficiency	Exergy	Primary Energy Ratio	CO_2 Emissions	NOx Emissions	Particles Emissions	CAPEX	OPEX	Payback period	Job Creation	Benefits	Social Acceptability
Onshore Wind	1.000	1.000	0.907	1.000	1.000	1.000	1.000	1.000	0.000	1.000	1.000	1.000

Wave and Tidal	0.200	0.205	1.000	0.538	0.583	1.000	0.000	0.000	0.278	0.000	0.000	0.000
Hydropower	0.000	0.000	0.000	0.000	0.000	0.000	0.681	0.558	1.000	0.600	0.681	0.000

Normalized matrix

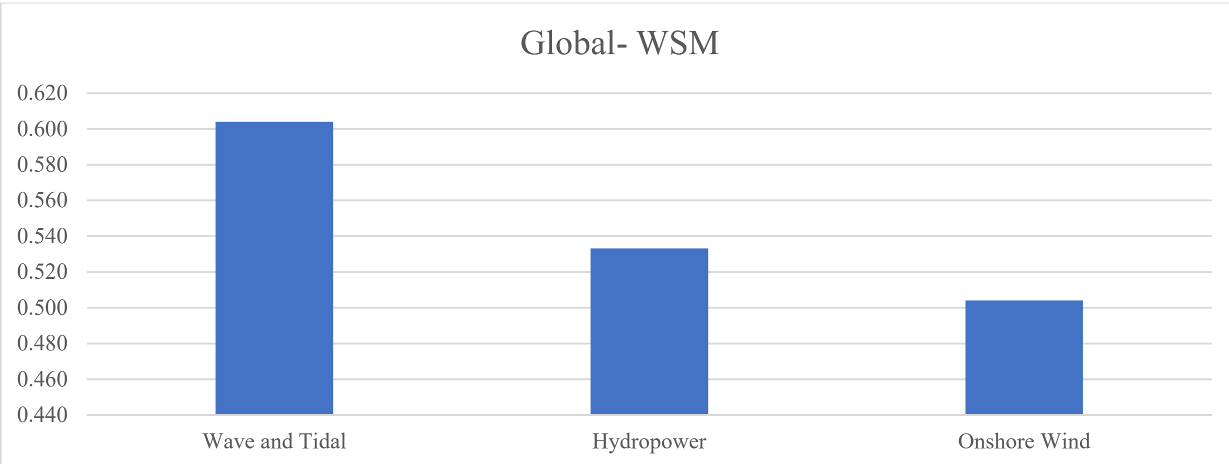
	Technical			Environment			Economic			Social		
	Efficiency	Exergy	Primary Energy Ratio	CO_2 Emissions	NOx Emissions	Particles Emissions	CAPEX	OPEX	Payback period	Job Creation	Benefits	Social Acceptability
	18%	11%	11%	11%	9%	12%	7%	5%	5%	5%	3%	2%
Onshore Wind	0.000	0.000	0.093	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.000	0.000
Wave and Tidal	0.800	0.795	0.000	0.538	0.583	1.000	0.000	0.000	0.722	1.000	1.000	1.000
Hydropower	1.000	1.000	1.000	0.000	0.000	0.000	0.681	0.558	0.000	0.400	0.319	1.000

Analysis and Result

	Technical			Environment			Economic			Social			
	Efficiency	Exergy	Primary Energy Ratio	CO_2 Emissions	NOx Emissions	Particles Emissions	CAPEX	OPEX	Payback period	Job Creation	Benefits	Social Acceptability	Result
Onshore Wind	0.000	0.000	0.011	0.113	0.089	0.120	0.070	0.048	0.053	0.000	0.000	0.000	0.504
Wave and Tidal	0.143	0.091	0.000	0.061	0.052	0.120	0.000	0.000	0.038	0.051	0.026	0.022	0.604
Hydropower	0.179	0.115	0.115	0.000	0.000	0.000	0.048	0.027	0.000	0.020	0.008	0.022	0.533

Ranking

1	0.604	Wave and Tidal
2	0.533	Hydropower
3	0.504	Onshore Wind


Global- WSM
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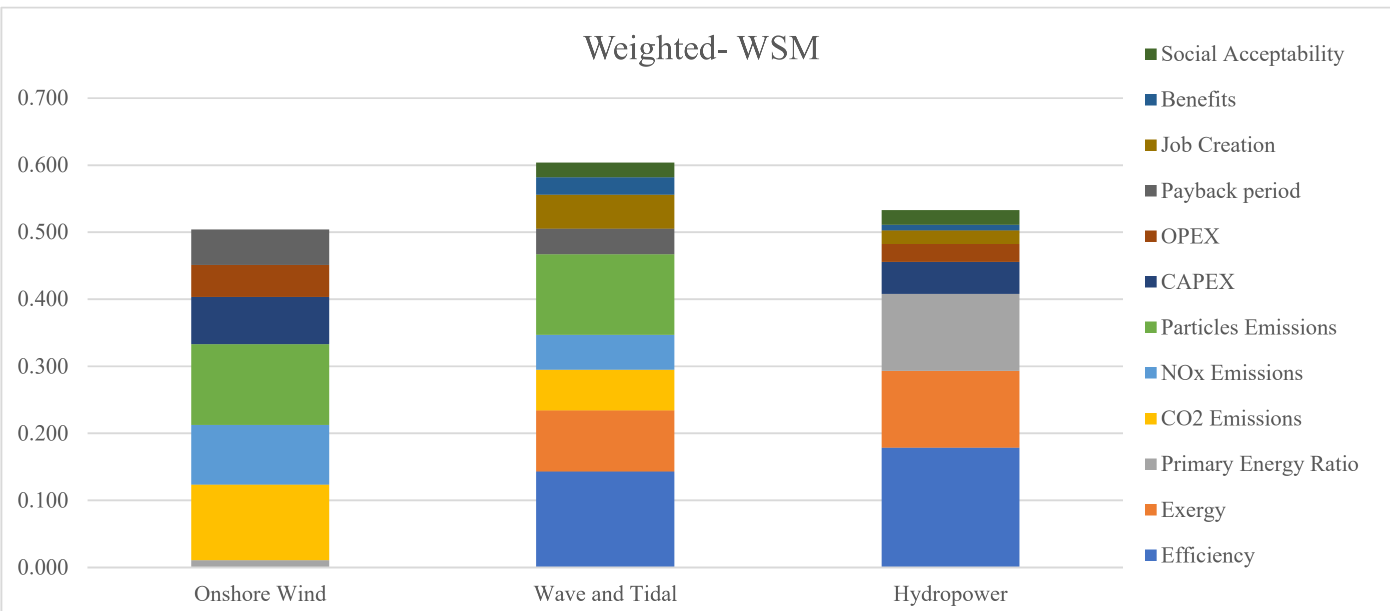
0.600
0.580
0.560
0.540
0.520
0.500
0.480
0.460
0.440
Wave and Tidal
Hydropower
Onshore Wind


Weighted- WSM
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
Onshore Wind
Wave and Tidal
Hydropower
Social Acceptability
Benefits
Job Creation
Payback period
OPEX
CAPEX
Particles Emissions
NOx Emissions
CO2 Emissions
Primary Energy Ratio
Exergy
Efficiency

8.10 Sensitivity Analysis and Recommendations

The new global weight was calculated, and the results are shown in Simulation 6-24.

Simulation 8-23: Sensitivity Weight Change

Technology

	Aggregate result	Weight	Sub-criteria global weight
Primary Energy Ratio	18.094%		0%
Maturity	7%		
Exergy	18.095%	30%	12%
Safety	14%		
Reliability	15%	24%	10%
Efficiency	28%	46%	19%
	61%	100%	41%

Environment

	Aggregate result	Weight	Sub-criteria global weight
Land Use	3%	12%	4%
Noise	3%		
NOx Emissions	9.34%		
SO2 Emissions	9.79%		
CO2 Emissions	12%	43%	14%
Particle Emission	13%	45%	15%
	0.28	100%	32%

Economic

	Aggregate result	Weight	Sub-criteria global weight
CAPEX	26%	41%	7%
NPV	14%		
OPEX	17%	28%	5%
Payback Period	19%	31%	5%
Maintenance	12%		
Cost of fuel	11%		
	0.62	1.00	17%

Social

	Aggregate result	Weight	Sub-criteria global weight
Job Creation	51%	51%	5%
Benefits	26%	26%	3%
Social Acceptability	22%	22%	2%
	100%	100%	10%

The new calculations and the results are shown in Simulation 6-25 for the MAUT method and 6-26 for the WSM method.

Simulation 8-24: Sensitivity MAUT

Raw Scale

	Technical			Environment			Economic			Social		
	Efficiency	Exergy	**Reliability**	CO_2 Emissions	**Land Use**	Particles Emissions	CAPEX USDm/MW	OPEX USD/MW/yr	Payback period (yrs)	Job Creation	Benefits USDm/MW	Social Acceptability
	19%	**12%**	**10%**	**14%**	**4%**	**15%**	**7%**	**5%**	**5%**	**5%**	**3%**	**2%**
Onshore Wind	70%	48.70%	3.00	11	8	0.1	1.52	28,750.00	8	11	0.304	5
Wave and Tidal	90%	62%	9.00	17	0	0.1	9.03	130,000.00	7.5	21	1.806	9
Hydropower	95%	66%	5.00	24	60	0.5	3.915	73,500.00	6.2	15	0.783	9

Normalize Scale: Maximize Criterion

	Technical			Environment			Economic			Social		
	Efficiency	Exergy	**Reliability**	CO_2 Emissions	**Land Use**	Particles Emissions	CAPEX	OPEX	Payback period	Job Creation	Benefits	Social Acceptability
Onshore Wind	0.000	0.000	0.000	0.000	0.133	0.000	0.000	0.000	1.000	0.000	0.000	0.000
Wave and Tidal	0.800	0.795	1.000	0.462	0.000	0.000	1.000	1.000	0.722	1.000	1.000	1.000
Hydropower	1.000	1.000	0.333	1.000	1.000	1.000	0.319	0.442	0.000	0.400	0.319	1.000

Normalized Scale: Minimize Criterion

	Technical			Environment			Economic			Social		
	Efficiency	Exergy	**Reliability**	CO_2 Emissions	**Land Use**	Particles Emissions	CAPEX USDm/MW	OPEX USD/MW/yr	Payback period (yrs)	Job Creation	Benefits USDm/MW	Social Acceptability
Onshore Wind	1.000	1.000	1.000	1.000	0.867	1.000	1.000	1.000	0.000	1.000	1.000	1.000
Wave and Tidal	0.200	0.205	0.000	0.538	1.000	1.000	0.000	0.000	0.278	0.000	0.000	0.000
Hydropower	0.000	0.000	0.667	0.000	0.000	0.000	0.681	0.558	1.000	0.600	0.681	0.000

Normalized matrix

	Technical			Environment			Economic			Social		
	Efficiency	Exergy	**Reliability**	CO_2 Emissions	**Land Use**	Particles Emissions	CAPEX	OPEX	Payback period	Job Creation	Benefits	Social Acceptability
	max	max	max	min	min	min	min	min	max	max	max	max
Onshore Wind	0.000	0.000	0.000	1.000	0.867	1.000	1.000	1.000	1.000	0.000	0.000	0.000
Wave and Tidal	0.800	0.795	1.000	0.538	1.000	1.000	0.000	0.000	0.722	1.000	1.000	1.000
Hydropower	1.000	1.000	0.333	0.000	0.000	0.000	0.681	0.558	0.000	0.400	0.319	1.000

Marginal Utility

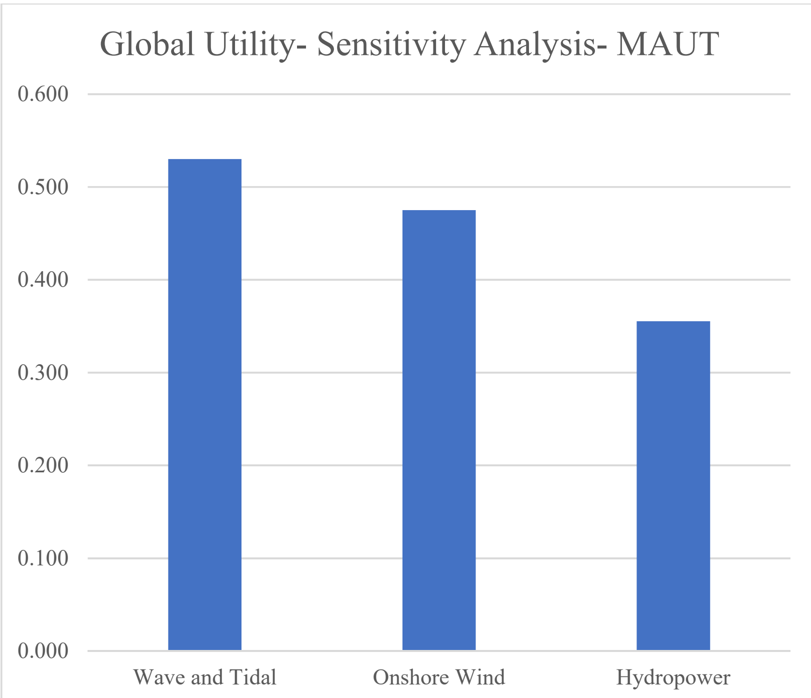
	Technical			Environment			Economic			Social		
	Efficiency	Exergy	**Reliability**	CO_2 Emissions	**Land Use**	Particles Emissions	CAPEX	OPEX	Payback period	Job Creation	Benefits	Social Acceptability
Onshore Wind	0.000	0.000	0.000	1.000	0.534	1.000	1.000	1.000	1.000	0.000	0.000	0.000
Wave and Tidal	0.389	0.380	1.000	0.098	1.000	1.000	0.000	0.000	0.266	1.000	1.000	1.000
Hydropower	1.000	1.000	0.022	0.000	0.000	0.000	0.216	0.110	0.000	0.038	0.019	1.000

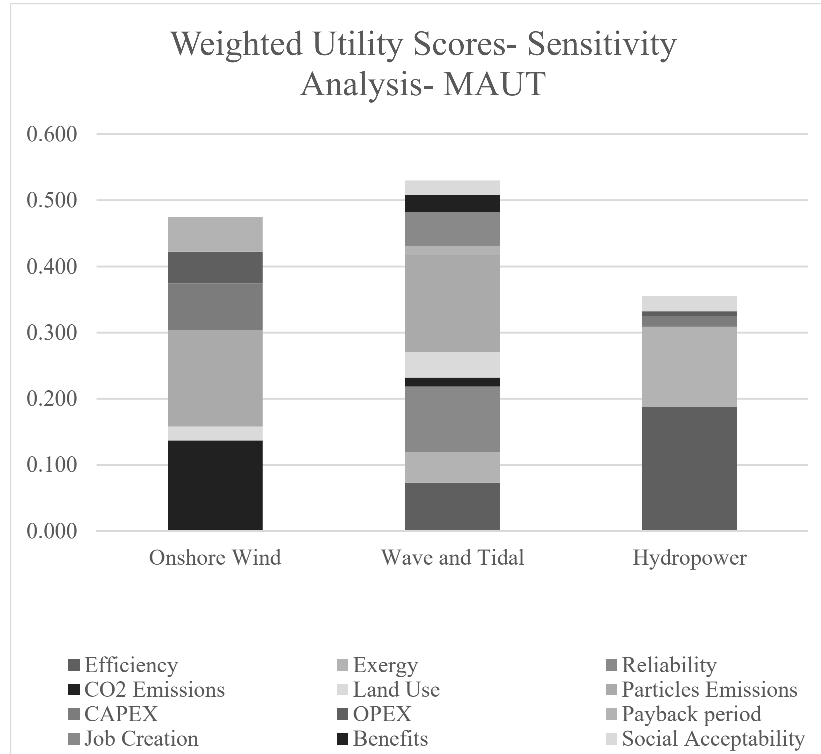
Analysis and Result

	Technical			Environment			Economic			Social			
	Efficiency	Exergy	**Reliability**	CO_2 Emissions	**Land Use**	Particles Emissions	CAPEX	OPEX	Payback period	Job Creation	Benefits	Social Acceptability	Result
	19%	**12%**	**10%**	**14%**	**4%**	**15%**	**7%**	**5%**	**5%**	**5%**	**3%**	**2%**	
Onshore Wind	0.000	0.000	0.000	0.137	0.021	0.146	0.070	0.048	0.053	0.000	0.000	0.000	0.475
Wave and Tidal	0.073	0.046	0.100	0.013	0.039	0.146	0.000	0.000	0.014	0.051	0.026	0.022	0.530
Hydropower	0.188	0.120	0.002	0.000	0.000	0.000	0.015	0.005	0.000	0.002	0.000	0.022	0.355

Ranking

1	0.530	Wave and Tidal
2	0.475	Onshore Wind
3	0.355	Hydropower


Global Utility- Sensitivity Analysis- MAUT
0.600
0.500
0.400
0.300
0.200
0.100
0.000
Wave and Tidal
Onshore Wind
Hydropower


Weighted Utility Scores- Sensitivity Analysis- MAUT
0.600
0.500
0.400
0.300
0.200
0.100
0.000
Onshore Wind
Wave and Tidal
Hydropower
Efficiency
Exergy
Reliability
CO2 Emissions
Land Use
Particles Emissions
CAPEX
OPEX
Payback period
Job Creation
Benefits
Social Acceptability

Simulation 8-25: Sensitivity -WSM

Raw Scale

	Technical			Environment			Economic			Social		
	Efficiency	Exergy	**Reliability**	CO_2 Emissions	**Land Use**	Particles Emissions	CAPEX USDm/MW	OPEX USD/MW/yr	Payback period (yrs)	Job Creation	Benefits USDm/MW	Social Acceptability
	19%	**12%**	**10%**	**14%**	**4%**	**15%**	**7%**	**5%**	**5%**	**5%**	**3%**	**2%**
Onshore Wind	70%	48.70%	3.00	11	8	0.1	1.52	28,750.00	8	11	0.304	5
Wave and Tidal	90%	62%	9.00	17	0	0.1	9.03	130,000.00	7.5	21	1.806	9
Hydropower	95%	66%	5.00	24	60	0.5	3.915	73,500.00	6.2	15	0.783	9

Normalize Scale: Maximize Criterion

	Technical			Environment			Economic			Social		
	Efficiency	Exergy	**Reliability**	CO_2 Emissions	**Land Use**	Particles Emissions	CAPEX USDm/MW	OPEX USD/MW/yr	Payback period (yrs)	Job Creation	Benefits USDm/MW	Social Acceptability
Onshore Wind	0.000	0.000	0.000	0.000	0.133	0.000	0.000	0.000	1.000	0.000	0.000	0.000
Wave and Tidal	0.800	0.795	1.000	0.462	0.000	0.000	1.000	1.000	0.722	1.000	1.000	1.000
Hydropower	1.000	1.000	0.333	1.000	1.000	1.000	0.319	0.442	0.000	0.400	0.319	1.000

Normalized Scale: Minimize Criterion

	Technical			Environment			Economic			Social		
	Efficiency	Exergy	**Reliability**	CO_2 Emissions	**Land Use**	Particles Emissions	CAPEX	OPEX	Payback period	Job Creation	Benefits	Social Acceptability
Onshore Wind	1.000	1.000	1.000	1.000	0.867	1.000	1.000	1.000	0.000	1.000	1.000	1.000
Wave and Tidal	0.200	0.205	0.000	0.538	1.000	1.000	0.000	0.000	0.278	0.000	0.000	0.000
Hydropower	0.000	0.000	0.667	0.000	0.000	0.000	0.681	0.558	1.000	0.600	0.681	0.000

Normalized matrix

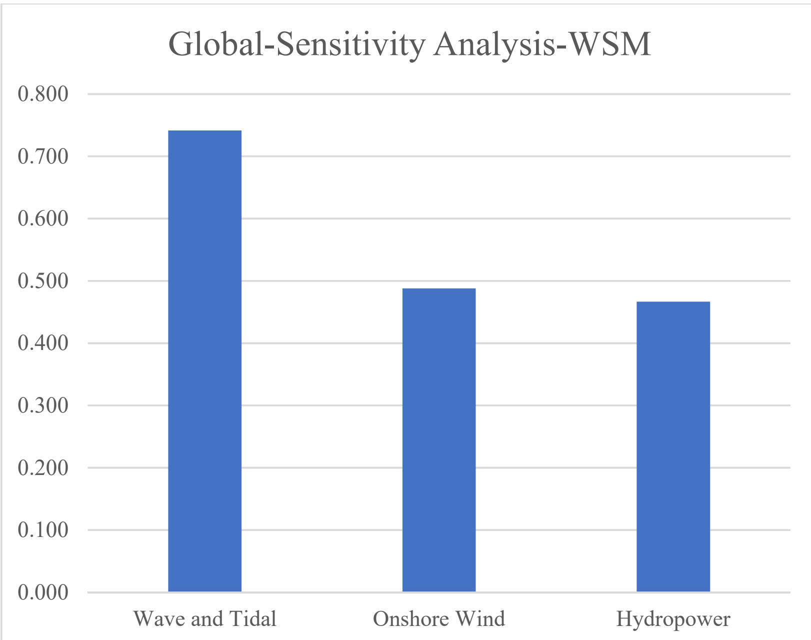
	Technical			Environment			Economic			Social		
	Efficiency	Exergy	**Reliability**	CO_2 Emissions	**Land Use**	Particles Emissions	CAPEX	OPEX	Payback period	Job Creation	Benefits	Social Acceptability
	19%	12%	10%	14%	4%	15%	7%	5%	5%	5%	3%	2%
Onshore Wind	0.000	0.000	0.000	1.000	0.867	1.000	1.000	1.000	1.000	0.000	0.000	0.000
Wave and Tidal	0.800	0.795	1.000	0.538	1.000	1.000	0.000	0.000	0.722	1.000	1.000	1.000
Hydropower	1.000	1.000	0.333	0.000	0.000	0.000	0.681	0.558	0.000	0.400	0.319	1.000

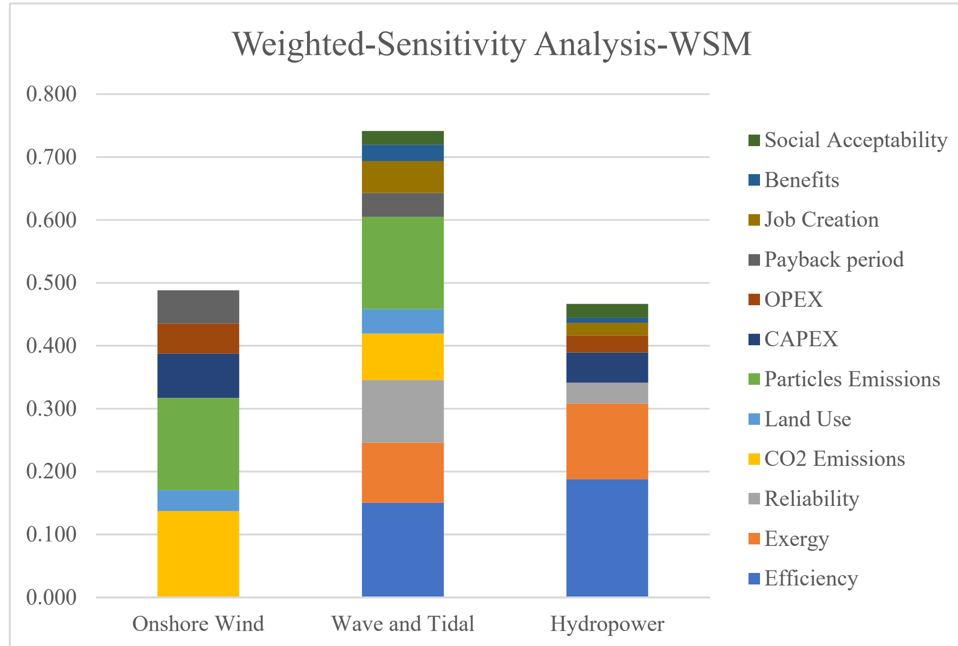
Analysis and Result

	Technical			Environment			Economic			Social			
	Efficiency	Exergy	**Reliability**	CO_2 Emissions	**Land Use**	Particles Emissions	CAPEX	OPEX	Payback period	Job Creation	Benefits	Social Acceptability	Result
Onshore Wind	0.000	0.000	0.000	0.137	0.034	0.146	0.070	0.048	0.053	0.000	0.000	0.000	0.488
Wave and Tidal	0.150	0.096	0.100	0.074	0.039	0.146	0.000	0.000	0.038	0.051	0.026	0.022	0.742
Hydropower	0.188	0.120	0.033	0.000	0.000	0.000	0.048	0.027	0.000	0.020	0.008	0.022	0.467

Ranking

1	0.742	Wave and Tidal
2	0.488	Onshore Wind
3	0.467	Hydropower


Global-Sensitivity Analysis-WSM
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
Wave and Tidal
Onshore Wind
Hydropower


Weighted-Sensitivity Analysis-WSM
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
Onshore Wind
Wave and Tidal
Hydropower
Social Acceptability
Benefits
Job Creation
Payback period
OPEX
CAPEX
Particles Emissions
Land Use
CO2 Emissions
Reliability
Exergy
Efficiency