# A Decision Aiding Framework for Concentrated Solar Thermal Power Technologies Assessment in Developing Countries

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# ABSTRACT

**A Decision Aiding Framework for Concentrated Solar Thermal Power Technologies Assessment in Developing Countries**



**Abdulrahman Ibrahim Kassem, Ph.D.**
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The diversification of electricity generation is necessary for sustainable development. The planning for renewable energy sources (RESs) integration is an essential goal set by many developing countries. Enormous investments are allocated accordingly to renewable energy projects, including solar power utilities. Concentrated solar thermal power (CSP) technologies are advancing and are expected to play a significant role in energy portfolios in the future. CSP planning is a complex process owing to the involvement of various contradicting factors and players. This thesis proposes a structured aiding framework to assess utility-scale CSP alternatives to support national grids in developing countries. It is common in many fast growing developing countries that the power plants are owned by the state, which enlarges the scope of electric power projects beyond the technical and economic drivers to include environmental, social, and political aspects, which accordingly increases the planning process complexity.

The developed methodology consists of three main phases. The first phase is concerned with formulating a value tree for CSP technologies evaluation. This phase is intended to explicitly capture a generic evaluation criteria through a rigorous process of expert deliberation and consensus-seeking. Expert elicitation is conducted through the Delphi method, with a total of 140 experts participating from multidisciplinary solar thermal power fields from 32 countries. Based on participants' judgments, as expressed during two rounds of Delphi questionnaires, parameters with importance and consensus degrees > 50% are incorporated to construct the final value tree. The recommendations of this phase set a foundation for stakeholders' assessment of

regional CSP utilities planning in developing countries.

The second phase considers analyzing, defining, and simulating alternative scenarios. Large-scale CSP deployment is in its infancy with a lack of sufficient data in many developing countries and various available technology combinations. Accordingly, this phase intends to focus the planning process toward practical alternatives given the regional requirements. A techno-economic analysis is conducted that considers the strengths, weaknesses, opportunities, and threats (SWOT) for each technology. As RESs are location dependent, Saudi Arabia defines the scope of this phase. The analysis outcomes are incorporated with the Saudi energy sector requirements and local weather conditions to define alternative scenarios. Six power plant scenarios are defined for performance and financial evaluation. A simulation is subsequently carried out through the System Advisor Model. The alternative scenarios are assessed by defining weather, technical, and financial parameters. Satellite observations and field measured data are integrated to synthesize a typical meteorological year weather profile. The outputs of this phase provide accurate results that represent a solid ground for the assessment of alternative CSP scenarios with consideration of all relevant parameters.

The third phase considers a comprehensive assessment of the scenario-based CSP alternatives. A multi-criteria decision-making (MCDM) model is developed in a fuzzy environment to tackle uncertainty, ambiguity, and imprecision. The evaluation is conducted based on extensive analysis of the performances of each alternative scenario in accordance with 4 main criteria and 29 sub-criteria. Quantitative and qualitative data as well as input from 44 local stakeholders are incorporated. The obtained results constitute an accurate basis to derive recommendations for CSP integration to national grids and relate them to stakeholders' priorities.

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"رب أوزعني أن أشكر نعمتك التي أنعمت علي وعلى والدي وأن أعمل صالحا ترضاه وأصلح لي في ذريتي"

**"My Lord, enable me to be grateful for Your favor which You have bestowed upon me and upon my parents and to work righteousness of which You will approve and make righteous for me my offspring"**

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## List of Nomenclatures and Abbreviations

| | |
|---|---|
| ADP | Analytic deliberative process |
| CAS | Complex adaptive system |
| CBA | Cost benefit analysis |
| CED | Cumulative energy demand |
| CFI | Capacity factor per initial cost index |
| CSP | Concentrated solar thermal power |
| CV | Coefficient of variation |
| DHI | Diffuse horizontal irradiance |
| DNDO | Domestic Nuclear Detection Office |
| DNI | Direct normal irradiance |
| DOE | Department of Energy |
| DSG | Direct steam generation |
| ENSAD | Energy-related severe accident database |
| EPBT | Energy payback time |
| EPC | Engineering, procurement, and construction |
| FAHP | Fuzzy analytic hierarchy process |
| FiT | Feed-in Tariff |
| GCC | Gulf Cooperation Council |
| GHG | Greenhouse gas |
| GHI | Global horizontal irradiance |
| HCE | Heat-collecting element |
| HTF | Heat transfer fluid |
| IEA | International Energy Agency |
| IRENA | International Renewable Energy Agency |
| ISCC | Integrated solar combined cycle |

| | |
|---|---|
| K.A.CARE | King Abdullah City for Atomic and Renewable Energy |
| KACST | King Abdulaziz City for Science and Technology |
| LCA | Life cycle assessment |
| LCOE | Levelized cost of energy |
| LF | Linear Fresnel |
| MAUT | Multi-attribute utility theory |
| MCDM | Multi-criteria decision-making |
| MCE | Multi-criteria evaluation |
| MENA | Middle East and North Africa |
| NASA | National Aeronautics and Space Administration |
| NPV | Net present value |
| NRC | National Research Council |
| NREL | National Renewable Energy Laboratory |
| OPEC | Organization of the Petroleum Exporting Countries |
| PPA | Power purchase agreement |
| PD | Parabolic dish |
| PT | Parabolic trough |
| QFD | Quality function deployment |
| RES | Renewable energy source |
| RNA | Rank number of alternatives |
| RPS | Renewable portfolio standard |
| ROI | Return of investment |
| RRMM | Renewable Resource Monitoring and Mapping |
| RIDM | Risk-informed decision-making |
| SAM | System Advisor Model |
| SCA | Solar collector assemblies |

| | |
|---|---|
| SEGS | Solar Energy Generating System |
| SM | Solar multiple |
| SPV | Solar photovoltaic |
| SWOT | Strengths, weaknesses, opportunities, and threats |
| ST | Solar tower |
| UAE | United Arab Emirates |
| TES | Thermal energy storage |
| TFN | Triangular fuzzy number |
| TMY | Typical meteorological year |

# Chapter 1: Introduction

## 1.1. Background

Electricity generation is an essential driver for the advancement of modern life. Today, the electrical national grids face many challenges, including the growing world population, the need to provide electricity to more than one billion people who still have no proper access to it, and the electrification of many aspects of modern life. These factors add to the ever-increasing demand, while on the other hand there are pressures to reduce greenhouse emissions and integrate infinite energy sources into national grids. These challenges lead to a growing worldwide awareness of the importance of renewable energy sources (RESs) to support sustainability. The majority of electricity generated in the world today is based on finite sources of energy such as coal and natural gas [1]. Many countries around the globe are adopting energy plans that involve the integration of RESs with their grids to enhance environmental conditions and sustainability for the coming generations. Accordingly, the total installed RESs capacities have increased from nearly 60 GW in 2000 to over 885 GW in 2016, excluding hydropower.

Harnessing large portions of practically infinite energy reserves such as the sun effectively and profitably would provide a sustainable energy supply. For instance, the sun sends more energy to the earth in 45 min than humans consume in one year [3]. Solar power technologies have undergone remarkable developments during the past decade, and are expected to continue to grow. Looking closely at the breakdown of RESs capacities worldwide (Figure 1–1), the solar photovoltaic (SPV) represents the majority of solar technology developments compared to the concentrated solar thermal power (CSP) technology. While the PV technology utilizes solar global horizontal irradiance (GHI), which includes direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI), the CSP only capitalizes on DNI.

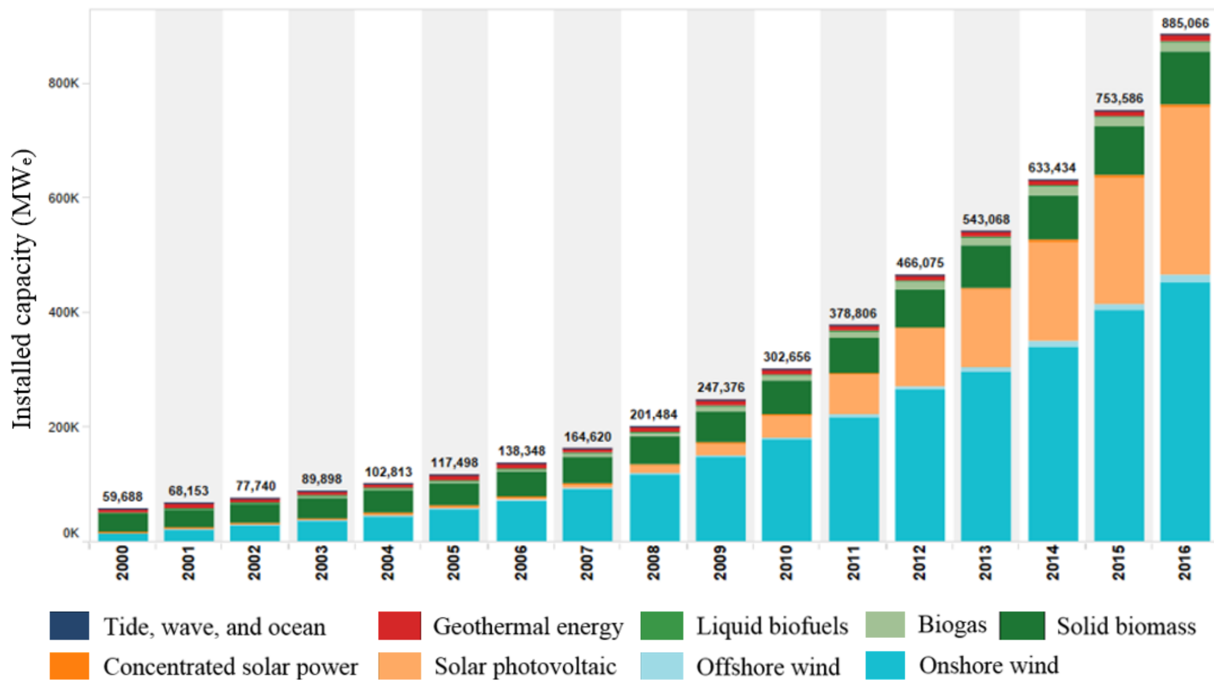



*Figure 1-1: Cumulative installed RESs capacities worldwide*
*Source: IRENA Data and Statistics, 2017 [2]*

Considering that the level of exposure is higher for GHI than for DNI (Figure 1–2), there were more opportunities for PV technology. This led to massive scale of residential and large-scale PV deployments that consequently facilitated the cost reduction of PV modules through economies of scale and research and development (R&D). There was an annual growth in cumulative installed capacity of PV modules of 30–40% between 2012 and 2015 [4]. The total installed capacity of PV exceeded 290 GW in 2016. CSP remains behind PV both in technology development and costs reduction. That said, CSP has witnessed a 27% increase of total capacity growth during the last decade exceeding 4.5 GW [5].

The CSP costs are declining, mainly in the global sunbelt, i.e., countries located within 35° of the Equator. A wide variety of CSP technologies are under development with special focus on TES [5]. CSP has key advantages, including efficient thermal energy storage (TES) and hybridization capabilities with conventional power plants and auxiliary burners, which reduce intermittency and extend generation hours [6]. These benefits support potential CSP development, including the International Energy Agency (IEA) roadmap vision that predicts solar thermal technologies alongside PV will each cover 11% of the global electricity generation by 2050 [7]. The main difference between the two technologies in accordance with demand is that PV essentially helps covering demand during module production hours, while CSP can also facilitate covering base load after sunset. The performance of CSP, when coupled with thermal storage, is thus enhanced in terms of energy cost reduction.

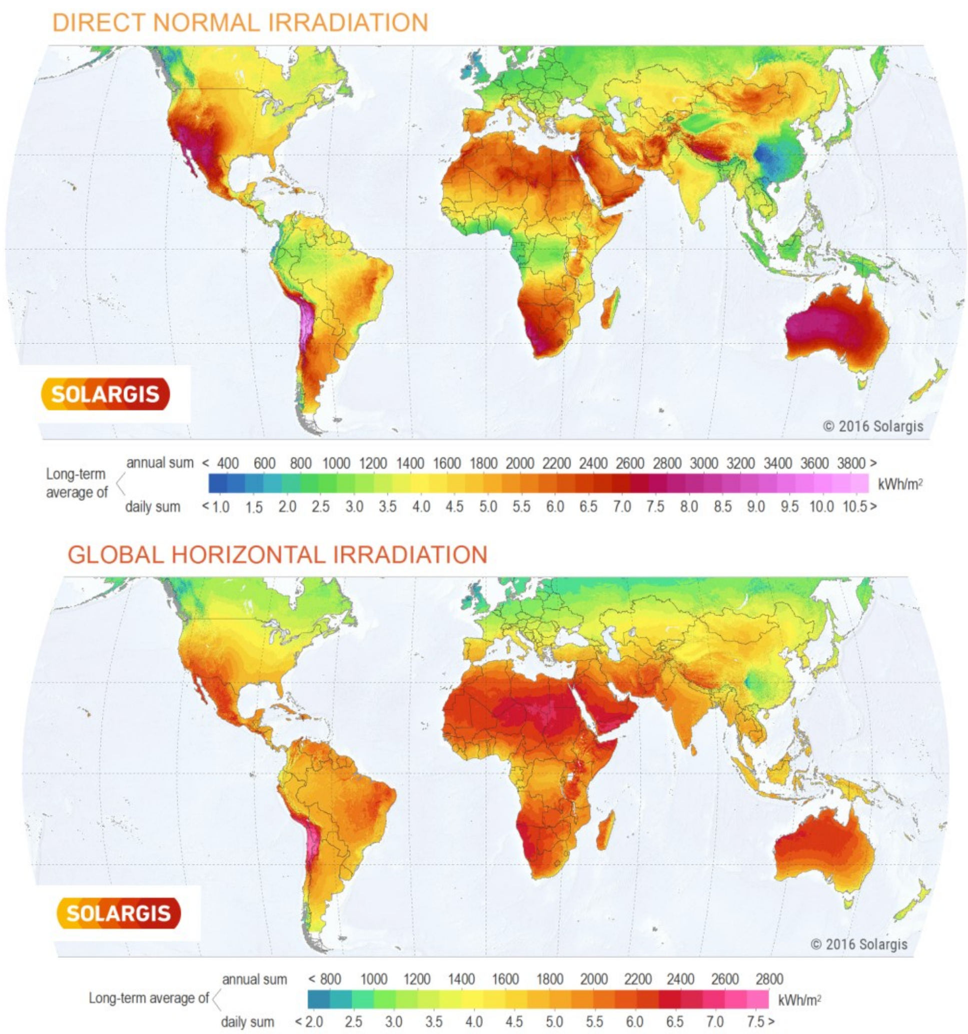



*Figure 1-2: World map for DNI (Up) and GHI (Down)*
*Source: Solar GIS, 2016 [8]*

The IEA vision predicts the continued growth of PV installation. This will lead to increasing the need to shift energy production, which is a crucial capability of CSP coupled with thermal storage. With more CSP projects coming online, the CSP industry can benefit from similar learning curves and economies of scale as those of PV modules and wind turbines. PV modules and wind turbines benefitted from learning curves of 24.3% and 19%, resulting in cost reductions of 80% and 50%, respectively, in less than a decade (Figure 1–3).

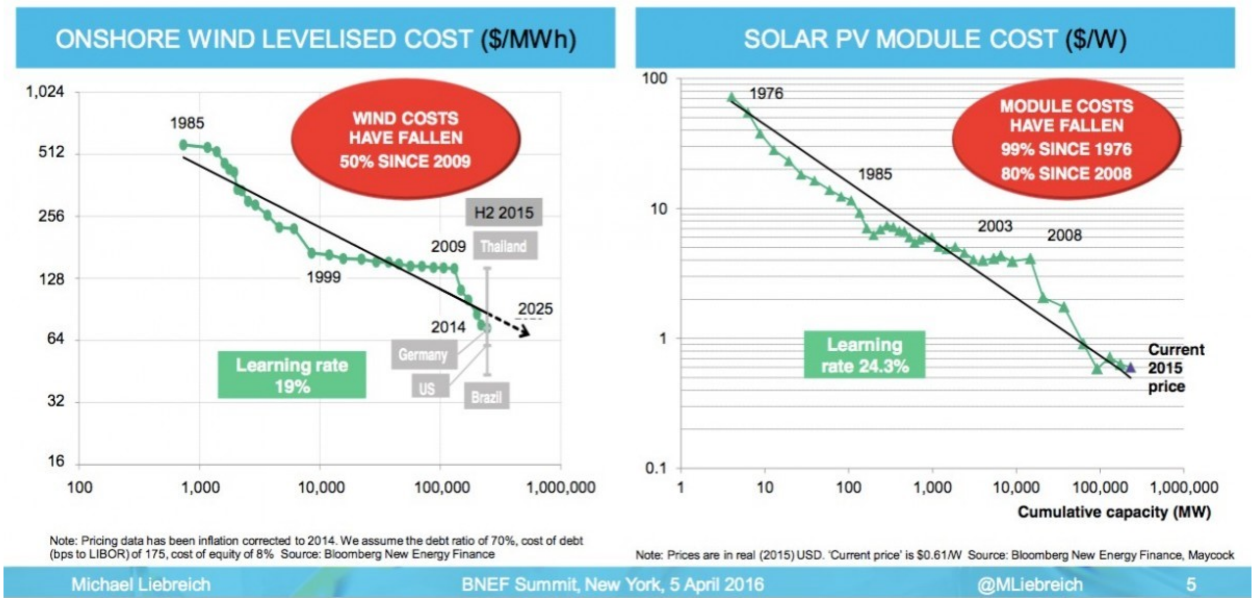



*Figure 1-3: Learning curves and cost reductions of PV modules and wind turbines*
*Source: Strid, 2016 [9]*

### 1.2. CSP in developing countries

Past capital investments in fossil fuel based power plants make it hard to switch to new technologies unless legislators impose policy interventions to accelerate such technologies. This situation, known as the lock-in effect, is common in developed countries that have national grids covering the majority of inhabited areas due to long-lived capital [10]. The situation significantly changes in fast growing and developing countries, particularly with respect to their electrical grids, where substantial electric capacity increases are continuously demanded to accommodate accelerated growth. These countries are required to make complex decisions regarding technology selections for electrical grid expansions.

The World Bank conducted a comprehensive study [11], focusing on the technical and financial regulations required to scale up CSP usage in developing countries. The study identified India, South Africa, and the Middle East and North Africa (MENA) region as potential large-scale CSP project sites [11]. Among those countries, India and South Africa are leading in terms of the CSP's total installed capacities, coming only after the top two developed countries (i.e., Spain and the US). In the Arabic region, Morocco has the highest capacity of operational power plants, with more under construction and under development projects [2]. Energy exporting countries are aware of the importance of diversifying their economic resources. With a future perspective, some Arabian Gulf countries, which depend heavily upon revenues from oil and gas exports in their development, became concerned about taking advantage of other energy sources available in the region. The region is blessed with an abundance of alternative energy sources, such as solar power and wind. In fact, the Middle East is one of the wealthiest regions on earth in terms of solar radiation [12]. The United Arab Emirates (UAE) has taken initiative in the area by building a city called Masdar (meaning "source") which depends solely on clean alternative energy sources. In addition, R&D is being conducted on a large scale, and the International Renewable Energy Agency (IRENA) has its headquarters located in the UAE. The Shams 1 CSP plant is one of the world's largest. It was completed in 2013 in the city of Masdar and has a capacity of 100 MW [2]. Oman and Kuwait are planning to deploy CSP for enhanced oil recovery operations at heavy crude oilfields [13].

Saudi Arabia is among the world's leaders in oil production. The country's economy is heavily dependent on petroleum exports, which accounted for 85% of Saudi Arabia's exports revenue in 2013 according to the Organization of the Petroleum Exporting Countries (OPEC) [14], [15]. Saudi Arabia has expressed increasing concern regarding the sustainability of its economic development and prosperity. It was estimated that the power peak demand of Saudi Arabia will exceed 120 GW by 2032 [16]. Critical decisions thus had to be made for electricity infrastructure expansion. To address such challenges, the King Abdullah City for Atomic and Renewable Energy (K.A.CARE) was established in 2010 [17]. K.A.CARE aims at drawing strategic portfolio plans for the sustainable development of Saudi Arabia's energy sector to support economic diversification. Plans of generating 54 GW of renewable energy by 2032 were announced. Enormous investments of 109 billion dollars were allocated to solar energy projects.

### 1.3. Problem statement

The ongoing development process and the rapid growth of population in many developing countries impose expansion of the national grid networks to meet the electricity demand growth. In addition, the Arabian Gulf is an arid area exposed to very hot summers. Electricity demand increases drove various leading energy exporting developing countries like Saudi Arabia to plan to direct strategic investments in alternative energy. K.A.CARE announced in 2012 an energy portfolio strategic plan for Saudi Arabia including conventional, renewable, and nuclear energy sources. Among RESs, the largest portion was allocated to solar technologies, with capacities of 25 GW for CSP and 16 GW for PV by 2032 [17], [18]. In 2015, the president of K.A.CARE announced that the alternative energy outlook was revised and the target year was postponed due to the need for additional assessment regarding technology selection [19]. In 2016, closer targets were announced to achieve 9.5 GW of RESs by 2023 as part of the 2030 vision of the country.

Power plant projects are of critical importance for sustainable development and societal prosperity. The enormous investments directed to power utility projects are essentially diverted from other developing projects, which adds significant importance to gaining the most out of them in all possible aspects. Furthermore, for countries in the Arabian Gulf, the realization has been made that oil reserves and prices may have already peaked; as such, it is urgent that they diversify their sources of income while they still benefit from massive income from the exportation of fossil fuels. It is thus vital to carry out in depth studies regarding CSP technologies to ensure obtaining optimal options for sustainable development. The selection of generating technologies can be considered as one of the most essential aspects in the decision process for utility projects. Decisions during the early stages of planning dictate future performance. Many studies have been carried out to aid decision-making in the power generation field based on mathematical programming, stochastic approaches, and matrix operations. However, these approaches are driven by profit motives. While these approaches are mainly suitable for industrialized developed societies, in which utility projects are generally initiated by private sector companies, they are less appropriate for developing countries, where the commissioner and owner of utility projects is often the government [20]. In this case, the scope of project objectives extends far beyond cost benefit aspects.

Many of the developing countries that are exposed to high rates of solar radiation and considered to have high potential for harnessing solar energy lack sufficient experience in commissioning CSP projects. Adding to this is the infancy of large-scale CSP deployment, availability of various technologies and combinations that conceptually differ from one another, and insufficiency of data required to accurately assess feasibilities. Combining these obstacles increases the associated uncertainties that influence investor's willingness to commit to CSP projects. Therefore, it is important to adopt frameworks that can conceptualize all available data and address intangible factors to support a structured decision-making process that covers all involved trajectories, including technical, economic, environmental, social, and political. Figure 1–4 illustrates the solar power technologies including PV and several available solar thermal power concepts.

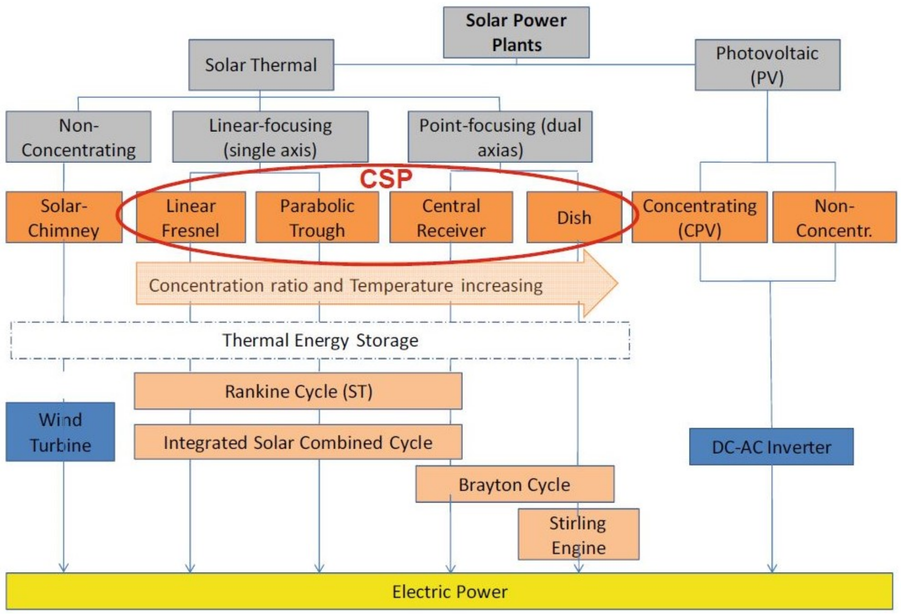



*Figure 1-4: Solar power technologies overview*
*Source: Konstantin and Kretschmann, 2010* [21]

The complexity of the energy planning problem involves multi-dimensional attributes, which leads to the potential problem that these attributes contradict with each other while considering alternative solutions. Moreover, it should be emphasized that energy systems consist of many actors, interacting through networks, leading to emergent properties and adaptive and learning processes, and are considered as complex systems [22]. This fact has to be taken into consideration in the overall decision-making process. It therefore becomes harder to grasp and contend with the complexity of the problems to obtain an optimized solution that performs best in all different aspects. Instead, tradeoffs are required in order to achieve the best solution that satisfies the stakeholders' requirements given local energy sectors and weather characteristics. In addition to the technical and financial considerations associated with energy projects, environmental concerns are presently raised to reduce greenhouse gas (GHG) effects. This led many authors to incorporate environmental aspects in planning processes regarding energy generation. Cavallaro [23] indicates that the traditional decision-making tools focus on finding the one optimal decision for a given problem, whereas the nature of environmental management activity, such as in CSP technologies assessment, requires subjective judgment from different aspects. Moreover, social aspects are evolving with society representative groups bringing public concerns to the authorities. Politics strongly relate to energy independency for sustainable development of nations [24], [25].

The planning of renewable energy projects is inherently associated with huge uncertainties as well as various stakeholders and their interests. The uncertainty is even greater in developing countries that lack similar projects and accurate data. In addition, it is required to start from defining the assessment criteria considering quantitative and qualitative factors that are involved in the planning process to facilitate decisions in terms of selecting the best technologies to meet both short and long term needs of the people. This situation suggests the adoption of a modeling framework that can associate the perspectives of experts and stakeholders of energy projects with their different standpoints. The approach is required to include quantitative and qualitative attributes. Furthermore, quantitative data must be acquired through exhaustive data collection and simulations owing to the sparsity of needed data in developing countries, while qualitative data are required to be obtained through quantifying experts' evaluations and stakeholders' preferences.

### 1.4. Motivations and applications

The literature lacks comprehensive definitions of the evaluation criteria that need to be considered in selecting CSP technologies in developing countries from global and heterogeneous perspectives. Involving data providers from different backgrounds enriches the results and ensures all perspectives are taken into account. A developing country like Saudi Arabia can generate electric power from RESs and export excess fossil fuels, which have been compensated by renewable energy for electricity generation and water desalination processes, to other countries. Moreover, Pazheri et al., [26] suggested that integrating RESs into the grid, and enhancing the grid by means of upgrading it to the next generation known as "smart grid", can help Saudi Arabia become an exporter of electricity.

It is important to note that the need for a single phase evaluation depending on cost benefit analysis (CBA) has evolved, and it became necessary to consider multiple attributes for decision-making [25]. Cavallaro [23] found that in many cases, traditional evaluation methods, such as CBA, and main financial indicators, such as net present value (NPV) and return of investment (ROI), are not adequate to handle all energy project components. As the complexity of energy portfolio planning increases, it becomes more difficult to identify an alternative that can maximize all decision criteria. In addition, it is necessary to consider both quantitative and qualitative attributes. It is assumed in CBA that everything has a value that can be determined in order to perform the analysis. Nevertheless, it becomes complicated for decisions that involve multi-dimensional attributes to convert all factors into monetary values. CBA thus works when only material loss and gain are involved [27]. In energy projects, the financial aspect is an extremely vital part; however, several other quantitative and qualitative aspects must also be reflected. Furthermore, there is an absence of required data to aid decision makers in prioritizing CSP technologies based on global perspectives and local requirements of adequate attributes and alternatives. All of the aforementioned factors constitute motivations to carry out a framework that aids the decision-making process for prioritizing CSP technologies.

### 1.5. Research objectives and scope

This research aims to facilitate decision makers in the early stages of CSP integration to focus on practical alternative scenarios. It provides a holistic strategic basis for the evaluation of different CSP technologies in developing countries. Accordingly, the primary goal is to provide a structure-oriented framework for CSP planning that brings together quantitative and qualitative data as well as judgments of international experts and local stakeholders. The significance of the framework lies in the aid it lends to support directing the enormous investments associated with CSP projects towards maximized benefit for sustainable development considering local conditions.

With respect to previous literature, this research proposes to contribute to the body of knowledge by means of developing a methodology to support the planning process associated with CSP assessment through integrating analytic deliberative process (ADP) and fuzzy analytic hierarchy process (FAHP). The ADP is often utilized in research involve uncertainty to compensate the lack of real data [28]. ADP is widely used through structured expert elicitation approaches that grasp subjective judgments from data providers, in research related to risk management and technology planning and roadmapping, to clearly define objectives, evaluation attributes, and alternatives for the assessment as well as set efficient and fair tradeoffs for the decision-making process [29]–[31]. Nevertheless, ADP does not serve as a strong calculation tool to overcome uncertainties. FAHP, on the other hand, offers an explicit and strong tool for modeling, including quantifying the qualitative factors attained through deliberation. Hence, the alternatives prioritization matrix can be calculated to obtain assessment outputs. Together, ADP and FAHP can represent a significant framework to minimize the impact of subjectivity and uncertainty resulting from data deficiency and occurring as an unavoidable by-product during the assessment of data providers' perspectives. The proposed ADP/FAHP framework provides a transparent tool to verify factors that are influencing the decision-making process rather than a black box process in which a decision is unveiled as the final solution. The proposed framework also provides the required instrument for clearly understanding the problem and monitoring the evolution of the decision-making process. To achieve the research goal, three objectives are defined as follow:

- Objective 1: To develop a value tree that explicitly identify parameters combination required for evaluation of CSP technologies through a rigorous process of expert elicitation and consensus-seeking.
- Objective 2: To analyze CSP plant configurations and technology combinations, define practical alternative scenarios, and carry out a techno-economic analysis based on local weather conditions and energy sector requirements.
- Objective 3: To assess CSP alternatives with respect to the defined evaluation criteria considering the uncertainties and tackling the quantitative date and qualitative inputs of local stakeholders.

The focus of this research is on large-scale CSP for electricity generation (i.e., Megawatt power plants). This research also focuses on developing countries with fast growing electricity demand, in which many aspects of life need essential enhancement to expedite modernization. Critical decisions must thus be made regarding energy planning by taking into account all relevant influencing factors. In developing a holistic decision framework, input data are collected from international heterogeneous experts from the CSP field as well as local stakeholders to bring together the experience and knowledge of the regional requirements.

A stakeholder is defined to be “an individual or organization that is materially affected by the outcome of a decision or deliverable but is outside the organization doing the work or making the decision” [30]. Stakeholders of the energy system in Saudi Arabia were comprehensively studied by Alonso [32], who defined and measured the values and interactions of the stakeholders as those who 1) have direct or indirect influence on the energy consumption or production in Saudi Arabia; 2) Receive direct or indirect benefits from the energy consumption or production in Saudi Arabia; 3) Hold important legitimate interest in energy consumption or production in Saudi Arabia. On the other hand, an expert is defined by Amer and Daim [31] as a person possessing inherently important characteristics that are useful for the elicitation process. Such characteristics include, but are not limited to, having acquired extensive knowledge in the subject matter, having the ability to simplify complexity associated with the problem, and having the ability to clearly communicate expertise.

### 1.6. Methodology overview

The proposed methodology aimed to provide a supporting framework to help decision makers in evaluating alternatives of large-scale CSP projects by means of integrating ADP with FAHP. The research was conducted in three phases, as shown in Figure 1–5. This section introduces an overview on the proposed methodology, while extended discussions of each phase will be provided in Chapters 2, 3, and 4, respectively.

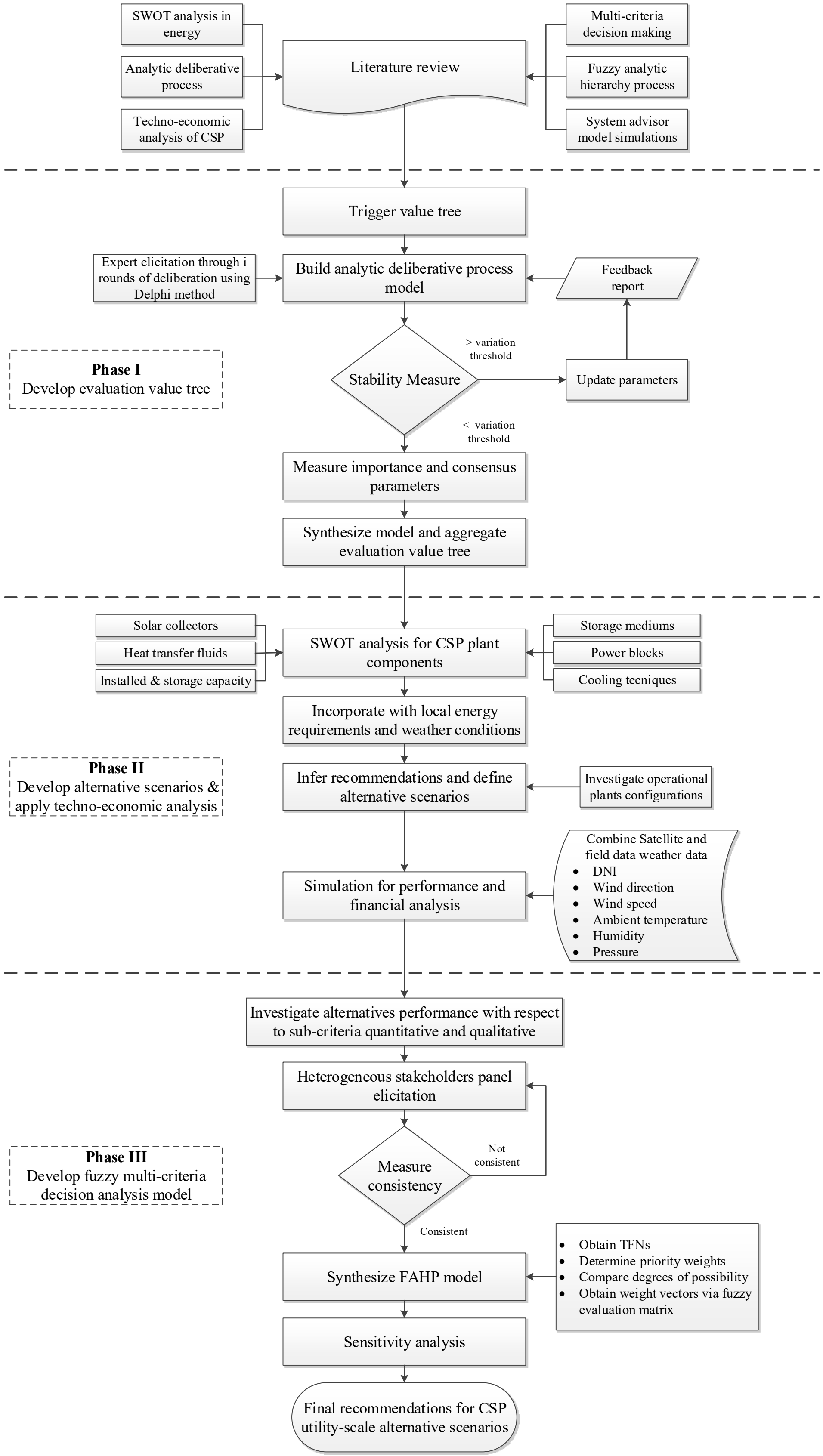



*Figure 1-5: Research methodology*

### 1.6.1. Value tree construction

The first phase began with developing a value tree, as per the first step of ADP, to capture a comprehensive perspective of the adequate decision attribute combination for evaluating CSP technologies in developing countries. A Delphi method was utilized to conduct a comprehensive elicitation in order to select the required parameters based on the aggregated perspective of heterogeneous experts working in the CSP fields. Cavallaro [23] indicated that the selection of criteria is of prime importance for problem resolution while Phdungsilp and Wuttipornpun [33] emphasized that it is the most sensitive part of applying multi-criteria approaches as it shapes the path of all subsequent steps. Few studies have discussed the assessment of CSP technologies from multi-criteria standpoints. While there is plenty of research relating to the general assessment and selection of power energy sources and RESs specifically. However, the decision criteria that are considered for the assessment were vaguely derived in the literature. It was noticed that researchers commonly consider self-definition of the evaluation criteria through literature with no explicit explanation of how the decision criteria were determined. Accordingly, different combinations of evaluation criteria were adopted based on researchers' perspectives.

With respect to previous literature, this phase aimed to explicitly identify parameters combination required for the evaluation of CSP technologies through a rigorous and structured process of experts' judgments elicitation and consensus-seeking. The value tree was ultimately constructed based on the perspectives of a heterogeneous panel of data providers from solar thermal power field, with a utility-scale focus in developing countries serving as a potential market for solar projects. Different affiliations and backgrounds of participants facilitated the elimination of biases and ensured that a coherent family of attributes were defined for CSP technologies evaluation. The output of this phase was a generic value tree with parameters that can be utilized locally by stakeholders and decision makers as a foundation for evaluating CSP project models at the planning stage, with possible slight modifications of parameters based on individual case requirements.

#### 1.6.2. Alternative scenarios definition and analysis

In the second phase of the proposed methodology, various CSP scenario-oriented alternatives were identified with the alteration of power utilities components including solar thermal collectors, heat transfer fluids (HTFs), thermal energy storage (TES) mediums, plant capacities, and storage capacities. As renewable energy projects are location dependent, Saudi Arabia defined the scope of this phase considering local energy sector requirements and weather characteristics. CSP technologies combinations and configurations were analyzed by means of strengths, weaknesses, opportunities, and threats (SWOT). Alternative scenarios were subsequently defined given the SWOT analysis incorporated with local weather conditions and energy requirements.

For developing countries, the lack of available data from operating renewable energy projects urges the exploitation of data acquired from similar projects records in developed countries or international databases, which was done by numerous authors in renewable energy planning studies [34]–[37]. In an attempt to enhance the accuracy of research results, simulations were carried out in this phase for the defined scenarios through the System Advisor Model (SAM). SAM is a modeling tool developed by the National Renewable Energy Laboratory (NREL) to simulate the performance and cost of renewable energy systems. The simulations were held to obtain performance predictions including the estimation of energy yield over a lifetime, annual predictions, and the hourly performance of the power system output. The simulation also provided key financial model estimations including energy costs and NPVs.

### 1.6.3. Fuzzy multi-criteria decision-making (MCDM) model

The third phase aimed to assess the defined practical CSP options. An MCDM approach was considered in a fuzzy environment to tackle ambiguity and imprecision. The evaluation was conducted based on extensive analysis of the alternative scenarios performances in accordance with the defined evaluation parameters. An FAHP model was developed to incorporate quantitative and qualitative data as well as input from forty-four stakeholders from the potential developing countries for large-scale CSP deployment. A scaling method was adopted for stakeholders' solicitation, followed by the utilization of triangular fuzzy numbers (TFNs) for pairwise comparisons, to address the associated uncertainty, linguistic vagueness, and incomplete knowledge. The developed FAHP model provided the mathematical foundation to evaluate the alternative scenarios in a hierarchical manner with respect to the evaluating decision criteria and sub-criteria as well as the main goal of assessing CSP projects. It also facilitated the incorporation of the generic value tree defined in first phase and the simulation results obtained in the second phase into the third phase of the proposed methodology. The priority weights of alternatives were obtained through the final matrix of the FAHP model as follows:

$$\begin{bmatrix} \begin{matrix} \text{Priority} \\ \text{weights of} \\ \text{alternatives} \\ \text{with respect} \\ \text{criterion } (1) \end{matrix} & \begin{matrix} \text{Priority} \\ \text{weights of} \\ \text{alternatives} \\ \text{with respect} \\ \text{criterion } (2) \end{matrix} & .. & \begin{matrix} \text{Priority} \\ \text{weights of} \\ \text{alternatives} \\ \text{with respect} \\ \text{criterion } (n) \end{matrix} \\ & m\,(x)\,n & & \end{bmatrix} * \begin{bmatrix} \begin{matrix} \text{Priority} \\ \text{weights of} \\ \text{decision criteria} \\ \text{with respect} \\ \text{to goal} \end{matrix} \\ n\,(x)\,1 \end{bmatrix} = \begin{bmatrix} \begin{matrix} \text{Priority} \\ \text{weights of} \\ \text{alternatives} \\ \text{with respect} \\ \text{to goal} \end{matrix} \\ m\,(x)\,1 \end{bmatrix}$$

where *m* denotes the number of alternatives and *n* denotes the number of criteria.

The results of this phase illustrated the merits and weakness for each of the studied alternative scenarios in accordance with local energy sectors requirements. Moreover, the obtained results constitute a foundation to make recommendations for early stages of CSP integration to national grids and relate them to stakeholder priorities.

### 1.7. Thesis organization

This thesis intends to promote strategies in the early stages of the planning of large-scale CSP integration in developing countries. In this outline, the rest of the thesis is organized as follows: Chapter 2 presents fundamental knowledge of the topics and tools related to the proposed methodology and presents a literature review. Chapter 3 focuses on the development of a value tree for the parameters required to evaluate large-scale CSP deployment in developing countries. The construction of the value tree was conducted through a structured expert elicitation, including the contribution of heterogenous expert panelists from the CSP field and the following data analysis. Chapter 4 introduces a SWOT analysis of the different technologies involved in a CSP plant. The main purpose of this chapter is to define potential and practical alternative scenarios of CSP given the local energy sectors requirements, weather characteristics, and available CSP combinations and capabilities, as well as to carry out a techno-economic analysis of the defined scenarios. Chapter 5 develops an MCDM model in a fuzzy environment for the evaluation of the defined alternative scenarios with respect to the identified parameters. The focus of the chapter is on tackling the assessment of different CSP combinations with consideration of stakeholders' interests and local needs. The integration of the MCDM with fuzzy set theory is intended to address the quantitative and qualitative data as well as the subjectivity and uncertainty and then process them mathematically to make recommendations and reach results. Chapter 6 presents the summary, contributions, limitations, and future work directions.

# Chapter 2: Literature Review

This chapter introduces fundamental knowledge and review of the literature related to the research areas of the thesis, including the evaluation and planning of energy, RESs, and, in particular, CSP, for sustainable development. In addition, the development of the proposed methodology involves several tools, such as ADP, Delphi method, SWOT analysis, CSP modeling with SAM, performance analysis, and FAHP models. This section summarizes some important contributions in these areas.

## 2.1. Analytic deliberative process (ADP)

ADP is a systematic approach which focuses on the deliberation procedure for problem understanding. The provided format facilitates capturing the influences of subjectivity that impact decisions. ADP aims to enhance the decision-making process and to assign a fair share of responsibility. It provides stakeholders with insight to help reach consensus through the utilization of analytical tools and to make hard decisions as objective as possible.

The National Research Council (NRC) [38] proposed ADP for risk understanding, which consists of two major parts. The first part is the analysis in which an understanding of the problem is built through systematically applying methods that have been developed in the engineering communities and the decision science. The second part consists of the deliberation by means of any formal or informal communication process and the collective consideration of problems. ADP is commonly carried out in consecutive steps starting with capturing experts' and/or stakeholders' objectives by building value tree aggregating goals, impact categories, and performance measures. The next step involves formulating decision alternatives that are considered by stakeholders. The analyst then analyzes these decision options through quantitatively determining how they achieve each objective based on data providers' priorities.

Subsequently, a deliberation is conducted in an attempt to reach a consensus. In this step, data providers are involved in reviewing the analytical results and considering subjective and objective factors that led to a final decision.

Shattan [39] adopted the ADP proposed by the NRC combined with AHP for decision-making in order to select radiation detection systems for shipping ports and border crossing as an alternative for CBA. The study concluded that ADP outperforms CBA in these types of decisions. According to Shattan, ADP uses analytical tools to help quantify objective and subjective influences which affect the decision. It is pointed out that the effectiveness of the deliberation that follows the completion of the analysis is considered to be the greatest strength of the ADP. Renn [28], [29] proposed and discussed a cooperative discourse model for the ADP in risk management related to urban planning, sustainable development, and waste management arenas. He indicated that the potential and needs for ADP are associated with resolving dilemmas, making tradeoffs, and answering hard questions encountered by managers and decision makers. Renn showed that value trees proved to be sufficient to identify and select concerns and evaluative criteria. Dezfuli et al., [30] introduced ADP to provide a guideline for implementing risk-informed decision-making (RIDM) as an integral part of systems engineering at NASA. Dezfuli et al., emphasized that the significant challenge of applying ADP was practically associated with the organizational complexities. Elliott [40] also utilized ADP in the context of RIDM. He indicated that early phases of advanced systems design witness information scarcity in terms of the involved components, technologies, and processes, nonetheless it is the time in which stakeholders are required to make critical decisions to guide the system development. Elliott studied the scales associated with the conversion of subjective expressions during expert elicitation to verify their efficiencies in capturing preferences. He applied ADP to a study associated with the passive secondary auxiliary cooling system of nuclear fission reactor plants evaluating two ultimate heat sink systems.

Stagl [41] discussed the importance of deliberation for public involvement in long-term planning for energy policies in the UK. The study focused on social learning through deliberation related to planning or adjusting goals of policies considering past experience and new information. The scope of the study included opening public discussions, obtaining public perception, surveying public attitude towards energy scenarios, and explicitly defining associated terminologies. Stagl emphasized the need for the combination of analytical tools with deliberation methods. Similarly, Rogers et al., [42] conducted a study to explore a rural community's response regarding a proposed sustainable energy project. Deliberation was carried out through surveys and semi-structured interviews to obtain comprehensive insight of local attitudes toward renewable energy. In addition, Canfield et al., [43] conducted deliberative forums to solicit citizen participants to develop opinions informed by relevant facts, experts' information, and multi-perspective understanding with regard to energy policies to mitigate climate change.

Proctor and Drechsler [44] combined multi-criteria assessment with formal deliberative process to support decisions associated with natural resources options selections related to recreation and tourism activities of catchments. Liu et al., [45] utilized deliberative multi-criteria assessment in conjunction with fuzzy sets to support decisions in invasive species management. Both studies focus on the social learning aspects through involving citizens' juries in the deliberation process.

## 2.2. SWOT analysis in energy sector

SWOT is a common systematic analysis method in strategic planning. It provides a framework that can be used to categorize a wide range of inputs, which facilitates the decision-making process. SWOT analysis has proven to be effective in strategic analysis and policy planning as a baseline to diagnose problems and outline future actions [46], [47]. Several studies in the fields of energy and RESs have involved SWOT analysis. With regard to solar energy, Williams et al., [48] utilized SWOT analysis to develop a strategic plan to ensure that the US industry can be a market leader in CSP technologies. Tsoutsos [49] identified the actions required to reduce the barriers to applying solar thermal technologies in Greece through SWOT analysis, including hot water production, space heating and cooling, power generation, and desalination. Makwana [50] conducted SWOT analysis to address the production and policy of solar power in India, while Liou [51] used SWOT analysis to investigate Taiwan's legislations, policy developments, and industrial strategies to promote the PV industry. Xiaohong et al., [52] analyzed the electric energy management and control of a PV system with the SWOT model.

Considering a larger scope that included energy and RESs, Jaber et al., [53], performed SWOT analysis to assess the current status and formulate policy advice for enhanced utilization of RESs in Jordan. They noted that the SWOT analysis resulted in a vision that can easily be translated to objectives and activities in Jordan as well as other neighboring countries, including Saudi Arabia, as a first step to promote RESs utilization. Iglinski et al., [54] employed SWOT analysis to assess the current state, energy potential, and future prospects for the development of RESs in Poland. They conducted SWOT analysis for each potential type of renewable energy technology and demonstrated the importance of using SWOT analysis to inform later planning steps to achieve the objectives. Li et al., [55] adopted the SWOT method to analyze the development of energy and renewable energy in China. They noted the importance of using SWOT analysis to develop strengths, overcome weaknesses, grasp development opportunities, and avoid threats. Such analysis can facilitate the development of predictive and practical objectives and execution tactics. Subsequently, a general development strategy was concluded for the energy industry in Beijing. Shi [47] assessed the competing outlooks for energy mixing and undertook SWOT analysis to define and propose action plan strategies to promote a green energy mix in Southeast Asian nations. Terrados et al., [46] structured an energy system diagnostic in a Spanish region through SWOT analysis to assess the impact on renewable energy development. They concluded that it is advantageous to incorporate SWOT analysis with other techniques, such as the widely utilized MCDM method, to conduct comprehensive energy planning. Afterward, Terrados et al., [56] proposed a hybrid model combining SWOT with characteristics extracted from the MCDM and Delphi methods to design a regional renewable energy plan, set strategic actions, and fix strategic goals in Spain.

### 2.3. Techno-economic analysis and SAM simulation of CSP

Several studies involving techno-economic evaluations of CSP technologies have been conducted. Lemmer [57] investigated parabolic trough (PT) and parabolic dish (PD) technologies and compared their markets' developments. He studied the economic feasibility of PT in Morocco. Lemmer used SAM to perform a simulation for techno-economic analysis of a PT project in Morocco based on local ambient solar data. SAM was also utilized by Hinkley et al., [58] for a solar tower (ST) simulation in Australia. The analysis was undertaken to illustrate the potential of ST collection technology to minimize the long-term costs in Australia. Guzman et al., [59] conducted solar radiation potential analysis in Colombia and used SAM to simulate a CSP plant adopting PT technology to calculate the energy cost. Sundaray and Kandpal [60] investigated local DNI data to design a CSP plant in India. By using SAM, they identified the appropriate solar multiple (SM) and number of storage hours necessary to achieve the optimal energy cost through PT collectors. Purohit et al., [61] evaluated the CSP potential in north-west India. They utilized SAM to calculate the energy yield of CSP and pointed out that the special characteristics, designs, and conditions of CSP require cautious assessment when conducting deployment potential studies. Ibarra et al., [62] presented a model for sizing and performance simulations of PT plants in several locations in Saudi Arabia. The model was intended to create an interactive mapping tool to be integrated into the Renewable Resources Atlas of Saudi Arabia to indicate utility performance in addition to solar radiation.

### 2.4. Multi-criteria decision-making (MCDM) in energy sector

MCDM greatly contributed to theoretical and practical progress in different fields. MCDM methods have been widely adopted in the field of strategic planning and energy portfolios. They gained popularity in the energy planning field owing to the ability to deal with large amounts of conflicting data and information in a systematic structure as a result of increased complex energy management problems which cannot be resolved by traditional single-criteria approaches [63]. MCDM methods promote decision quality through more explicit, rational, and efficient quantification and problems analysis. Pohekar and Ramachandran [25] indicated that MCDM overcomes single-criteria methods through providing enhanced understanding of inherent features of decision problems, promoting the role of participants in the processes of decision-making, facilitating compromise and collective decisions, and providing a good platform to understand the different perceptions involved.

Among the better known and more utilized modeling approaches are multi-attribute utility theory (MAUT), AHP [34]–[37], analytic network process (ANP) [64], the technique for order of preference by similarity to ideal solution (TOPSIS) [65], [66], and outranking methods such as the method of elimination and choice expressing reality (ELECTRE) [67]–[69] and the preference ranking organization method for enrichment evaluation (PROMETHEE) [23], [68]–[71]. Of these modeling methods, there is no best method, as each has its own benefits and drawbacks. Analysts decide which model to adopt depending on the problem at hand [64]. Furthermore, it is well understood that, although it would be the ideal option, it is difficult to find an alternative with the best performance in all considered aspects. MCDM thus facilitates justifying the selection of alternatives by making tradeoffs between decision criteria rather than finding one optimum alternative [23].

Pohekar and Ramachandran [25] discussed over 90 published papers using various MCDM methods in order to highlight the trends through classifications of methods and application areas, including renewable energy planning, resources allocation, building energy management, transportation energy systems, and project planning. In addition, Taha and Daim [63] introduced a literature review on MCDM applications in the renewable energy field. They discussed the spectrum of equipment and tools utilized for renewable energy policy planning, evaluation, and projects selection. Mateo [72] also discussed the use of MCDM in the renewable energy industry with greater focus on mathematical explanations of the different methods as well as the definition of criteria.

### 2.4.1. MCDM in solar thermal power assessment

Various studies in the literature assessed RESs through regular and fuzzy MCDM methods [34], [35], [73]–[76]. For CSP studies specifically, many evaluated CSP technologies for electricity generation, but were mostly focused on the technical and economic aspects [58], [77]–[80]. Few studies have discussed the assessment of solar thermal power technologies from a multi-criteria viewpoint. Nixon et al., [37] utilized AHP to select an optimal solar thermal collection technology for north-west India. The authors suggested additional evaluation criteria in future work in addition to increasing the number of participants to acquire more accurate results. The study concluded that linear Fresnel (LF) technology with a secondary compound PT or PD reflectors was the preferred option. Aragonés-Beltrán et al., [64] conducted a study to assess the economic feasibility and analysis of projects risks, and prioritized CSP projects for medium-sized Spanish companies to maximize their profits. The study was completed in three phases, where each phase included a set of decision criteria defined by local project teams and decision makers. The study aimed mainly at aiding companies in evaluating and selecting the project offers they received. CSP projects were analyzed with a focus on a financial opportunistic perspective. Cavallaro [23] utilized PROMETHEE to assess CSP technologies in Italy. Twelve different alternative scenarios were defined in the study, including changes in plants technologies and components. Seven decision criteria were defined for the evaluation process based on technical, environmental, and economic perspectives, which were derived primarily from the European concentrated solar thermal roadmapping report [81]. Peterseim et al., [82] utilized AHP to evaluate the suitability of CSP technologies for hybridization with conventional and renewable energy plants. They assessed the capability of each collection technology to generate the host plant temperatures and subsequently evaluated the available options based on the defined criteria. Nixon et al. [83] evaluated novel designs of LF collectors through a model that combines MCDM and quality function deployment (QFD) methods.

### 2.4.2. Analytic hierarchy process (AHP) in energy sector

AHP is categorized as an MCDM method and was developed by Thomas Saaty to facilitate the evaluation and prioritization of multiple alternatives considering several decision criteria

[84]–[86]. Amer and Daim [34] built a model using AHP for the selection and prioritization of four RESs in Pakistan considering 25 parameters, in which stakeholders' judgments were collected via questionnaire for pairwise comparisons. The authors recommended the use of AHP for renewable energy regional development and national roadmapping. Ahmad and Tahar [35] constructed a model through AHP for RESs assessment in Malaysia to prioritize four renewable alternatives based on 16 parameters in two hierarchical levels. The authors highlighted that the conditions of resource availability vary between countries, which results in different production costs. Daniel et al., [87] utilized AHP with the Delphi technique for evaluating three RESs in India considering 7 criteria. Gok [88] prioritized solar, hydropower, biomass, geothermal, and wind energy sources in Turkey considering 2 evaluation criteria and 8 sub-criteria. The author underlined the suitability of AHP in dealing with problems that involve conflicts.

In addition, Chatzimouratidis and Pilavachi used AHP to evaluate 10 alternatives including conventional, nuclear, and renewable power plants considering economic, technical, and sustainability criteria [36], and considering their impact on living standards of local communities [89]. Kablan [90] conducted a study for the evaluation of energy conservation policies in Jordan using AHP. The study presented five policy measures suggested to governments as alternatives to support energy conservation considering demand satisfaction, economic growth, increased RESs utilization, and clean environment as assessing criteria. Phdungsilp and Wuttipornpun [33] provided a supporting tool for decision makers for promoting sustainable energy systems through assessing the benefits of power plant generation systems from both environmental and social points of view. Adopting AHP, they emphasized that the most sensitive part of applying multi-criteria analysis is the selection of criteria. Furthermore, Mousavi-Seyedi et al., [91] evaluated various distributed generation alternatives for microgrid through AHP. They also used HOMER simulation software to obtain the quantitative data to be incorporated in the model. Lee et al., [92] associated AHP, based on three criteria, with the benefits, opportunities, costs, and risk (BOCR) method for a strategic selection of wind farm projects.

### 2.4.3. Fuzzy analytic hierarchy process (FAHP) in energy sector

Extensions of fuzziness have been proposed to AHP by several authors, such as Van Laarhoven and Pedrycz [93] and Chang [94]. The fuzzy concept provides different systematic approaches, computational methods, and problem justification to deal with the uncertainties, decrease subjectivity, and enhance accuracy in capturing participants' perceptions. Kahraman et al., [73] combined an FAHP with an axiomatic design to select among 5 RESs in Turkey considering 4 criteria and 17 sub-criteria. Tasri and Susilawati [74] developed an FAHP to determine the most appropriate RES for commercial electricity generation in Indonesia. Zheng et al., [75] used an FAHP to develop a model that facilitates the conservation assessment of building energy. Ansari et al., [76] integrated an FAHP with a fuzzy VIKOR (Višekriterijumsko kompromisno rangiranje) for selecting the best energy generating technology in India. Bozbura et al., [95], [96] and Demirel et al., [97] presented extensive comparisons of the different AHP fuzzy extents and their advantages and disadvantages.

It is essential to note that the studies introduced in this section obtained decision criteria directly through the literature or practical experience considering the perspectives of local technical teams associated with certain projects. In addition, the required quantitative data were mostly acquired from similar projects or international databases based on data from developed countries, due to lacking data availability in developing countries.

# Chapter 3: A Value Tree for Identification of Evaluation Criteria for Solar Thermal Power Technologies in Developing Countries

## 3.1. Introduction

The selection of electricity generating technology can be considered one of the most important aspects of the decision-making process for power plant projects. The evaluation of energy projects has evolved from focusing only on financial perspectives to also considering several other aspects. As the complexity of energy portfolio planning increases, it becomes more difficult to identify comprehensive decision criteria for the evaluation of power plants. In addition, CSP is in its infancy in terms of large-scale deployment with various options, great potential, and increasing installation. The stage of selecting the combination of evaluation criteria is critical for the accuracy of the assessment process. It is however noticed that researchers commonly consider self-definition of the evaluation criteria through literature with no explicit explanation of how the decision criteria were determined. Accordingly, different combinations of evaluation criteria were adopted based on researchers' perspectives.

Expert elicitation is a key step performed prior to portfolio analysis of renewable energy projects. It is useful for quantifying uncertainty associated with the scarcity of historical data. The latter is a characteristic of renewable energy project planning in many developing countries [98], with these countries being the intended beneficiaries of this study. Quantitative and qualitative assessing parameters can be defined either through ordinary surveying [34], [37] or through the Delphi method [24]. With respect to previous literature, this research contributes to the body of knowledge through a structured expert solicitation with the involvement of large number of worldwide data providers to obtain the aggregated perspectives. This study aimed to explicitly identify parameters combination required for evaluation of CSP technologies through a rigorous process of expert elicitation and consensus-seeking. A value tree was constructed, based on the perspectives of a heterogeneous panel of data providers from solar thermal power field including but not limited to electric power companies' CEOs and chairmen, university professors, research fellows, power plants senior managers, managing directors, CSP design and optimization engineers, R&D leaders, and site and deputy managers. The resulted value tree can be utilized locally by stakeholders and decision makers as inputs for evaluating CSP project models at planning stage, perhaps with slight modification of parameters based on individual case requirements.

The remainder of the chapter is organized as follows: Section 3.2 discusses the deliberation process and its importance. Section 3.3 introduces the solar thermal collecting technologies. Section 3.4 presents the proposed methodology, explains the data collection process, discusses experts' solicitation, and introduces key metrics analysis. In Section 3.5, the results and sensitivity analysis are presented, and Section 3.7 concludes the study.

### 3.2. Deliberation

The deliberation process facilitates leading the early stages of the planning process, problem formulation, and the validation of participants' consensus. It has been widely used for energy sources roadmapping and technology planning, especially in the absence of deterministic information [10], [31]. Elicitation of experts' opinions is informative and helpful with data insufficiency to complement available data. Deliberation and analysis are complementary and need to be integrated to be representative of the problem. Deliberation frames the analysis, while analysis informs the deliberation, and the process benefits from the feedback between them [38]. The effectiveness of the deliberation that follows the completion of the analysis is considered as the greatest strength of the ADP [39]. It encourages further research to focus on areas that are critical to the decision and to prevent losing time and resources on attempts to reduce uncertainties that are not significantly impacting the decision. In this thesis, the deliberation of experts and stakeholders is involved and explicitly conducted during the identification of the value tree through the Delphi method (Chapter 3) and the FAHP weighting process (Chapter 5). It is important to note that deliberation does not assume consensus; instead, it helps the consideration of judgments and knowledge obtained from different standpoints to develop an understanding of the problem informed by all involved perspectives, which leads to more rational and legitimate decisions. As indicated by Dezfuli et al., [30], the deliberation is appropriate for decisions that involve uncertainty, multiple attributes, diversity of stakeholders, and high stakes which reflect significant costs, importance of meeting objectives, or potential safety impacts. Applying ADP aims at responding to primary issues associated with the mismatch between stakeholders' expectations and the required resources to achieve them, and the miscommunication in considering the alternatives which results in misunderstanding the consequences in the presence of uncertainty to avoid unforeseen pitfalls.

### 3.3. Concepts of CSP collecting technologies

CSP plants are gaining in popularity with advances in technology. In fact, some of the highest capacity solar plants globally are now using CSP. The variety of CSP technologies available nowadays is the driver of this research to exhaustively model parameters for their assessment. Solar thermal collectors are the major component of CSP systems. They work by absorbing the sun's heat (through its radiation), changing this to internal energy. The obtained thermal energy is transformed to fluid (i.e., water, oil, or air) to be either directly utilized in applications such as heating systems or converted to electricity using generating technologies such as steam turbines [99]. In addition, generated thermal energy can be stored for later use. This section outlines the most common solar thermal collecting technologies.

### 3.3.1. Parabolic trough (PT) collectors

PT collectors utilize curved, highly reflective, mirrored troughs that direct sunlight into a linear vacuumed glass tube attached to its focal axis. PT collectors are configured to move in one axis from east to west, in order to follow the concentration of sunlight during the day. PTs are used in some of largest CSP utilities in the US and Spain [37]. The Solar Energy Generating System (SEGS) in the US is the largest PT power plant complex in the world [100], with a capacity of 354 MW. There are many other plants with capacities of ≥ 100 MW in the US, Spain, South Africa, India, and the UAE. It should be noted, however, that the selection of optimal CSP technologies is location dependent, thus influencing most decision attributes. The best technology for the US and Spain is not necessarily the best for other locations, which may differ economically, environmentally, socially, and politically. Thus, given increased interest in CSP around the world, it is necessary to establish a framework for assessing alternative technologies [99].

### 3.3.2. Solar tower (ST)

ST is another CSP plant technology that uses heliostat mirrors. These are less expensive than trough mirrors because they utilize standard flat glass, instead of glass that is manufactured at specific curves. However, heliostat mirrors are configured to have dual-axis movement in order to direct the sun's heat into a central receiver. A power tower field consists of thousands of mirrors and a central tower which holds the heat receiver at the top. The largest solar thermal plant operating through ST technology is the Ivanpah Solar Power Facility in the US, with a capacity of 392 MW [101]. It is worth noting that STs are a newer technology compared to PTs.

When planning new facilities, it is hence important to avoid being prejudiced by the fact that there are many existing PT facilities around the world but few STs; the latter, or other technologies, may have only been operated recently but could be better suited for particular specifications.

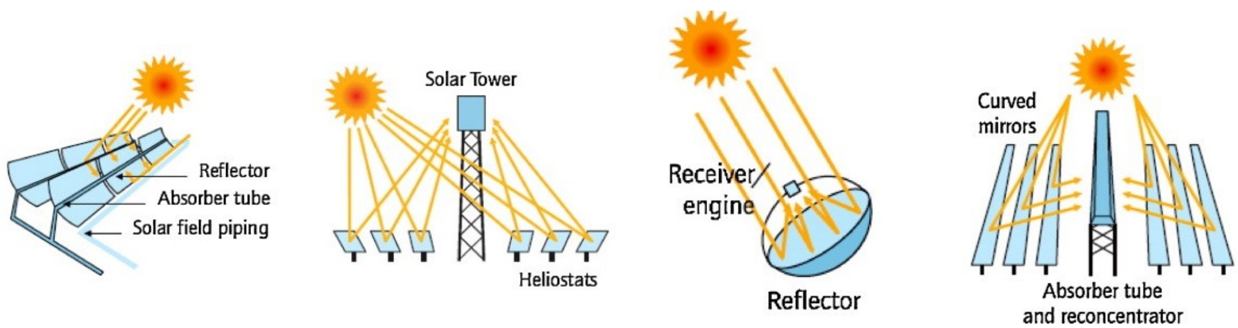
### 3.3.3. Parabolic dish (PD) collectors

PD collectors use a concave dish with a receiver attached above it. The dish is covered with parabolic mirrors. The heat of the sun strikes the troughs and is then directed to the receiver. This system also requires a dual-axis tracking system to follow the sun from east to west during the day, and from north to south throughout the year. To date, there are no large utilities using PD technology, owing to several difficulties. The design of reliable engines for large plants is still under development. Additionally, the initial cost of such systems is high, compared to the systems described earlier, and there are also challenges associated with storage capability [37]. Nevertheless, of all technologies, the Stirling dish system has the highest efficiency for transforming heat into electricity, with a net average annual yield rate that is 18–23% higher than any other solar energy system [23]. PDs are presently considered a potential technology for solar thermal power generation and many pilot projects have been launched in the US and Spain. With more R&D, this will be a potential alternative candidate technology for CSP plants [99].

### 3.3.4. Linear Fresnel (LF) collectors

This technology is similar to PT collectors, with slight differences. It consists of linear flat mirrors instead of parabolic trough mirrors and the receiving tube is located above the mirrors, without being attached to them [100]. Flat mirrors and shared receivers result in lower expenses, while at the same time, this technology benefits from the long-term success and operational experience of PT technology utilized in the largest solar thermal plants in the world.

Furthermore, similar to the PT system, LF does not need two-axis tracking since the mirrors are linearly oriented. The tradeoff that comes with lowering LF prices compared to PT is lower efficiency due to the gap between mirrors and receivers. The largest CSP plant using LF technology is Dhursar in India, with a capacity of 125 MW [101]. Figure 3–1 shows the techniques used by these different technologies for collecting the sun's radiation and transferring this into heat.




Parabolic Trough | Power tower | Parabolic dish | Linear Fresnel

*Figure 3-1: Concentrating solar collection technologies*
*Source: Ummadisingu and Soni, 2011* [102]

### 3.3.5. Heat storage systems

The aforementioned technologies are used to collect heat from the sun. The generated heat is subsequently utilized for electricity generation via classic techniques such as steam turbines and Stirling engines. This is an advantage for solar thermal plants, as steam generation has been utilized for a long time and operators thus have extensive experience with this aspect of planned solar thermal utilities. The benefits of thermal energy storage have been demonstrated by several CSP power plants that are equipped with up to 15 h of storage, enabling both base load coverage and the mitigation of late peaks occurring after sunset [82], [103]. In addition, such plants can produce electricity continuously for 24 h, given suitable conditions. Thermal storage still has the potential for additional cost reduction to increase the competitiveness of CSP systems. The installation cost is expected to decrease to 22 $USD/kWh_{th}$ in 2020 compared to 90 $USD/kWh_{th}$ in 2011 [82]. Additionally, the utilization of conventional electricity generation technologies with CSP facilitates the hybridization of new solar thermal utilities in old power plants.

The selection of a technology is critical for a utility that requires significant investment. Another significant decision must be made is whether to use a storage system in a plant; if such a system is adopted, the type of storage system to use must also be decided. A storage system strengthens the utility, allowing production of electricity during cloudy weather or at night. An important advantage of CSP is that its built-in thermal storage capability is both more effective and cheaper than PV battery storage and hydropower's pumped storage [7]. The storage capacity provides power plants with improved dispatchability and coefficient of utilization factor [60]. There are several storage options for solar thermal systems, such as steam accumulators, in which energy is stored as pressurized hot water that is later utilized in turbine steam [104], oil mixed with crusted rock, liquid sodium, and molten nitrate salt [99]. Molten salt is a low cost liquid that can be used at the high temperatures required to operate steam turbines.

### 3.4. Methodology

The methodology utilized in this study commenced with identifying parameters for evaluating technologies from a multi-criteria viewpoint from the literature. There is plenty of research regarding assessment and selection of power energy sources generally, and renewable energy specifically; however, few studies focus on CSP technologies. Owing to the similarity of the majority of parameters that need to be considered in both cases, a literature review of energy source evaluation studies was carried out, as will be discussed in the following section. Figure 3–2 illustrates the proposed methodology; i equals 0, 1, 2….n, and n is the total number of rounds of expert elicitation. A trigger value tree consisting of commonly utilized parameters related to solar thermal technologies assessment was provided to participants as obtained from the literature. Subsequently, the first round of the Delphi questionnaire was carried out to develop individual value trees. Thereafter, key parameters were determined in order to combine individual value trees into an aggregated value tree of the round. Based on stability measure, a decision was made whether a next round was required or not. After obtaining satisfactory levels of key parameters, the value tree was synthesized and recommendations formulated.

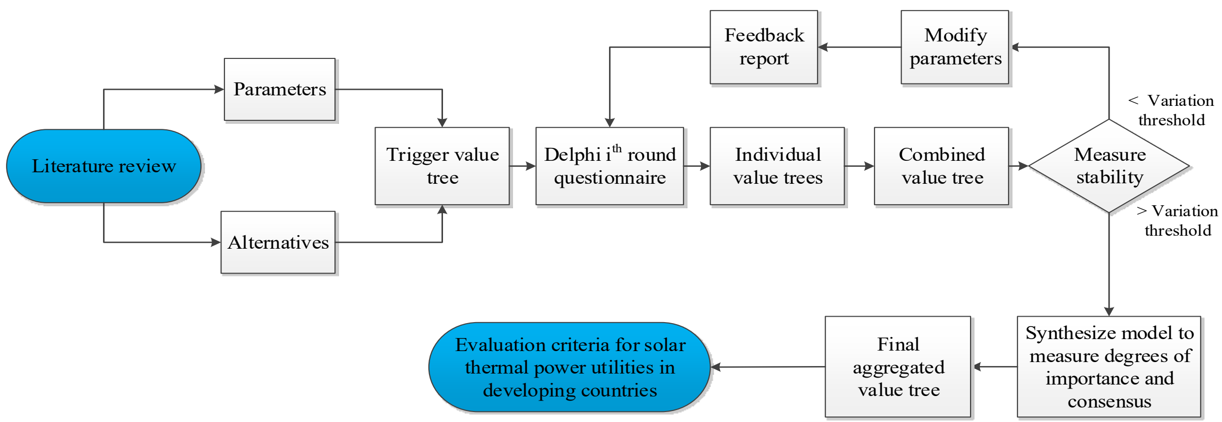



*Figure 3-2: Methodology of identifying CSP evaluation parameters in developing countries*

### 3.4.1. Expert elicitation

The strength of the expert elicitation process is evident when data is sparse; the process complements available data while also compensating for the weaknesses associated with using only operating experience-based analysis, particularly in the case of complex subjects with significant implications. Applications of expert elicitation include (but are not limited to) the determination of the present state of knowledge in certain fields, prediction of service or product performance, and most relevant to our case, identification of required decision-making elements when various alternatives are available [31]. There is inherent uncertainty associated with renewable energy portfolio planning, especially in developing countries with little historical data and experience [10]. In this research, panel of experts from solar thermal power field were surveyed through a questionnaire gathering data about CSP technology evaluation. Expert elicitation provides a formal structured process for quantitative estimation, enhancing the accuracy, consistency, and credibility of results, and thus their acceptability. It also reduces bias. The drawback of formal structured expert elicitation is associated with the increased time needed, as well as reduced flexibility to apply changes during the process [105].

As per Figure 3–2, a review was conducted and a preliminary value tree was developed, with this including the most common parameters utilized in the literature for assessment of energy sources. Table 3–1 describes obtained parameters. The Delphi method was adopted for expert elicitation and is explained in the following section.

| | Performance Measure | | Description | References |
|---|---|---|---|---|
| Technical | | | | |
| 1 | Maturity | ($P_{t1}$) | Maturity of the technology | [34], [67], [68], [70], [72], [73], [106], [107] |
| 2 | Efficiency | ($P_{t2}$) | The extent to which useful energy can be obtained from an energy source | [34]–[36], [68], [72], [87], [92], [106]–[111] |
| 3 | Reliability | ($P_{t3}$) | System's ability to perform its intended function | [34], [67], [70], [72], [73], [87], [92], [106], [107] |
| 4 | Deployment time | ($P_{t4}$) | Time needed to establish a power plant | [34], [35], [69], [73] |
| 5 | Experts' availability | ($P_{t5}$) | Availability of experts (manpower) | [34], [107] |
| 6 | Safety | ($P_{t6}$) | Safety of energy system based on accidents count | [65], [72], [73], [89], [106], [107], [109] |
| 7 | Scalability | ($P_{t7}$) | Capacity for later expansion of the utility | [37] |
| Economic | | | | |
| 1 | Capital cost | ($P_{ec1}$) | Initial cost required for each technology | [34]–[36], [65], [66], [68], [69], [71]–[74], [106]–[113] |
| 2 | O&M cost | ($P_{ec2}$) | Operation and maintenance (O&M) cost | [34], [36], [65], [66], [72], [106], [107], [109], [113] |
| 3 | Energy cost | ($P_{ec3}$) | Cost of produced electricity | [34], [66], [72], [88], [106]–[108], [111], [112] |
| 4 | Operational life | ($P_{ec4}$) | Estimated number of years before decommissioning | [35], [65], [72], [106], [107] |
| 5 | Market maturity | ($P_{ec5}$) | Market availability, commercial competitiveness, and compatibility with existing economic system. | [67], [73] |

| | | | | |
|---|---|---|---|---|
| Environmental | | | | |
| 1 | Required area | ($P_{en1}$) | Area of land needed | [34], [35], [65], [70], [72]–[74], [89], [106], [107], [110], [111], [113] |
| 2 | Emission reduction | ($P_{en2}$) | Capacity of each technology to reduce GHG emissions, including $CO_2$ | [33]–[35], [65], [66], [68], [71]–[74], [88], [107]–[113] |
| Social | | | | |
| 1 | Job Creation | ($P_{s1}$) | Potential for job opportunities | [34], [35], [65]–[68], [72], [73], [89], [106], [107], [109], [110], [113] |
| 2 | Social Acceptance | ($P_{s2}$) | Public attitudes towards each technology | [34], [35], [66], [68]–[70], [72]–[74], [87]–[89], [106], [107], [112] |
| Political | | | | |
| 1 | National economic benefits | ($P_{p1}$) | Through local manufacturing share | [34], [66], [70], [88], [110], [113] |
| 2 | Logistical Feasibility | ($P_{p2}$) | Existence of supporting legislation and administrative regulations | [67], [69], [73], [110] |
| 3 | Political acceptance | ($P_{p3}$) | Politicians' attitudes towards each technology | [69], [73] |

*Table 3-1: Common impact categories and performance measures used in the evaluation of energy sources, as derived from the literature*

To minimize bias and to ensure incorporation of the perspectives of different panelists, careful selection of participants was regarded. A definition for experts was adopted as introduced by Amer and Daim [31], which was stated in Section 1.4.

- ***Delphi method***

The Delphi method is a structured technique allowing experts and stakeholders to forecast or to attempt to reach higher levels of consensus in a systematic manner. The most unique features of the Delphi method that distinguish it from other expert judgment techniques are as follows: First, the process is characterized by anonymity, freeing individuals from any social, career, or other pressures that might influence their judgment. Feedback is provided anonymously and without an obligation to meet in person, thus eliminating confrontation and the potential impact of powerful or senior members on others' opinions, minimizing subjectivity and sharing of responsibility. These aspects have contributed to the popularity of the Delphi method. Second, Delphi outperforms ordinary surveying techniques by taking place over several rounds. The iteration procedure increases accuracy and reliability of results and drives group output towards consensus and stability by providing participants with feedback reports and giving them the opportunity to reassess their answers [114]. However, the iteration process has been indicated by some authors as a disadvantage of the Delphi method, owing to the long time it requires. Notwithstanding, Delphi has been widely used in various fields of research, including policy analysis, national roadmap planning, technology forecasting, and resource utilization to develop comprehensive lists of alternatives [115].

From the perspective of participants, the Delphi method allows them to check whether their views vary from those of expert peers through feedback reports, while still maintaining the anonymity of their answers. Moreover, participants are asked to comment on the reasons for their answers, with these also reported in the feedback summary. Contributors whose views deviate from those of the majority therefore have an opportunity to reassess their evaluation and to decide whether or not they would like to change their views. This procedure helps in moving towards an increasing level of consensus. Studies indicate that most changes in panelists' opinion occur during the second round [31]. Geist [114] carried out Delphi studies in a paper-based as well as web-based and provided informatics recommendations and lessons. He found that web-based Delphi overcomes some classic Delphi difficulties; it is less costly, overcomes geographical constraints, and helps to reach a higher number of participants.

#### 3.4.2. Value Tree

Value trees provide a hierarchal framework for parameters that are believed to add value to stakeholders when evaluating different options. They aid analysts in identifying all factors that influence a decision [33]. Value trees are used in several decision-making methods, such as the

ADP, as an appropriate first step in expert elicitation to obtain required attributes for evaluation of alternatives [116]. Keeney et al., [117] conducted a study for the German government that aimed to create a value tree for the development of energy policy in the country; hard decisions had to be made, with several alternative energy paths available. In addition, many other studies have considered combining the step of developing value tree with the evaluation of alternatives, with literature and researcher judgment utilized for defining value tree parameters combination, as shown in Table 3–1.

The current study utilizes Delphi method to develop a value tree which aims to explicitly define appropriate parameters combination based on the aggregated knowledge of data providers who are experts in the solar thermal power field, and to enhance the level of consensus between participants via a structured framework. The final value tree provides comprehensive and generic foresight through a unique snapshot of parameters that participants consider to be important for evaluation of CSP technologies and utility projects in developing countries.

### 3.4.3. Model application

#### *3.4.3.1. Delphi questionnaire*

A total of 140 data providers from solar thermal power field from 32 countries participated in the first round of the questionnaire. During the second round, 36 data providers participated after the provision of the feedback report. The contribution of heterogeneous data providers from different fields enriched the aggregated value tree, ensuring that different perspectives were represented. It is noteworthy to indicate that Delphi method states that only respondents of a certain round are consulted in the following round. Figure 3–3 shows the distribution of participants based on country. Participants were also grouped according to their general affiliation into four categories: educational, industrial, research institutes, and governmental organizations (Figure 3–4).

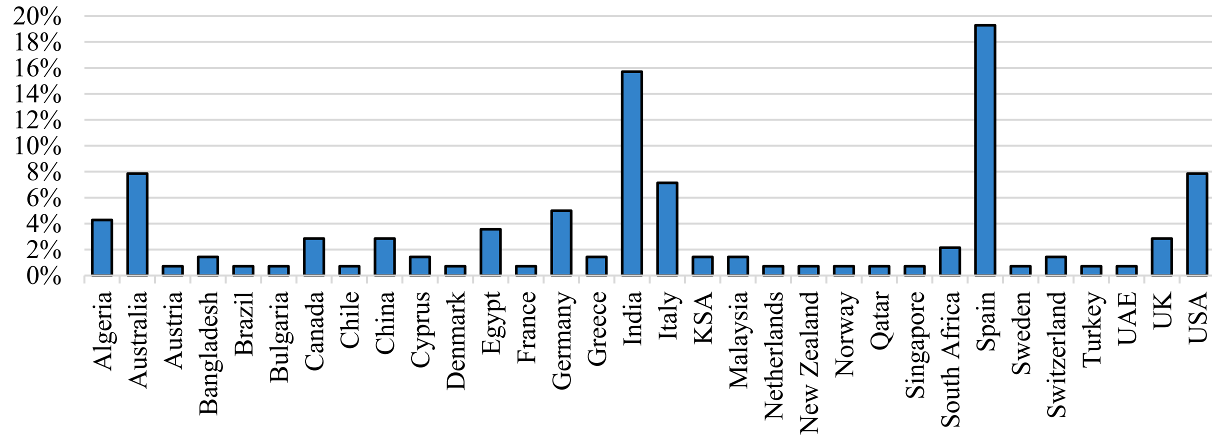



*Figure 3-3: Distribution of participants across countries*

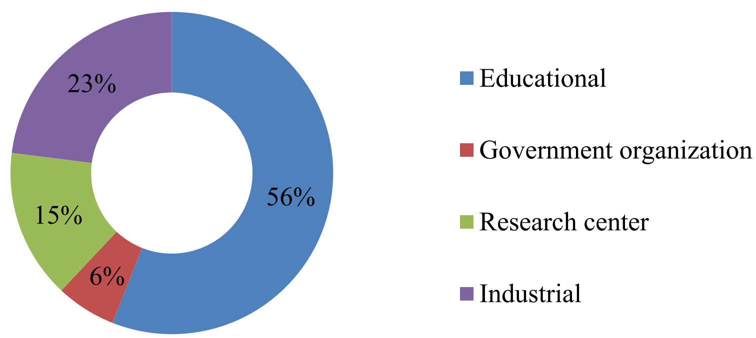



*Figure 3-4: Affiliation of experts*

Concept mapping is a method used for organizing the ideas of groups in a structured manner. Concept mapping was adopted in the current study to apply Delphi questionnaire, following the six steps outlined by Kane and Trochim [118], and Klenk and Hickey [119]. First, a focus statement was prepared through a comprehensive literature review, to provide participants with indications of parameters that are most commonly considered in the literature. Accordingly, a trigger value tree for evaluation of CSP technologies was created. The value tree was sorted into 24 parameters, of which 5 are impact categories representing main trajectories, with these subdivided into 19 performance measures. The data collected from the literature were provided to participants in an introductory report, including a brief about the study, along with the invitation to the first round of the questionnaire. Second, rating of statements was carried out through a series of close-ended questions to weight the relative importance of parameters for the evaluation process. Participants evaluated the importance of including each parameter presented in the preliminary value tree for multi-criteria assessment on a Likert scale. Third, brainstorming was conducted through open-ended questions asking about additional parameters that need to be considered or removed from the preliminary value tree. The added parameters were meant to be aggregated in the final value tree of the first round and evaluated in the next round. Fourth, statistical analyses were performed through measurement of importance, consensus, and stability indices of each parameter, to refine the preliminary value tree by developing a generic value tree based on contributors' judgments. Fifth, findings were interpreted, thresholds were defined, and the parameter outputs were explained and discussed. Sixth, insights into contributors' judgments, based on their justifications, were presented, and a feedback report was prepared for participants' review, prior to the next questionnaire round. Figure 3–5 shows the preliminary value tree extracted from the literature, as per Table 3–1.

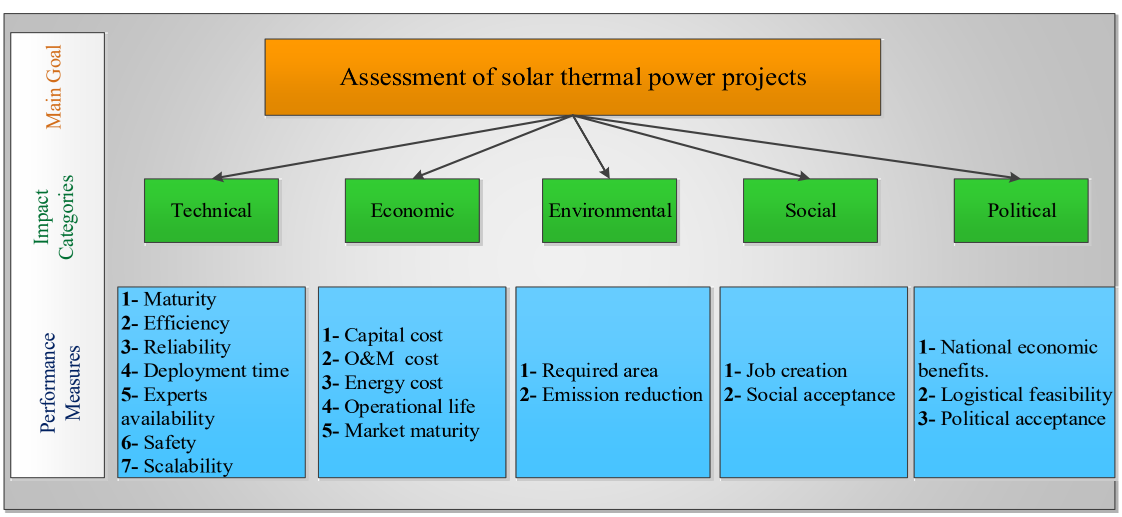



*Figure 3-5: Preliminary value tree for CSP evaluation*

#### *3.4.3.2. Analysis of key metrics*

Key metrics were calculated for each parameter included in the questionnaire. The results of these metrics determine whether each of the parameters is accepted, rejected in the aggregated value tree, or re-evaluated during the next questionnaire round. Participants were requested to assign weights to reflect the importance of each parameter, based on a five-point Likert scale ranging from "Very Important" to "Negligible", as shown in Table 3–2. Figure 3–6 shows results obtained for the five main impact categories. It provides a close look into parameters differences based on participants' judgments prior to calculating the degree of importance as per the following section. In subsequent sections, we present the key metrics and explain how these were obtained.

| Very Important | Important | Moderate | Not Important | Negligible |
|---|---|---|---|---|
| 5 | 4 | 3 | 2 | 1 |

*Table 3-2: Likert scale weights*

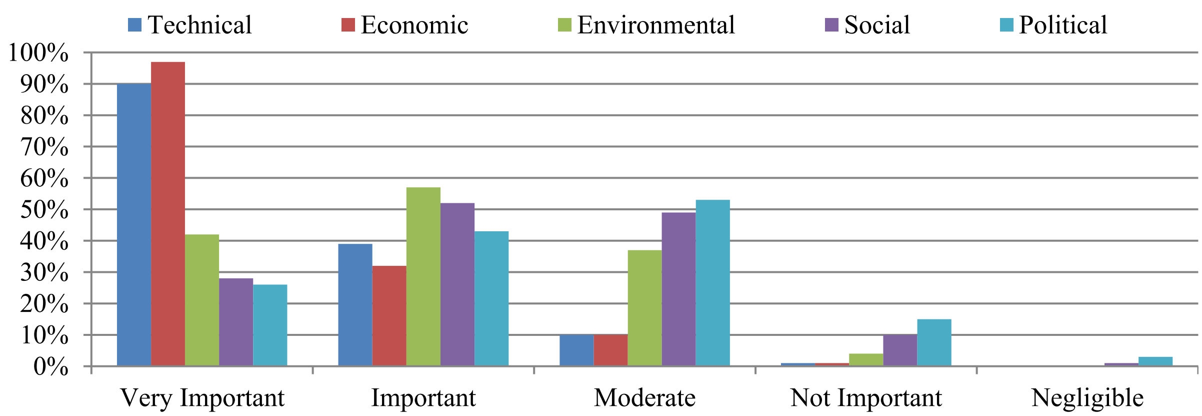


*Figure 3-6: Distribution of participants' answers on the Likert scale for different impact categories*

- Degree of Importance index

The degree of importance index reflects a percentage breakdown of respondents' Likert scale weightings, indicating how important each parameter is for evaluation of CSP projects in different scenarios [115]. The degree of importance index is calculated based on data providers' answers for individual parameters, as per the following equation [115]:

**Degree of important index of parameter (x) =**

*[(**100** × number of "**very important**" responses) + (**75** × number of "**Important**" responses) + (**50** × number of "**Moderate**" responses) + (**25** × number of "**Not important**" responses) + (**1** × number of "**Negligible**" responses)] – [**100** × number of "**Not necessary**" responses]/Number of responses ( 3-1 )*

- Degree of consensus index

The degree of consensus index reflects the level of agreement of participants in evaluating the importance of each parameter. It is essential to reach an acceptable degree of consensus before aggregating judgments. To measure the consensus level index, the Likert scale responses obtained through the questionnaire were classified into three categories, as per Table 3–3. The highest percentage of experts evaluating a parameter in one of these categories is considered to represent the consensus degree index of the parameter.

It is worth noting the absence of recommendations for determining thresholds for participant consensus measures in the Delphi method in the literature [120]. Amer and Daim [31] discussed the quantification of expert judgment, indicating that 50% consistency in respondents' answers can be considered to constitute majority agreement, in line with the opinion of analysts involved in this study. Accordingly, thresholds for importance and consensus degree indices were defined at 50%. In addition, sensitivity analysis was performed to assess the impact of changes in thresholds on results. Delphi-related research has shown that experts tend to achieve higher levels of agreement during the second round.

| Category (1) | Category (2) | Category (3) |
|---|---|---|
| Very important and Important | Moderate | Not important and Negligible |

*Table 3-3:Consensus categories*

- Stability Measure

Stability measures consider response consistency across successive Delphi rounds for validation; the measure is utilized in order to decide when to terminate Delphi method rounds

[121]. The coefficient of variation (CV) is calculated for each individual parameter to measure stability. CV is the ratio of the standard deviation of participants' responses to the corresponding mean for each parameter in order to gauge stability. The CV is calculated during every round of the questionnaire for each parameter. The CV value of the previous round is thus subtracted from the CV value of the later round in order to measure stability between two consecutive rounds.

$$\textbf{CV} = \textit{Standard Deviation / Mean} \qquad (3\text{-}2)$$

$$\textbf{CV Difference (i)} = CV\ (round\ i+1) - CV\ (round\ i) \qquad (3\text{-}3)$$

A CV value $\geq 1$ reflects scattered responses compared to the mean. On the other hand, a small CV value indicates that the variation of responses from the mean is small, reflecting good stability. There are other parametric and non-parametric methods utilized for stability measurement; the F-ratio, for instance, is a parametric method, while the McNemar change test and Spearman's Rank correlation coefficient are non-parametric methods that can be utilized to measure stability. Parametric methods are recommended for studies that involve high numbers of participants [122]. Shah and Kalaian [123], and Terrados et al., [56] recommended the utilization of CV for measuring stability and for termination decisions. Gracht [121] presented a study of consensus measures in the literature, finding that a CV $\leq 0.5$ can be considered good.

- Correlation coefficients

Another parametric stability measure is Pearson correlation analysis. This analysis aims to shed light on the relationship between participants' responses for different impact category level. A correlation coefficient of 1 between two parameters indicates total positive correlation, while a coefficient of –1 indicates total negative correlation; 0 indicates no correlation.

### 3.5. Results and discussion

Degrees of importance and consensus were measured to identify required parameters for evaluation of CSP technologies, while stability measures were also considered in deciding when to terminate the Delphi process for validation. Based on these results, two rounds of Delphi were conducted to obtain a generic aggregated value tree. Contributors received a report prior to each round, providing insights into collected data and outlining outputs from the previous stage. The following sections discuss the results of each round, in order to explain derivation of the final aggregated value tree.

### 3.5.1. First round outcomes

- ***Importance index***

Applying Equation (3–1) to all parameters, we obtain the degree of importance index for each parameter, as shown in Figures 3–7 and 3–8.

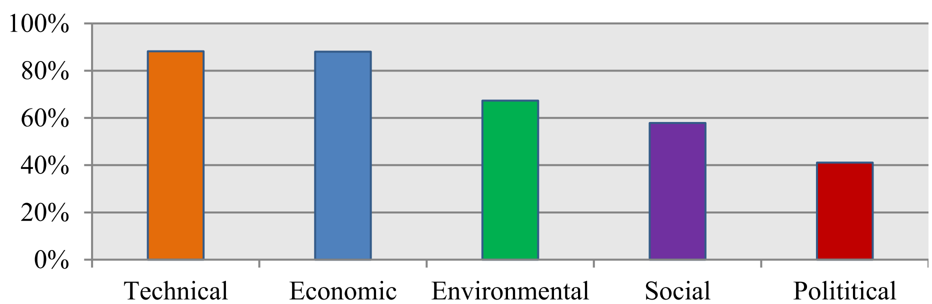



*Figure 3-7: Importance degree indices for impact categories*

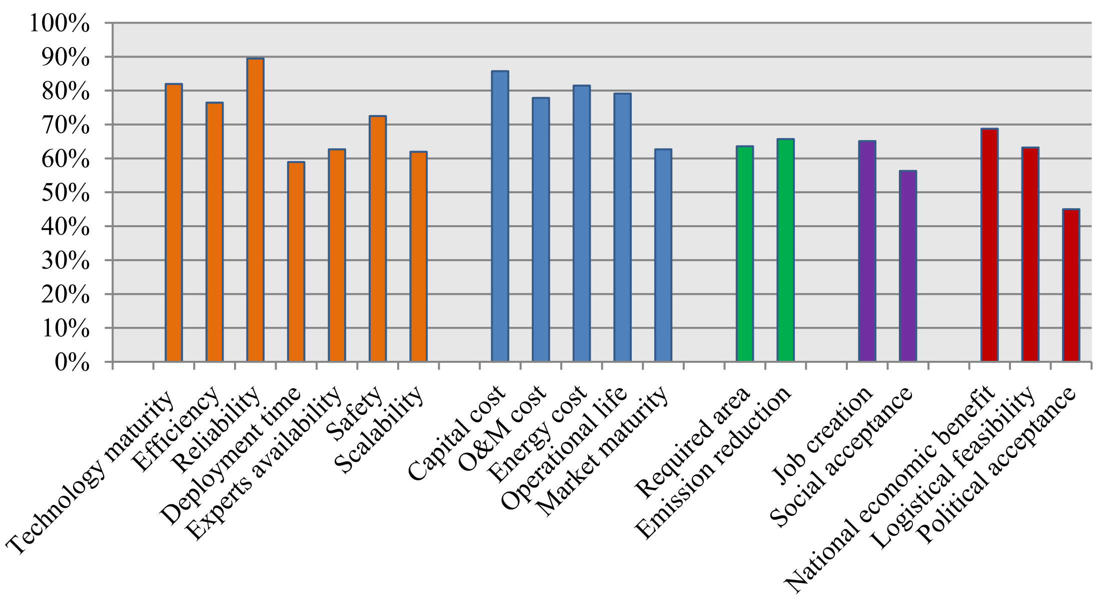



*Figure 3-8: Importance degree indices for performance measures*

Technical and economic categories had the highest importance index levels of the five impact categories (88% in both cases). When looking more closely at the weighting distribution of results, however, we find that economic parameter was referred to as very important more often than technical parameter. On the other hand, technical parameter obtained more scores than economic in the 'important' category which compensated the gap with economic parameter, as shown in Figure 3–6. Table 3–4 shows the distribution of data providers' answers for technical and economic impact categories.

| | Very Important (%) | Important (%) | Moderate (%) | Not Important (%) | Negligible (%) |
|---|---|---|---|---|---|
| Technical | 64.3 | 27.9 | 7.1 | 0.7 | 0 |
| Economic | 69.3 | 22.9 | 7.1 | 0.7 | 0 |

*Table 3-4: Technical vs. economic impact categories: distribution of responses on the Likert scale*

Moreover, technical and economic categories achieved the highest agreement levels (92% in both cases). These results are reasonable considering that technical and economic criteria are the obvious factors that have been considered in energy projects. When considering performance measures, reliability was rated most important (89 %) followed by capital cost, with both of these again relating to technical and economic aspects. In fact, capital cost and reliability obtained the highest levels of consensus at 97 %, and 96 %, respectively.

- ***Consensus index***

Figure 3–9 shows the relationship between importance and consensus indices for each individual parameter. The (x) axis shows the degree of importance index and the (y) axis shows the degree of consensus index. The figure is divided into four quadrants reflecting metric thresholds, in which the (x) axis is divided by the degree of importance threshold, while the (y) axis is divided by the degree of consensus threshold.

Table 3–5 explains each quartile and the actions applied to each parameter based on its placement in Figure 3–9 in relation to importance and consensus thresholds. Parameters located in quartiles (3) and (4) were included in the next questionnaire round for further evaluation. Moreover, data providers were asked to indicate any additional parameters that they believe need to be considered, with several such parameters proposed. These additional parameters are presented and described in the following section. The second round questionnaire evaluated these additional parameters, as well as re-evaluating parameters that had received a low level of consensus during the previous questionnaire round.

| Parameter location (quartile number) | Meaning of location | | Further action |
|---|---|---|---|
| | Importance level | Consensus level | |
| 1 | Low | High | Eliminated from aggregated value tree (does not proceed to next questionnaire round) |
| 2 | High | High | Retained in aggregated value tree (does not proceed to next questionnaire round) |
| 3 | High | Low | Proceeds to next questionnaire round |
| 4 | Low | Low | Proceeds to next questionnaire round |

*Table 3-5: Further parameter actions based on parameter placement in Figure 3–9*

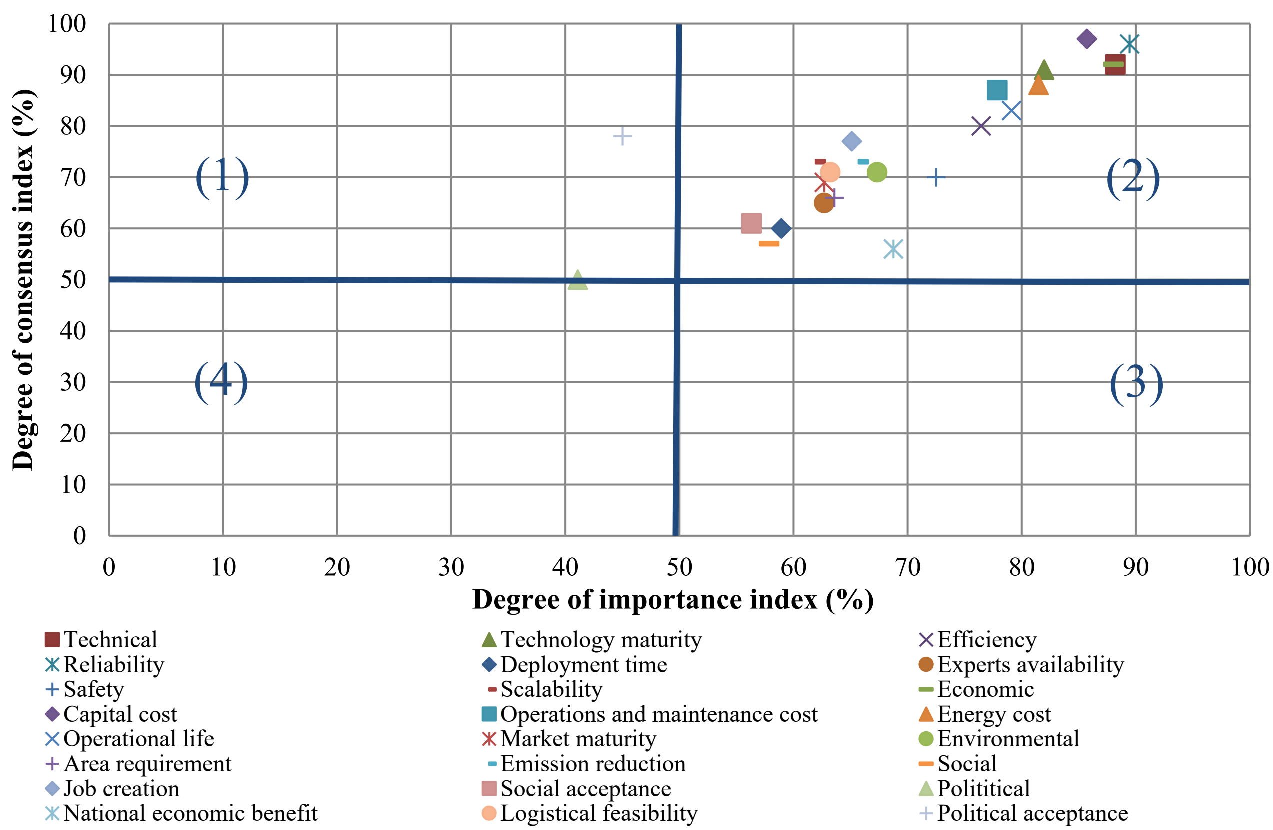



*Figure 3-9: Degree of importance index vs. degree of consensus index after first round*

***Stability measure***

By applying Equation (3–2) to all parameters, we obtain 24 CVs, 5 of which are for impact categories and 19 for performance measures. All CV values obtained were found to be < 0.29, within the accepted area of stability (i.e., < 0.5); this indicates a low level of variation from the mean. CV values were calculated in the same way after the second questionnaire round and CV differences were calculated as per Equation (3–3).

- ***Correlation coefficient***

Correlation coefficient analysis indicated insignificant correlations between impact categories. It is worth noting, however, that there were positive correlation coefficients between environmental and social (0.349), social and political (0.327), and technical and economic (0.211) categories, indicating that participants who find one impact category important also consider the other impact category to be important with respect to the associated correlation coefficients. On the other hand, a negative correlation between economic and environmental impact categories was recorded (–0.202). Table 3–6 shows correlation coefficients between impact categories, based on Pearson correlation analysis.

| | Technical | Economic | Environmental | Social | Political |
|---|---|---|---|---|---|
| Technical | 1 | 0.211 | 0.088 | 0.043 | –0.036 |
| Economic | 0.211 | 1 | –0.202 | 0.07 | 0.146 |
| Environmental | 0.088 | –0.202 | 1 | 0.349 | –0.101 |
| Social | 0.43 | 0.07 | 0.349 | 1 | 0.327 |
| Political | –0.36 | 0.146 | –0.101 | 0.327 | 1 |

*Table 3-6: Pearson correlation coefficients of impact categories*

#### *3.5.1.1. Parameters with low importance and consensus degrees*

In this section we shed light on parameters that were found to have a low level of importance or low level of consensus, in an attempt to understand critical points of disagreement. Based on the 50% index thresholds explained above, it could be noted that the political impact category was considered to have a low degree of importance. It was explained that political involvement tended to lack objectivity and to be associated with corruption and interests other than the benefits that such projects can provide in terms of other impact categories (i.e., technical, economic, environmental, and social). It was noted that CSP projects can be conducted without political support and that political acceptability is dependent on achieving satisfactory levels of technical, economic, and social aspects. However, dissenting opinions pointed to the importance of political support, especially considering that the scope of this research is developing countries.

The political acceptance performance measure also scored low in terms of the degree of importance. However, both parameters did not achieve an acceptable level of consensus; they were thus included in the second questionnaire round to allow participants the opportunity to reassess their responses in light of the entire expert panel perspectives.

#### *3.5.1.2. Supplementary parameters for evaluation*

In order to supplement parameters identified from the literature, participants were requested to indicate additional parameters that they considered important for CSP evaluation. In Table 3–7, these additional parameters are presented and described.

| | Performance Measure | | Description |
|---|---|---|---|
| Technical | | | |
| 1 | Storage hours | ($P_{t8}$) | Consideration of this parameter will give higher weights to projects with storage systems, owing to their abilities to be dispatchable to load during evenings and insufficient weather which reduces intermittency. One participant indicated that there should not be further solar thermal power construction without storage, due to the higher energy price compared with PV. |
| 2 | Availability of key components | ($P_{t9}$) | This parameter corresponds to the availability of components needed by the system. For instance, it is cheaper to acquire flat mirrors used in ST systems than to obtain PTs. However, tower flat mirrors usually need individual 2-axis tracking systems, while parabolic troughs need single-axis systems and use one system for several mirrors (the entire axis). |
| 3 | Hybridization | ($P_{t10}$) | This parameter differentiates between systems based on their ability to be hybridized with other renewable or conventional systems. Besides utilizing the same generation systems, integration of solar thermal systems into existing power plants will help the utilization of existing transmission infrastructure. |

| | | | |
|---|---|---|---|
| 4 | Level of complexity | ($P_{t11}$) | This parameter reflects system complexity. Some systems are more complex than others; for instance, systems with 2-axis tracking are more complex than 1-axis tracking (in return obtaining higher efficiencies). Reduced technological complexities reduce cost and increase the ability of developing countries to be self-sufficient in terms of operation, control, and maintenance of CSP plants, without the need for foreign experts to provide such services. |
| 5 | Technology advancement potential | ($P_{t12}$) | Some CSP technologies have a higher potential than others for advancement, leading to cost reduction through increased efficiency. This parameter therefore helps differentiate between CSP technologies based on their potential for advancements. |
| 6 | Microgrid suitability | ($P_{t13}$) | Some CSP technologies could be more suitable for distributed generation with micro-grid connections than others; such systems facilitate the electrification of rural areas and of small populations that are not connected to the national grid (e.g., PDs can be implemented in small systems). |
| 7 | Augmentation capability | ($P_{t14}$) | This parameter differentiates between technology scenarios that can be augmented and others that cannot. For instance, it might be better to build small systems instead of one bulky plant (e.g., 10 of 10 MW systems vs. one 100 MW system). |
| 8 | Temperature | ($P_{t15}$) | This parameter refers to the temperature generated by the solar field of each technology. Higher temperatures are desired due to increased efficiency of the CSP system [23]. |
| Economic | | | |
| 1 | Economic feasibility | ($P_{ec6}$) | This parameter measures the feasibility of the system from a financial standpoint. Methods such as ROI, Payback Period, or NPV could be utilized to calculate economic feasibility when considering each scenario as an investment and comparing revenues. |
| 2 | Fuel cost | ($P_{ec7}$) | This parameter favors plants that are completely dependent on RESs (i.e., only solar thermal or hybridized with other renewables such as biomass or PV) over other plants that are hybridized with conventional power utilities (e.g., gas). |
| 3 | Offsetting infrastructure cost | ($P_{ec8}$) | This parameter reflects the extra cost of a power plant owing to required infrastructural support. For instance, if a system is not using storage, then what is the grid capacity that is required to compensate for the absence of storage? |
| Environmental | | | |
| 1 | Water consumption | ($P_{en3}$) | This parameter differentiates between scenarios based on the selection of Rankin cycle cooling systems and mirrors cleaning requirement. The substantial water use by CSP plants could be critical considering that desert areas are the most favorable locations for such plants, owing to optimal sun radiation. |
| 2 | Ecosystem disruption | ($P_{en4}$) | This parameter reflects the impact of each scenario system on the environment and on sensitive habitats; including humans, flora, and fauna (e.g., impact on birds). |
| 3 | Land requirement | ($P_{en4}$) | This parameter is different from the area of land needed (which was evaluated in the first round). It indicates the field requirements of each technology, such as slope tolerance; with respect to these aspects, some technologies are more flexible than others. |
| 4 | Life cycle assessment (LCA) | ($P_{en5}$) | This parameter reflects the assessment of a product from the environmental impact standpoint throughout its lifetime, starting from the raw material stage through to disposal or recycling. |
| 5 | Environmental conditions impact | ($P_{en6}$) | The quality and efficiency of some technologies might be influenced more than others by environmental conditions, such as wind speed and dust contamination. |
| Social | | | |
| 1 | Local industrialization possibilities | ($P_{en3}$) | This reflects opportunities for localizing industries associated with each technological system. |

*Table 3-7: Supplementary parameters added by experts*

### 3.5.2. Second round outcomes

An aggregated value tree was obtained based on analysis of the first questionnaire round. Figure 3–10 shows the aggregated value tree, with all parameters color-coded. As shown in Table 3–8, parameters were classified into four main categories, colored green, red, orange, and blue, according to their status after the first questionnaire round. A fifth category was added and colored yellow to highlight parameters that are within 10% of thresholds, with these re-evaluated in the next round as part of sensitivity analysis, regardless of their quartile location; the color code of these parameters is yellow, integrated with their original color based on their quartile location, as per Table 3–8. During the second round, based on the aggregated value tree illustrated in Figure 3–10, data providers evaluated newly added parameters and re-evaluated parameters that achieved a low degree of consensus.

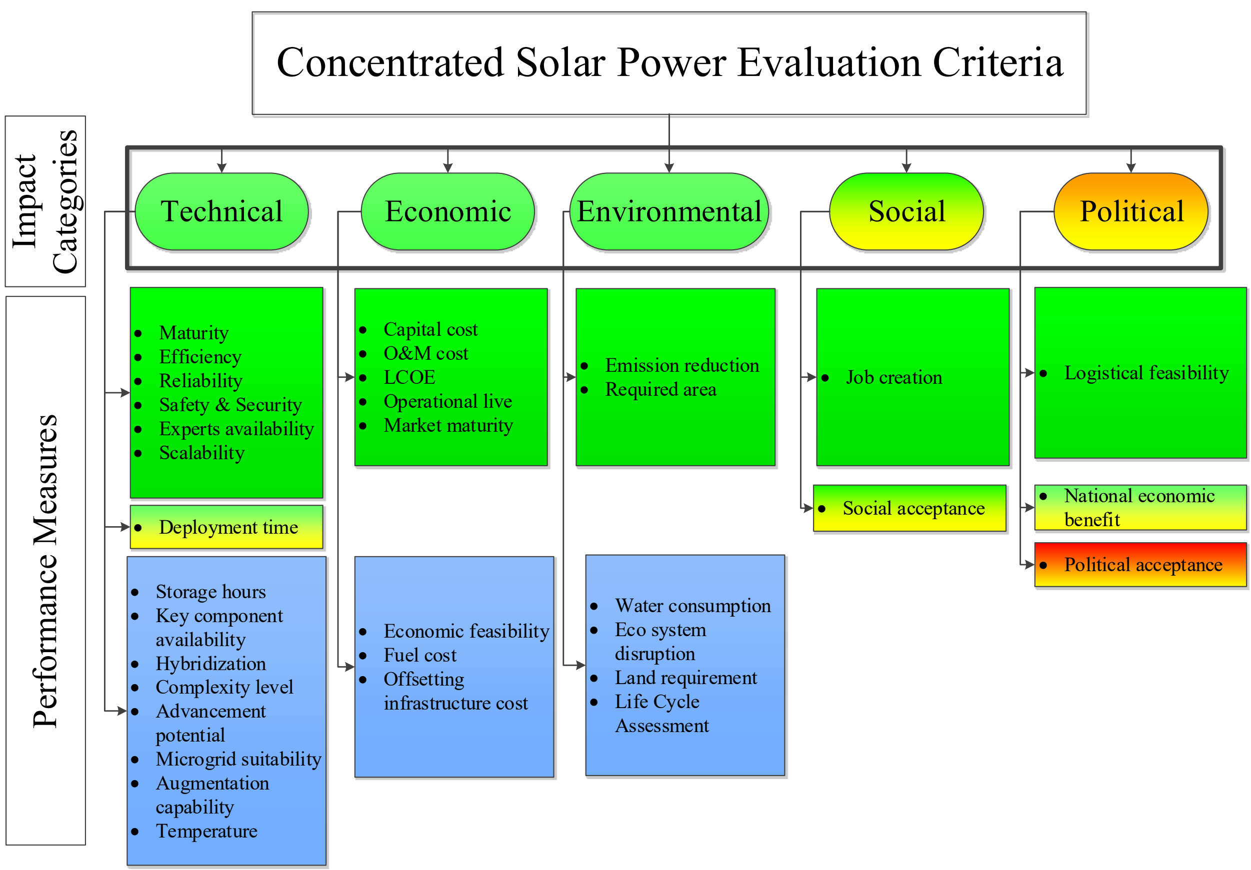



*Figure 3-10: Aggregated value tree from round one of the questionnaire*

| Parameter color | Meaning | Location in Figure 3–9 (quartile) | Further action | Inclusion in next round |
|---|---|---|---|---|
| Green | Accepted consensus and importance degrees | 2 | Retained in final aggregated value tree | No |
| Red | Accepted consensus and not accepted importance degree | 1 | Eliminated from final aggregated value tree | No |
| Orange | Not accepted consensus degree (regardless of importance degree) | 3 or 4 | Re-evaluation in second round questionnaire | Yes |
| Blue | New added parameters | N/A | Evaluation in second round questionnaire | Yes |
| Yellow | 10% range around thresholds | 1, 2, 3, or 4 | Re-evaluation in second round questionnaire | Yes |

*Table 3-8: Description of color codes and further action taken based on Figure 3–10*

- **Importance index**

Figure 3–11 illustrates the importance degree index of each parameter after conclusion of the second round. Four performance measures were re-evaluated, as can be seen in Figure 3–10 (entities integrated with yellow) and Figure 3–11 (patterned colored bars). Of these, three (deployment time, social acceptance, and national eco benefit) experienced a slight decrease in their degree of importance but remained above the threshold. Political acceptance increased above the threshold. Two impact categories were also re-evaluated (colored black). Of these, the political impact category, which had an importance level lower than the threshold during the first round, witnessed a further decrease, while the degree of social importance increased slightly.

In addition to the re-evaluation, 16 supplementary performance measures were evaluated during the second round. All added performance measures achieved levels of importance above the threshold, except for complexity level and temperature, which had importance degrees of 48% and 42%, respectively. Economic feasibility had the highest degree of importance across the two rounds (92%), while the importance degrees of water consumption and storage hours were 86% and 85%, respectively.

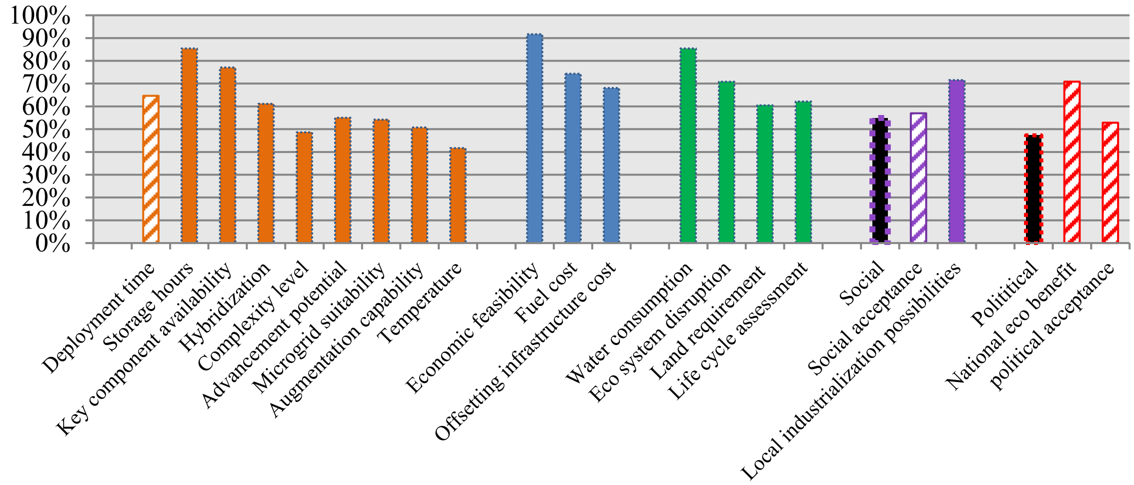



*Figure 3-11:Importance degree indices for parameters after second round*

- **Consensus index**

Figure 3–12 plots the importance degree index against the consensus degree index for each parameter, following conclusion of the second round. The political impact category was re-evaluated and obtained a higher consensus degree than during the first round, but with an importance degree lower than the threshold. It was suggested that the importance of political aspects is primarily during regulation and adoption stages, while these are not as significant during the selection of technology. Similarly, the temperature performance measure achieved an acceptable consensus degree but a low importance degree. These were therefore eliminated from the final value tree. It is noteworthy that performance measures under political impact categories obtained acceptable degrees of importance and consensus and were thus re-located under the most relevant impact categories. In addition, the land requirement and microgrid suitability measures obtained low consensus degrees but acceptable importance degrees. These were thus also eliminated, owing to high levels of disagreement among participants. A closer look at the distribution of responses shows that the rate with which these parameters' (i.e., land requirement and microgrid suitability) were indicated as important or very important was similar to the rate with which they were indicated as being not important or negligible; however, they obtained acceptable importance degrees owing to frequent selection as moderate importance parameters.

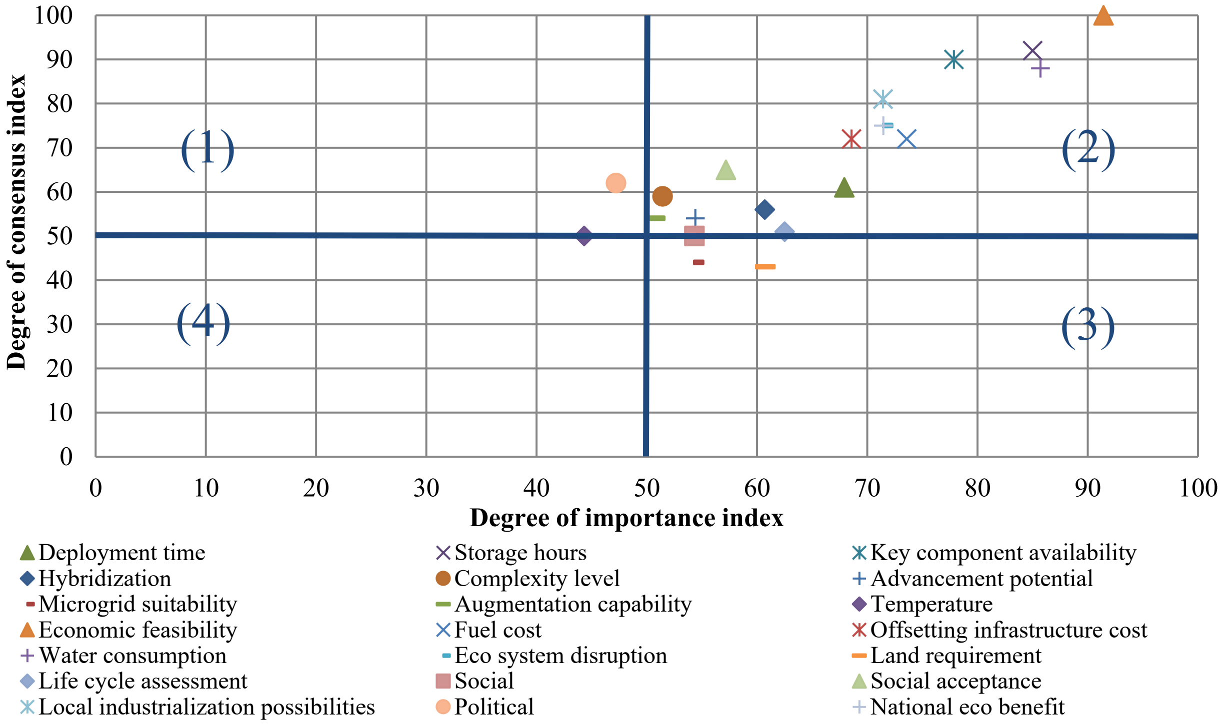



*Figure 3-12: Degree of importance index vs. degree of consensus index after second round*

- **Stability measure**

As noted above, the stability measure helps indicate when the Delphi rounds can be terminated for results validation. Gracht [121], in reviewing consensus measurement in Delphi studies in the literature, emphasizes the importance of distinguishing between consensus and stability concepts and points out that stability is a necessary criterion to be considered when deciding to terminate. Table 3–9 illustrates CVs of all parameters after conclusion of round 2. The CVs of parameters considered in only one round were calculated as per Equation (3–2), while the CVs of parameters considered in both rounds were derived through Equation (3–3). All parameters achieved an acceptable level of stability (i.e., < 0.5), as per Table 3–9. The Delphi process was therefore terminated after the second round and the value tree was aggregated based on importance and consensus indices.

| Parameter | $CV_1$ | $CV_2$ | $CV_{2-1}$ | Parameter | $CV_1$ | $CV_2$ | $CV_{2-1}$ | Parameter | $CV_1$ | $CV_2$ | $CV_{2-1}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Technical | 0.14 | | | ($P_{t14}$) | 0.26 | | | ($P_{en3}$) | | 0.18 | |
| ($P_{t1}$) | 0.15 | | | ($P_{t15}$) | 0.27 | | | ($P_{en4}$) | | 0.18 | |
| ($P_{t2}$) | 0.20 | | | Eco | 0.14 | | | ($P_{en5}$) | | 0.28 | |
| ($P_{t3}$) | 0.13 | | | ($P_{ec1}$) | 0.13 | | | ($P_{en6}$) | | 0.22 | |
| ($P_{t4}$) | 0.20 | 0.30 | 0.10 | ($P_{ec2}$) | 0.19 | | | Social | 0.24 | 0.26 | 0.02 |
| ($P_{t5}$) | 0.21 | | | ($P_{ec3}$) | 0.18 | | | ($P_{s1}$) | 0.20 | | |
| ($P_{t6}$) | 0.22 | | | ($P_{ec4}$) | 0.17 | | | ($P_{s2}$) | 0.23 | 0.23 | 0 |
| ($P_{t7}$) | 0.20 | | | ($P_{ec5}$) | 0.21 | | | ($P_{s3}$) | | 0.16 | |
| ($P_{t8}$) | | 0.15 | | ($P_{ec6}$) | | 0.10 | | Political | 0.28 | 0.26 | 0.02 |
| ($P_{t9}$) | | 0.14 | | ($P_{ec7}$) | | 0.22 | | ($P_{p1}$) | 0.18 | 0.22 | 0.04 |
| ($P_{t10}$) | | 0.23 | | ($P_{ec8}$) | | 0.20 | | ($P_{p2}$) | 0.19 | | |
| ($P_{t11}$) | | 0.19 | | Environmental | 0.21 | | | ($P_{p3}$) | 0.26 | 0.26 | 0 |
| ($Pt_{12}$) | | 0.21 | | ($P_{en1}$) | 0.23 | | | | | | |
| ($P_{t13}$) | | 0.28 | | ($P_{en2}$) | 0.22 | | | | | | |

Table 3-9: Coefficient of variation of all parameters after second round

#### *3.5.2.1. Aggregated value tree*

Based on previous measures, an aggregated value tree was derived for CSP utilities assessment in developing countries, as shown in Figure 3–13.

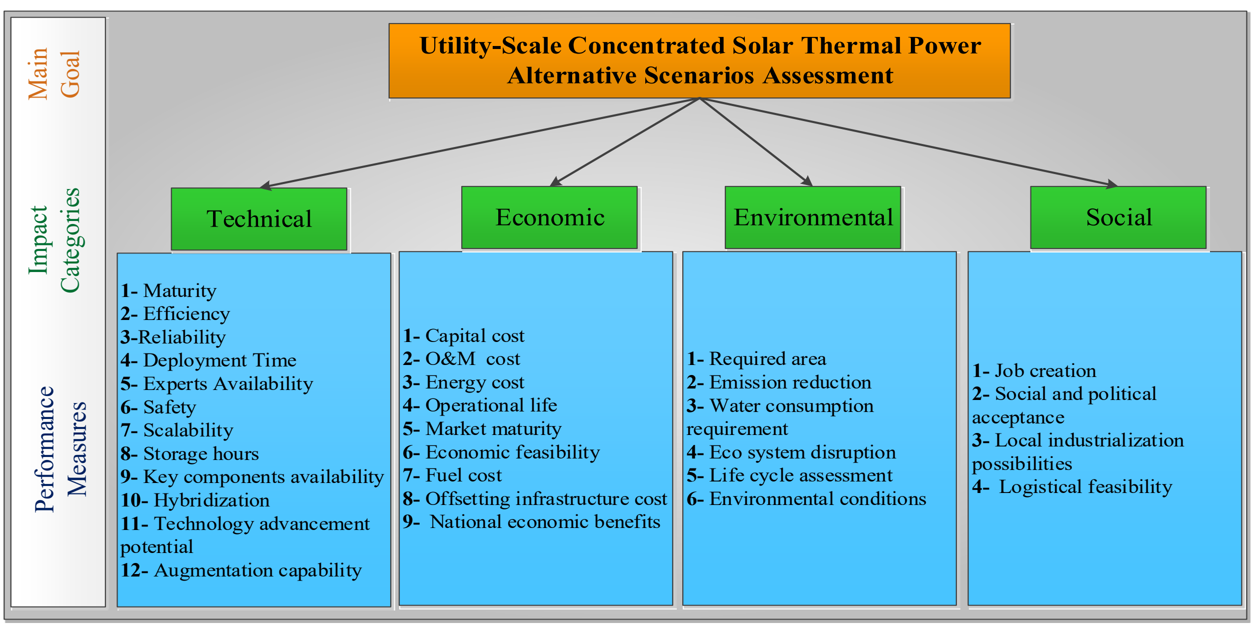



*Figure 3-13: Aggregated value tree*

This comprehensive value tree consists of 35 parameters; four of these are impact categories, representing main trajectories, and 31 are performance measures selected based on the model used in this study, following consultation with 140 data providers from 32 countries in two questionnaire rounds. All parameters were agreed on by at least 50% of experts and obtained importance degrees of 50% or more.

### 3.6. Sensitivity analysis

Sensitivity analysis is performed owing to the subjective nature of Delphi questionnaire evaluation and to subjectivity in threshold definition. In this section, we shed light on parameters that are only slightly higher or lower than the consensus threshold and that were considered for re-evaluation.

#### 3.6.1. Parameters adjacent to the consensus threshold

Parameters within a 10% range around the consensus thresholds were re-evaluated. In the first round, the consensus levels of the social impact category, and of social acceptance, national economic benefit, and deployment time performance measures were barely above the threshold. CSP projects are often implemented in deserts, far from societies, which reduces the significance of considering social aspects when comparing CSP projects, owing to low expected impact. It was also noted that national economic benefit is unlikely to fundamentally drive investment in CSP projects. However, it is important to point out that in developing countries, CSP projects are often owned by the government, unlike in developed countries, where CSP projects can be owned by private sector companies. Furthermore, it is inherently anticipated that large energy projects will take a long time to be commissioned, especially in developing countries. It is hence more important to focus on the sustainable development of reliable electrical systems, with no consideration of deployment time.

During the second round, there was a high degree of dispersion of answers for microgrid suitability, land requirement, and LCA. Based on consensus measurement categories, these parameters achieved consensus degrees of < 50%, yet > 40% in two of the categories, reflecting high level of disagreement among experts.

### 3.6.2. Indication of unnecessary parameters

Participants were also requested to weight the degree of importance of each parameter, to indicate separately whether they believe any are not necessary for evaluation of CSP technologies. During the first round, 69% of respondents thought that none of the impact categories were unnecessary. The political impact category was considered to be unnecessary by 23% of respondents, greatly influencing the degree of importance of this category. Figure 3–14 depicts the distribution of responses with regard to unnecessary impact categories. Similarly, contributors were asked to indicate unnecessary performance measures. Political and social acceptances were indicated to be unnecessary by 23% and 13% of respondents, respectively, while the majority again argued that none of the presented performance measures were unnecessary. In the second round, 71% of respondents indicated that both re-evaluated impact categories were necessary; however, the political category was again indicated as being unnecessary by 20% of respondents. The majority argued that none of the presented performance measures were unnecessary.

Several participants emphasized the importance of considering all presented parameters and that the whole package is necessary for evaluation. All parameters are interconnected; for example, technical competency is essential, but needs to be economically competitive. Furthermore, CSP is a relatively young technology; most projects would hence not be able to proceed without political assistance and social support to facilitate sustainability and environmental aspects, with these obtained through competency in all impact categories. It is therefore very important to consider all mentioned parameters for long-term success of CSP facilities. Poor performance of a system with respect to any of these aspects has the potential of increasing the project risk profile and cost, consequently preventing its deployment. The importance of the whole package is also derived through the fact that such projects are competing with already established conventional energy systems and their standards.

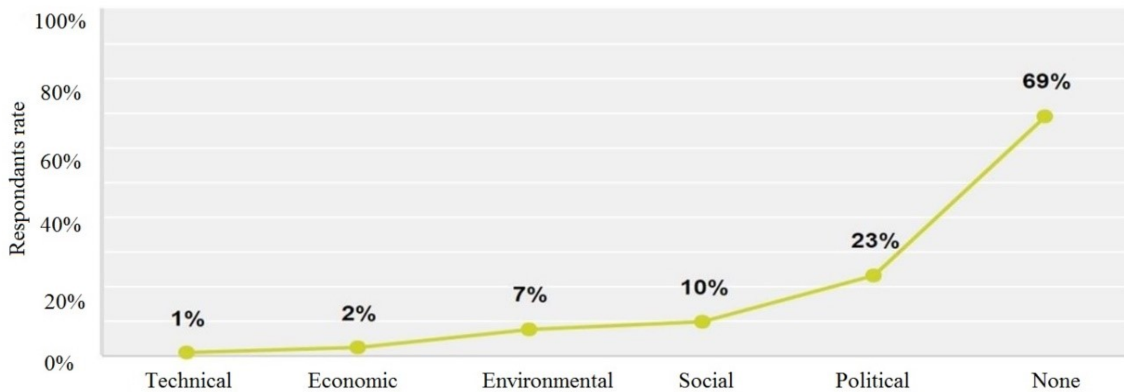



*Figure 3-14: Distribution of unnecessary impact categories according to participants*

### 3.7. Conclusions and implications

The planning of energy projects involves complications associated with their multi-dimensional aspects. In assessing alternatives, it is essential to adequately define required evaluation parameters. CSP has great potential to play a key role in meeting future electricity demand in many developing countries. Four major solar collecting technologies provide different alternatives for planners of CSP utilities; these are PTs, STs, PDs, and LFs. In addition, different generation, hybridization, and storage technology choices also need to be made. This study proposed a methodology to define a framework for large-scale CSP plants assessment. Following a comprehensive literature review to define a preliminary value tree, structured expert elicitation was conducted by means of two Delphi method rounds. A total of 140 experts from solar thermal power field participated in the first round and 36 in the second round, with these coming from educational institutes, research centers, governmental organizations, and industrial companies.

The output of the process was a recommended value tree of parameters (i.e., impact categories and performance measures) that need to be considered during the early planning stages of assessing CSP utilities in developing countries. At the end of each Delphi round questionnaire, key metrics were measured to define outcomes and prepare a feedback report for participants, prior to the following round. The degrees of importance, consensus, stability, and correlation coefficients of each parameter were calculated to define aggregated value tree parameters and to identify the termination round of expert elicitation. A final aggregated value tree was formulated, representing a generic value tree for CSP projects evaluation, based on data providers' judgments; it consists of four impact categories as main trajectories, subdivided into 31 performance measures.

Over two Delphi rounds, technical and economic categories were rated as most important and achieved the highest degrees of consensus, with slight differences. Economic feasibility obtained the highest level of importance and consensus degrees among performance measures, followed by reliability, capital cost, storage hours, and water consumption. In addition, a high level of stability was obtained throughout two rounds, facilitating the decision to terminate Delphi rounds.

The findings of this study have substantial implications for CSP projects stakeholders, providing a generic framework for CSP utilities assessment in developing countries; the framework is expected to be slightly modified in accordance with specific locations and circumstances. Finally, subsequent work focuses on the definition of CSP scenarios for individual case studies, as well as on obtaining accurate data for comparing alternatives by means of multi-criteria decision-making.

# Chapter 4: Concentrated Solar Thermal Power in Saudi Arabia: Definition and Simulation of Alternative Scenarios

## 4.1. Introduction

Decisions during the early stages of planning define the future performances of CSP systems. However, there are uncertainties related to using such technology while it is in the infancy of its deployment. In addition, several types of CSP technologies are available for utility-scale use, ranging from highly mature technologies to less mature technologies with high development potentials. Investors interested in solar energy projects in developing countries have been facing challenges associated with the lack of sufficient and long-term solar radiation data required for planning and evaluation of the technical and financial requirements. Assessments of these requirements would encourage interested developers to commit to these projects, which have high potentials in hot and arid countries. Furthermore, one of the major challenges regarding CSP development that planning bodies face is related to the selection of suitable technologies, especially taking into consideration the particularity of weather and energy market characteristics [124].

Several developing countries are exposed to high DNI levels and hence have high potentials for CSP. Since renewable energy projects are location dependent, in the investigation described herein, a case study of Saudi Arabia has been detailed, although the proposed methodology is suitable for other developing countries as well. This study aimed at analyzing the different technologies involved in CSP plants in the context of Saudi Arabia to exploit their merits. It additionally aimed at assessing the technical and financial performance of potential CSP utilities in Saudi Arabia.

In this study, early-stage definition and evaluation of the performances and financial parameters of different CSP scenarios in Saudi Arabia was conducted. A SWOT analysis was performed to provide an overview of the different technologies associated with CSP. Alternative scenarios were defined with respect to literature and existing operational CSP plants in the Arabic region and globally, with the modifications required to suit the characteristics of Saudi Arabia. In addition, local weather records based on satellites observations and ground-based measuring stations were integrated to create typical meteorological year (TMY) data to simulate the proposed alternatives. A simulation was then conducted using SAM modeling tool. Finally, the performance and financial parameters of the CSP scenarios were obtained for assessment.

The novelty of this research originates firstly from the SWOT analysis conducted for different technologies used in CSP plants, including solar thermal collectors, HTFs, and cooling systems. Secondly, the SWOT analysis outcomes were incorporated with the Saudi energy sector requirements and environmental characteristics with considering currently operating CSP projects in other countries to develop alternative scenarios for power plants in Saudi Arabia. Thirdly, the technical and financial performances of the defined CSP scenarios in Saudi Arabia were analyzed through a simulation in which the local weather records were considered by synthesizing satellites observations with field measurements of weather conditions.

The remainder of the chapter is organized as follows: Section 4.2 provides an overview of the CSP potential in Saudi Arabia. Section 4.3 describes the methodology. In Section 4.4, the definitions of the design parameters used in the scenarios are presented and the simulations are described. The results are discussed in Section 4.5, and finally, the conclusions are summarized in Section 4.6.

### 4.2. Solar thermal energy potential in Saudi Arabia

In Saudi Arabia, energy consumption is increasing at a rate of approximately 8% annually [103], which is the highest rate of consumption increase in the Middle East [125]. The five primary reasons for this high rate are as follows: First, the significant increase in population along with higher standards of living. Second, high volumes of water are desalinated; specifically, an average of 3.5 million cubic meters of water is desalinated daily in Saudi Arabia [125]. Third, Saudi Arabia is located in a hot and arid region with extremely hot summers; consequently, an estimated 70% of the residential peak electricity consumption, which represents the primary consuming sector, is caused by air conditioning. Fourth, the cost of energy is relatively low. Fifth, massive infrastructure development is ongoing [125].

Saudi Arabia is located in an area with an abundance of solar irradiation that could be harnessed for electricity generation. It lies in the sunbelt between 16° N and 33° N latitude and 34° E and 56° E longitude with a DNI that ranges from approximately 5000 Wh/m$^2$/day during the winter months to 9000 Wh/m$^2$/day during the summer months [126]. Hence, the weather conditions are optimal for harnessing solar power, and consequently, K.A.CARE allocated the highest share of RESs to solar technologies.

The powerful solar irradiation Saudi Arabia receives could yield a levelized costs of energy (LCOE) lower than those of other regions [26]. A standalone CSP plant requires a DNI of ≥ 1800 kWh/m$^2$/year [60]. Figure 4–1 illustrates a high-level map of the DNI in Saudi Arabia [8], in which it can clearly be seen that most regions of the country are exposed to DNI levels of 1800 kWh/m$^2$/year or more. Pazheri et al., [26] described the potential of Saudi Arabia not only to cover local demands by generating electric power through solar energy systems, but also to export power to other countries that have high demands and sparse electricity-generating resources, including low solar irradiation.

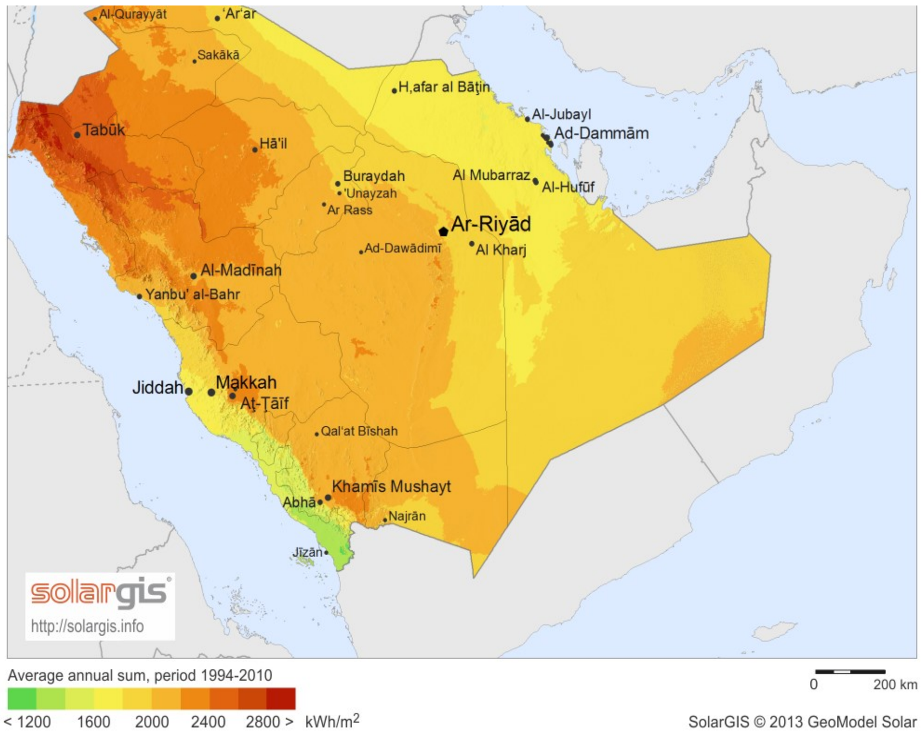



*Figure 4-1: High-level map of DNI in Saudi Arabia*
*Source: Solar GIS, 2016 [8]*

CSP plants consist mainly of three parts. The first part is the solar field, which contains concentrated solar thermal collectors. Four main collection technologies are used, which are categorized according to their focal or linear concentration properties. For linear concentration, either PT or LF collectors are used, while for focal concentration, ST or PD collectors are used. The collected heat is transferred through an HTF to the thermal storage tanks, if any, which constitute the second part of the power plant. The third part is the power cycle, which consists primarily of conventional turbines based on the Rankine cycle. Figure 4–2 presents a schematic of a CSP plant using PT collectors and energy storage.

Currently, the CSP market is dominated by PT-based plants, which constitute around 85% of the installed capacity; this portion will decline in the future considering that one-third of the projects under construction employ ST or LF collectors [79]. In fact, recent years witnessed various ST- and LF-based power plants coming online. An ST-based power plant is currently the largest CSP plant in the world (i.e., the Ivanpah Solar Electric Generating System).

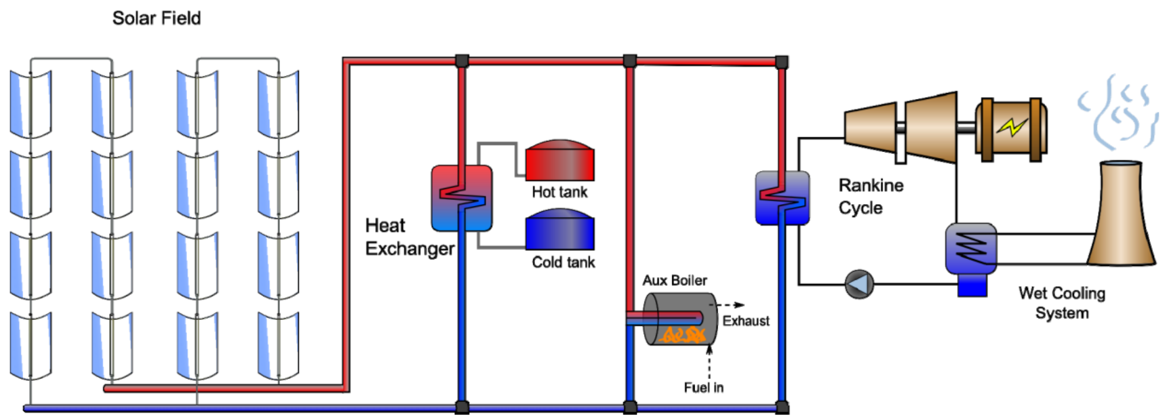



*Figure 4-2: Schematic of a PT-based concentrated solar thermal power plant*
*Source: Madaeni et al., 2011* [127]

### 4.3. Methodology

The proposed methodology aimed to define CSP plant scenarios and analyze their technical and financial performances. Figure 4–3 illustrates the proposed methodology, as applied in the present study. The most common CSP technologies were addressed, including solar thermal collectors, HTFs, storage technologies, and cooling systems. SWOT analysis was performed based on the literature to provide an overview of the CSP technologies through investigating the strengths weaknesses, opportunities, and threats faced by each of the technologies. The outputs of the SWOT analysis were incorporated with the local requirements and characteristics. Alternative CSP scenarios for Saudi Arabia were developed, in which the assemblies of technologies were integrated for CSP power plants. The analysis results were combined with information from CSP plants operated in the Arabic region, if existing, and globally otherwise. Afterward, the required weather, technical, and financial parameters were defined for the simulation. A local weather data profile (i.e., a TMY file) was synthesized by combining modeled and measured data. A simulation through SAM was subsequently conducted using weather data for Saudi Arabia to enable the required performance and financial analysis. The simulation yielded performance and financial parameters that were then employed to evaluate the proposed CSP scenarios.

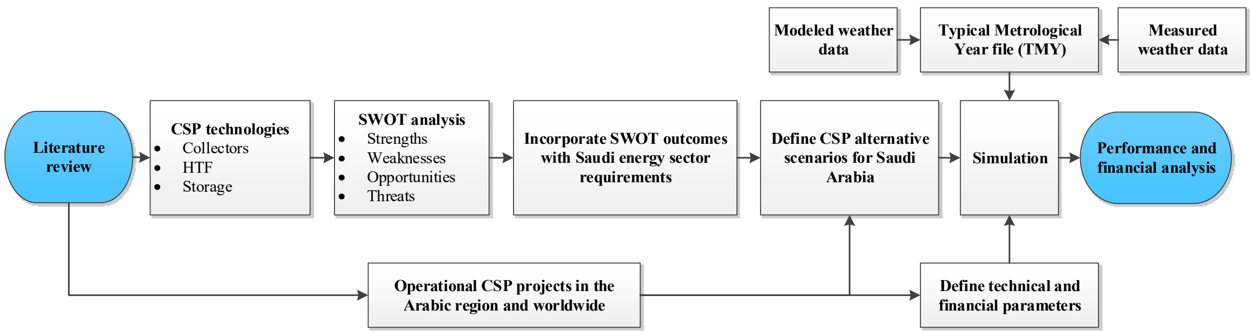



*Figure 4-3: Methodology of analyzing, defining, and simulating CSP alternative scenarios*

### 4.3.1. SWOT analysis

SWOT analyses have been conducted for regional energy planning, municipal solid waste management, policy prioritization, and sustainable national strategy development. They address two main components indicating the internal situation, i.e., strengths and weaknesses of the involved technologies, as well as two components corresponding to the external energy sector and environmental conditions, i.e., opportunities and threats. SWOT analysis results in a common understanding and vision to benefit from strengths, avoid weaknesses, exploit opportunities, and reduce threats effects [128]. In this research, SWOT analysis was undertaken using information provided in the literature [37], [82], [125], [129], in industrial reports [3], [103], [130], [131], and by renewable energy research institutes [7], [79], [101], [102], [132]. Table 4–1 compiles the analysis for the main parts of CSP plants. The analysis addresses the features of the CSP technologies to be incorporated with the Saudi requirements based on the local environment and energy sector characteristics, which are discussed in detail following Table 4–1.

| | Internal | | External | |
|---|---|---|---|---|
| | Strengths | Weaknesses | Opportunities | Threats |
| Parabolic trough | • Most mature and utilized<br>• High commercial availability<br>• Single-axis tracking<br>• Low material demand<br>• Low land-use factor | • Limited operation temperatures<br>• Limited solar field slope acceptance<br>• Low plant peak efficiency | • Proven hybridization with conventional facilities<br>• Many material providers | • Higher soiling effect on curved mirrors |
| Solar tower | • High operating temperatures<br>• High solar-to-electric efficiency<br>• Flexibility in terms of ground flatness<br>• Entire piping system in central zone | • Dual-axis tracking<br>• Low modularity<br>• High land-use factor | • Abundant potential lands<br>• Suitability for long thermal storage | • Tower problems result in significant production difficulties |
| Parabolic dish | • Highest operating temperatures<br>• Potential for highest conversion efficiency<br>• No level ground requirement<br>• High modularity and scalability | • Dual-axis tracking<br>• Demonstrational stage<br>• Expensive | • High potential for improvement<br>• On- and off-grid applicability<br>• Best suitability for air cooling | • Risk-driven financing cost<br>• Higher soiling effect on curved mirrors<br>• Hybridization and thermal storage difficulties |
| Linear Fresnel | • Simplicity<br>• Lowest material demand<br>• Lowest land-use factor<br>• Lowest capital cost<br>• Lowest O&M cost | • Lowest temperatures<br>• Low optical and conversion efficiencies<br>• No commercially available thermal storage | • Robotic cleaning technology for mirrors<br>• Potential for cost reduction | • Risk-driven financing cost<br>• Wasted high DNI in Saudi Arabia |
| Molten salts | • High temperatures<br>• Solar receiver can be started quickly<br>• Suitable for long TES<br>• Increases TES reliability | • Requires two fluid cycles<br>• Requires boiler in power cycle | • Improves dispatchability<br>• Ability to cover base load<br>• TES lowers LCOE | • High capital cost for systems with TES |
| Direct steam generation | • Low cost<br>• Requires one fluid cycle<br>• Less complex<br>• Steam generated in the solar field | • No commercially available storage<br>• Low reliability<br>• Lowest temperatures | • Steam-cycle temperature is suitable for PT-based plants<br>• Easy integration | • Not financially competitive with other renewables |
| Synthetic oil | • Most mature<br>• Most used as HTF in commercial plants<br>• High thermal stability<br>• High melting point | • Requires two fluid cycles<br>• Requires boiler in power cycle<br>• Lower temperatures than salt<br>• Expensive as HTF | • Long track record in PT-based plants | • Thermal oil degradation<br>• Toxic and flammable |
| Wet cooling | • Cheaper than dry cooling<br>• High efficiency | • High water consumption<br>• Requires water source | • Higher temperatures reduce water consumption | • Lack of water supply in Saudi Arabia |
| Dry cooling | • Ability to use in the absence of water supply<br>• Reduced parasitic loads | • Expensive<br>• Less efficient | • Highly suitable for use in PD-, ST-, and PT-based plants respectively | • High capital cost for dry cooling systems |

*Table 4-1: SWOT analysis of CSP technologies*

Hereafter we discuss in detail the attributes of each type of technology based on the SWOT analysis performed with consideration of the Saudi requirements concerning the energy sector and environmental conditions. The assessment of these attributes helps us reach a vision to identify the needs of the Saudi CSP portfolio and hence, to develop recommendations for defining alternative scenarios.

#### *4.3.1.1. Collecting technologies SWOT*

- PT collectors SWOT

PT technology is the most mature and utilized of the various CSP collection technologies [79], [82] with over 12 billion kWh in operation, which has led to its commercial availability [125]. Commercial availability is a key feature when considering CSP alternatives for Saudi Arabia, which is not an industrial country and would be heavily dependent on imported technologies during the initial phase of CSP portfolio implementation. In addition, PT collectors require only single-axis tracking mechanisms to follow the solar radiation from east to west during the day. There is no need to move in the north–south direction to follow the solar radiation during the year because of the linearity of the receiver design [37]; consequently, the initial costs of PT systems are lower than those of focal collection systems that require dual-axis tracking mechanisms. PT systems also have low material demands and land-use factors, which reduce their capital costs [125]. However, the land-use issue might not be a significant parameter for planning in Saudi Arabia given the abundance of desert acreage, which provides potential locations for CSP plants due to the high levels of solar irradiation.

Among the potential weaknesses of solar technologies in general in Saudi Arabia are the impacts of frequent sandstorms and soiling on energy production. Soiling reduces both the optical efficiencies of the mirror surfaces and the DNI due to the increased aerosol load, leading to increased losses and accordingly, lower system output. The impact of soiling depends on the technology type including materials, configurations, and collector shapes. This impact is reduced when flat mirrors are utilized, which is advantageous for ST and LF systems in the Saudi environment. In addition, PT technology allows for a solar field slope of only < 1–2%, compared to < 2–4% for ST technology, < 4% for LF technology, and ≥ 10% for PD technology, resulting in higher site improvement costs [132]. PT systems also have low peak efficiencies and limited operating temperatures compared to ST and PD systems [3], [132].

PT systems offer the opportunity to take advantage of existing conventional steam turbines either through hybridization of a CSP plant with a conventional plant or through the replacement of old, high-emission steam-producing parts of existing power plants with solar fields. Hybridization is theoretically possible with different CSP collecting technologies; however, it has been empirically proven with PT systems. The ability to hybridize CSP plants with conventional ones is an important point to address for CSP planning in Saudi Arabia, which has, as of 2014, a total of 65 GW of available generation capacity, of which 50%, 34%, and 14% are provided by gas, steam, and combined-cycle units, respectively [131]; these facilities could potentially be hybridized with CSP with the right site characteristics. The Saudi Electricity Company is planning two integrated solar combined cycle (ISCC) plants: Waad Alshamal and Duba 1, which are planned to have 1390 MW and 550 MW of installed capacity and will include 50 MW and 43 MW coming from PT fields, respectively [133]–[135].

- ST systems SWOT

The hot and arid environment of Saudi Arabia provides solar collectors with high temperatures. ST systems benefit from high operating temperatures. In addition, ST technology allows for a higher site gradient than PT technology does, which reduces the site improvement costs [82]. The ST system design enables the entire piping system to be located centrally in the power plant, which shortens the pipe system and consequently reduces the energy losses and facilitates the diagnosis of problems and maintenance [136]. Furthermore, ST technology has been commercially proven, and large ST facilities are operational, including the largest CSP plant, the Ivanpah solar power facility. It is essential to consider proof of commercial reliability when planning CSP plants in Saudi Arabia. In addition, the fact that ST technology benefits from high collection temperatures makes it the most suitable for long thermal storage (> 10 h) with molten salt, which serves the goals of Saudi Arabia to use CSP to meet the maximum demand difference between peak load covered by PV and base load [18].

Systems that focus the solar radiation to a single point require dual-axis tracking for each individual entity. Accordingly, ST fields involve high initial costs for heliostat systems. Relatively large spaces are required for ST systems, leading them to require more land than other proven CSP collection technologies [37], which again might not be significant for planning considerations in Saudi Arabia. In addition, with regard to the layout, the central towers of ST systems work on receiving the concentrated radiation of huge numbers of heliostats. Accordingly, problems occurrence to the central towers of such systems could lead to substantial power production shortages. Furthermore, ST systems have low modularity, which impedes their implementation in small capacities for decentralized projects [125]. This lack of modularity could be an important factor if considering CSP technologies for small-scale facilities, while the focus of this research was on large-scale utilities to be integrated into the national power grid.

- PD collectors SWOT

It is important for CSP collection technologies to be highly efficient to benefit from high solar spectrum. Two types of efficiencies must be considered: optical efficiency, which reflects the ability of each collector to concentrate solar rays; and solar-to-electric efficiency, which reflects the overall ability of each system to convert solar radiation into electricity. Focal collectors have the potential to achieve higher optical efficiencies than linear collectors because they focus solar radiation to single points instead of directing them into linear tubes. In addition, the dual-axis tracking systems of focal collectors enhance their optical efficiencies with the consequence of increasing their costs. Dish reflectors have the highest potential concentration levels, of up to 10,000 suns, followed by ST collectors, which can achieve concentration levels of over 1000 suns. PT collectors have concentration levels of 70–80 suns, while those of LF collectors are over 60 suns [79]. High energy concentration leads to high optical efficiency and consequently, high-temperature generation and solar-to-electric efficiency improvement. Accordingly, dish reflectors yield the highest optical efficiency of 94%, compared to 80% for PT collectors, 73% for ST collectors, and 65–75% for LF collectors [37]. Thus, PD collectors achieve the highest temperature gains among all of these collection technologies, reaching up to 750 °C [79], [102]. This crucial benefit leads to a high efficient steam cycle utilization, resulting in a high solar-to-electric conversion efficiency of 25–30%, and consequently reducing the LCOE. ST systems are characterized by long travel distances between their heliostats and receivers, which reduces their optical efficiencies. Nevertheless, the concentration of solar radiation to a single point through numerous heliostats increases the temperature gain, which can reach up to 565 °C, compared to 400 °C for PT systems and 350 °C for LF systems [79]. Subsequently, ST systems yield the highest annual solar-to-electric efficiencies, which have been reported to be 20–35% compared to 15% for PT systems and 8–10% for LF systems [102]. Ongoing R&D have shown that dish reflectors have the potential to achieve solar-to-electric conversion efficiencies 50% higher than those of ST systems and 100% higher than those of PT systems [37]. Furthermore, PD systems do not require level ground [102], are the best suited for air cooling, and are highly modular, which makes them suitable for decentralized generation to facilitate the electrification of small rural off-grid communities [79]. Dish reflectors are also advantageous due to their scalability, which enables them to be clustered to form larger systems [102], [125]. PD systems are seen as promising with high improvement potentials, especially in terms of lowering their costs and increasing their efficiencies by finding a reliable and efficient engine for converting heat into electricity.

The greatest weakness of PD systems is the absence of large-scale operational projects. The technology is in demonstration stage at the project level [79]. In fact, most of the existing systems are not connected to the grid. The absence of reference plants increases the loss risks and reduces the financial support chances [82]. It also makes it unlikely that Saudi Arabia, which lacks experience in large-scale solar energy projects, will decide to initiate the commissioning of plants utilizing PD technology. In addition, the capital cost and O&M costs of PD systems are the highest among those of the available collection systems for many reasons, including the required dual-axis tracking mechanisms, high material demands, and lack of large-scale projects. Dish systems are predominantly utilized with Stirling engines, which complicates synergies [82]. They also need enhancements to overcome difficulties related to reliability [125], hybridization, and thermal storage, all of which are critical for the development of large-scale CSP plants [37].

- LF collectors SWOT analysis

LF collectors are modified PT collectors with flat or slightly concave mirrors instead of curved ones. Thus, LF collectors benefit from simplicity [82] and have the lowest material demands among all of the discussed types of collectors since their concept is derived from PT collectors (which have the advantage of low material demands) but have less curved mirrors to reduce their costs and facilitate the acquisition of materials [79]. In addition, in an LF collector, the central receiver is separated from the reflectors, thus eliminating the need for high-pressure rotating components and accordingly reducing the capital cost as well as the O&M costs [37]. The linear and flat design of LF mirrors minimizes the amount of water required for cleaning since robotic cleaning technology can be employed. This characteristic thus contributes to the reduction of the O&M costs [82]. LF systems also require the lowest land-use factor compared to other systems discussed herein [37].

The LF design requires a lower cost, yet it leads to low optical efficiency, low collection temperatures, and consequently, decreased conversion efficiency due to the large gap between the reflectors and the central receiver. LF collectors also have fewer HTF pipes than PT collectors have [37], [79], [102]. The fact that Saudi Arabia lies in the sunbelt makes it a potential location for achieving high electricity generation rates by harnessing solar radiation, which requires technologies with high conversion efficiencies. Furthermore, there is a lack of large-scale operational plants (> 100 MW), with the exception of the Dhursar project in India with a capacity of 125 MW, whose operation began in 2014 [101]. This shortage increases the financial loss risk margin. Furthermore, no large-scale thermal storage is commercially available for LF systems [82]. Nevertheless, the simplicity of the LF design has led to high expectations for cost reduction.

##### *4.3.1.2. Heat transfer fluids (HTFs) and thermal energy storage (TES) SWOT*

Either direct or indirect configurations are used for HTFs and TES in CSP plants. Indirect configurations include synthetic oil or molten salt as HTFs and/or for TES; each of these liquids is later used to transfer water into steam by a boiler during the power cycle in order to operate a conventional steam turbine. The other configuration depends on direct steam generation (DSG);

in this configuration, water is used as the HTF and is boiled directly and converted into steam in the solar field to operate the steam generator [129].

Using DSG is cheaper than using oil and salt. DSG requires only one fluid cycle, while the use of salt and oil requires two cycles. The existence of fewer fluid cycles decreases the technical, operational, and maintenance complexities and risks [82]. DSG simplify hybridization with existing conventional plants. Another advantage of DSG is that the maximum operating temperature of PT receivers coincides with the steam-cycle temperature [129], [137]. However, compared to using oil and salt, DSG has lower operating temperatures. In addition, there is a lack of commercial available storage for steam [129], leading to more power supply fluctuations and consequently, lower reliability of such systems. An essential advantage of CSP is its ability to be thermally stored, which enables energy to be dispatched upon demand. Giving up this leverage might affect CSP's ability to compete with other RESs [7]. In addition, a point of strength for Saudi Arabia is its high DNI and hence, it is significantly important to consider high efficient systems to exploit its solar resources and decrease LCOEs.

On the other hand, the conventional synthetic oil and molten salt utilized for solar applications dedicated to power production are Therminol VP-1 and a mixture of salts (60% sodium nitrate $NaNO_3$ + 40% potassium nitrate $KNO_3$) [129]. Synthetic oil is the most mature HTF due to its long track record of utilization with PT technology [82]. Most of the operational CSP plants utilize the combination of PT technology and synthetic oil [101]. Therminol VP-1 has a high thermal stability, a high melting point, and a high vapor pressure in the operating temperature range of up to 400 °C [59]. However, thermal oil degradation limits the ability to realize efficiency improvements [82]. Moreover, synthetic oils are expensive as HTFs and are also toxic and flammable [138]. Consequently, small-scale facilities are being developed to investigate water-steam and molten salt as HTFs with PTs.

While synthetic oil is the most common HTF, molten salt is the most common TES fluid. It operates at higher temperatures of up to approximately 600 °C, compared to 400 °C for synthetic oil [129]. Higher temperatures enable steam cycle efficiency improvement [132], [136]. As an HTF, compared to water-steam, molten salt enables a quicker start of the receiver since it is a single-phase fluid [37]. However, neither of these two fluids is as mature as synthetic oil as an HTF in large-scale facilities. Some disadvantages, including problems related to salt freezing in some circumstances, have hindered the adoption of molten salt as an HTF thus far [139]. On the other hand, using molten salt for TES decreases the system fluctuations and enables the generation of electricity in the absence of solar radiation due to the presence of clouds or during the night. Molten salt has been integrated into ST systems to provide the longest TES, up to 15 h in an operational plant (i.e., the Gemasolar Thermosolar CSP plant), and up to 17.5 h in an under-construction plant (i.e., the Atacama CSP plant) [101]. These long storage systems help CSP plants cover base loads under proper conditions. The energy dispatchability that is provided by molten salt is a key feature when considering the development of alternative scenarios for Saudi Arabia given that K.A.CARE targets CSP allocation to cover the maximum demand difference between the peak load covered by PV technology and the base load [18].

#### *4.3.1.3. Cooling systems SWOT*

The cooling requirements of the thermodynamic cycle of a CSP plant are important since they are related to the system's efficiency, cost, and environmental constraints. The two conventional cooling technologies are wet and dry cooling. The wet cooling approach is cheaper in terms of capital cost and is more efficient. However, it is coupled with high water consumption. Current CSP plants adopting wet cooling require approximately 2100–3000 L/MWh, whereas conventional coal-fired and gas-fired plants require approximately 2000 L/MWh and 800 L/MWh, respectively [132]. Collection technologies that provide higher temperatures allow higher efficiency and require less water for condenser cooling. Accordingly, PD systems require by far the lowest amounts of water due to their high operating temperatures as well as the fact that they are the only collection systems that do not depend on the Rankine cycle; ST systems require the second-lowest amounts of water, followed by PT and LF systems [132].

Dry cooling, on the other hand, saves water while also increasing the capital cost and decreasing the efficiency [103]. An additional advantage of dry cooling is parasitic load reduction. Dry cooling is best suited for PD systems, followed by ST systems. The suitability varies for PT systems from low to good and is low for LF systems [132]. When considering the development of alternative scenarios, it is necessary to keep in mind that Saudi Arabia is an arid country and therefore potentially requires the use of less efficient and more expensive dry cooling in CSP plants [103].

### 4.3.2. Alternative scenarios definitions and simulations

The technical and financial performances of CSP plants were analyzed by defining several potential scenarios for evaluation. The power plants were designed and simulated by considering the current knowledge about the solar spectrum, ambient temperature, and wind direction and speed, as well as by altering the power plant components, including the solar thermal collectors, HTFs, plant gross capacities, and storage capacities. Table 4–2 lists the primary available combinations of technologies used in the existing operational plants. There are also other combinations, especially ones incorporating less mature technologies with ongoing R&D, such as PD systems with heat pipes, steam engines, and gas turbines [37], [57]. However, there is not yet any operational reference with regard to power plants using such technologies, which increases the analysis uncertainties as well as the technical and financial risks.

| Solar collector | HTF | Power cycle | Largest operational plants (gross capacity) | Comments |
|---|---|---|---|---|
| PT | Water-steam | Steam Rankine | Thai Solar Energy 1 (5 MW) | Limited use of DSG with PT |
| | Molten salt | | Archimede (5 MW) | Salt as HTF and for 8 h storage |
| | Synthetic oil (Most common scenario overall) | | SEGS (354 MW) | The oldest solar thermal utility. The complex consists of 9 stations |
| | | | Mojave Solar Project (280 MW) | Bulk project |
| | | | Solana (280 MW) | Oil as HTF and salt for 6 h storage |
| ST | Water-steam | Steam Rankine | Ivanpah (392 MW) | The largest CSP in the world |
| | Molten salt | | Crescent Dunes (110 MW) | Salt is also used for 10 h storage |
| | Volumetric air | | Jülich Solar Tower (1.5 MW) | With 1.5 h storage using ceramic heat sink |
| PD | Gas (helium, hydrogen or air) or liquid sodium | Stirling engine | Maricopa Solar Project (1.5 MW) | Demonstration project. Currently non-operational |
| | | | Hainan Nanshan Sanya Pilot (1 MW) | Demonstration project |
| LF | Water-steam | Steam Rankine | Dhursar (125 MW) | Largest LF plant in the world |
| | Synthetic oil | | Rende (1 MW each) | Demonstration project |

*Table 4-2: Existing CSP plant scenarios*

In this section, we define the CSP plant scenarios in Saudi Arabia for simulation. They are based on the literature, SWOT analysis outcomes, and CSP projects in other countries. The designed power plant scenarios are located in the capital (i.e., Riyadh). The SAM, which is a tool for renewable energy systems simulations, was utilized to obtain the techno-economic results for the scenario assessments.

Considering the SWOT analysis outcomes and CSP projects in other countries, preferably in the region with similarities to Saudi Arabia or globally otherwise, recommendations were derived to develop alternative scenarios based on benefiting from strengths and opportunities and avoiding weakness and threats. The recommendations were to give more attention to alternatives based on PT technology, which is the most mature, to meet the Saudi requirements during the early stages of commissioning the targeted CSP portfolio. ST alternatives were also considered as potential alternatives to integrate them with long TES to cover the maximum demand difference between the peak load covered by PV technology and the base load [18], as targeted in the Saudi plan. Less focus was given to the LF alternatives, for which commercial verification and technical experience are lacking, while no PD systems were considered due to the absence of operational large-scale power plants. The SWOT results illustrate the high potential for PD systems with advanced R&D; thus, it could be wise to consider this technology for later stages. However, this research was focused on defining potential CSP plant alternatives in the early stages of commissioning the targeted CSP portfolio. Various storage capacities, from no storage up to 12 h of storage, were considered for the evaluation. Molten salt was adopted for TES. It was also adopted as the HTF for the ST alternatives, while synthetic oil was coupled with PT alternative scenarios. DSG was considered for the LF alternative which has no storage. In terms of cooling systems, dry cooling systems were considered for all of the defined alternatives due to the scarcity of water resources in Saudi Arabia.

Three scenarios based on PT systems were developed. In the Arabic region, Shams 1 (100 MW in the UAE) and Noor 1 (170 MW in Morocco) are two major operational PT projects, while Noor 2 (200 MW in Morocco) is under construction. These plants were employed as references for the PT scenarios, with slight changes according to the location characteristics and data availability. Meanwhile, no operational ST plants exist in the Arabic region. Global ST reference plants were thus considered, such as the Ivanpah and Crescent Dunes ST projects in the US with 392 MW and 110 MW installed capacities, respectively. There is also the Khi Solar One project in South Africa with a capacity of 50 MW and several plants in Spain with lower capacities. The existing large-scale operational LF power plants are the Dhursar and Puerto Errado 2 projects in India and Spain, respectively, which have capacities of 125 MW and 30 MW. Finally, there are no existing large-scale operational PD plants since this technology is in the demonstration phase, as mentioned earlier. Hereafter, we define the alternative scenarios for CSP plants in Saudi Arabia, whereas the detailed design parameters are introduced in the following sections. Six alternative scenarios were defined as shown in Table 4–3:

| Scenario | Installed capacity (MW) | CSP collector | HTF | TES (Molten salt) (h) | Cooling system |
|---|---|---|---|---|---|
| 1 | 100 | PT | synthetic oil | No storage | Dry cooling |
| 2 | 170 | | | 3 | |
| 3 | 200 | | | 6 | |
| 4 | 110 | ST | Molten salt | 10 | |
| 5 | 200 | | | 12 | |
| 6 | 125 | LF | DSG | No storage | |

*Table 4-3: Defined alternative scenarios*

### 4.3.3. Design parameters

In this section, the weather, technical, and financial parameters that are common for all of the developed scenarios will be presented and discussed, while the specific parameters definition for each scenario will be presented in Section 4.4.

#### *4.3.3.1. Weather data*

The location of the power plants is the capital city (i.e., Riyadh), which is the most populated city with a DNI that reaches above 9000 $Wh/m^2/day$ [140] and with availability of long-term required weather data. The warm season lasts from May 14 to September 26 with an average daily high temperature above 43 °C, while the shorter cold season lasts from November 29 to February 25 with an average daily high temperature below 24 °C [141].

Over the past years, solar energy companies interested in projects in Saudi Arabia have mostly relied solely upon modeled data. One of the major challenges facing developers and investors interested in solar energy projects in Saudi Arabia is the scarcity of reliable and long-term solar radiation data, which is required for planning [142]. Some temporal and spatial data exist through sources such as the 12 monitoring stations of the King Abdulaziz City for Science and Technology (KACST) between 1998 and 2000; the Solar Wind Energy Resource Assessment; and the NASA Surface Meteorology and Solar Energy data set [142]. These data are available on daily, monthly, or annual bases, whereas the solar industry requires high-time-resolution (hourly) solar radiation data for judicious planning and designing as well as performance estimations. The lack of accurate data is one of the key reasons for solar projects delays in Saudi Arabia. To reduce the associated uncertainty, modeled and measured weather data were investigated and combined in this research for simulation.

A TMY weather file, as introduced by the US Department of Energy (DOE), provides one year of data representing a long-term weather profile, in which each month's measurements are from a different year. The weather data were obtained from two main sources to synthesize a TMY file to be utilized for the simulations. The first source was the hourly modeled data provided by the US DOE through satellite observations [143]. An EPW file (EPW is the extension of the weather files provided by the DOE) was obtained providing weather parameters including DNI, GHI, DHI, wind direction and speed, atmospheric pressure, and ambient temperature. The second source was the measured data provided by K.A.CARE which has 41 measuring stations spread throughout the kingdom. The Saudi Renewable Resource Atlas was launched in 2013 as part of the Renewable Resource Monitoring and Mapping (RRMM) program, with the aim of providing accurate data to guide policy development and reduce the technical and financial risks related to renewable energy projects [126]. The Atlas was created by K.A.CARE alongside the effort to develop a national plan for energy diversification. The data provided by the Atlas facilitated the execution of an enhanced simulation. However, these data are short-term, reflecting the launch date of each station, while the simulation requires long-term data. The measuring stations were categorized under three levels indicating the accuracy and data provided. Table 4–4 illustrates the devices utilized in each category and the associated accuracy.

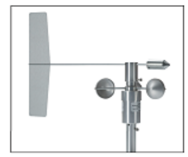
| Parameters | DNI | DNI, GHI, and DHI | Air temperature | Relative humidity | Wind speed | Wind direction | Barometric pressure |
|---|---|---|---|---|---|---|---|
| Measurement equipment | Pyrheliometer | Rotating Shadowband Radiometer | Air Temperature Probe | Relative Humidity Probe | Anemometer | Wind Vane | Barometer |
| Equipment picture |  |  |  | |  | |  |
| Uncertainty | ±2% | ±5% | ±0.6 °C | ± 3–7% | ±1.1% | ±4 deg. | ±1.5 mb |
| Tier 1 | √ | √ | √ | √ | √ | √ | √ |
| Tier 2 | x | √ | √ | √ | √ | √ | √ |
| Tier 3 | x | √ | √ | √ | x | x | √ |

*Table 4-4: Stations categories under the Saudi RRMM program*

Weather data for CSP simulation were obtained through the K.A.CARE Atlas for all locations in the Riyadh range. The data were then synthesized to create 10 single-year data files. Accordingly, a P50/P90 analysis was carried out using SAM. The P50/P90 analysis leverages the availability of several years of historical data by performing multiple simulations based on several weather files and providing the distribution of the results. On the other hand, a TMY file was synthesized using a combination of modeled and measured data to improve the simulation accuracy and avoid overly optimistic results. The confidence intervals were obtained from the P50/P90 analysis, and the outputs were compared with the synthesized TMY file output for a reference scenario. The LCOE based on the synthesized TMY simulation was found to be within the range provided by the Global Status Report of 2015 [5]. Accordingly, the synthesized TMY file combining modeled and measured data was adopted for simulation of the defined alternative scenarios. Alyahya and Irfan [126] compared the weather data measured at two of the K.A.CARE ground stations with that obtained from the US GeoModel solar model based on satellite observations. Their objective was to provide evidence of confidence in the Atlas data to facilitate it become instrumental in establishing solar energy projects in the country. They concluded that the combined DNI uncertainty is approximately ±17%. Figure 4–4 illustrates the hourly DNI breakdown obtained through the TMY synthesized file for Riyadh. It is noticed that the DNI reaches high beam levels in most months of the year, which indicates that adequate levels of energy can be generated throughout the year via solar thermal power generation.

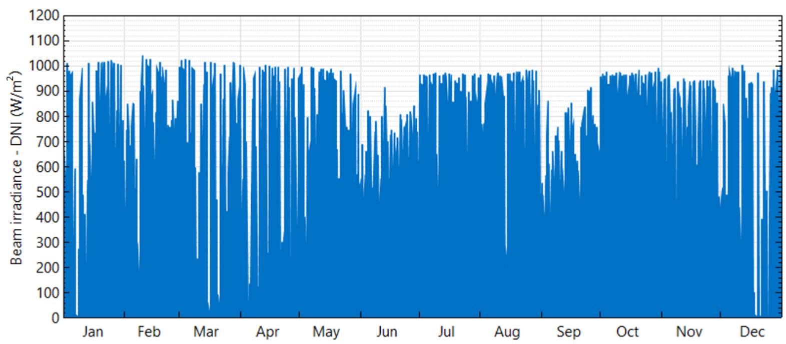



*Figure 4-4: DNI of Riyadh*

#### *4.3.3.2. Technical parameters*

Starting with the solar field size, a parameter defined as the solar multiple (SM) was utilized to express the aperture area of the solar field as a function of the power cycle capacity. The SM is defined as the ratio of the nominal thermal power collected in the solar field to the thermal input of the power block. It essentially differentiates between systems with and without storage [60]. In a system that stores thermal energy during solar radiation availability, the aperture reflective area must be increased compared to that of a system with no storage. Accordingly, the SM is theoretically preferred to be unity for systems without storage, delivering sufficient thermal energy to drive the power cycle at nameplate capacity. The excessive collected thermal energy will be dumped, but it requires initial cost and O&M costs owing to the additional solar collectors; this leads to higher LCOE. On the other hand, the SMs of systems with storage are required to be greater than one so that enough collected energy is available for both the power block and energy storage simultaneously. The increase of the number of storage hours requires higher SM levels up to the optimum value associated with each storage capacity; beyond SM optimum value, the collected thermal capacity will be beyond the capabilities of both the power block and the storage system, whereas extra cost is required for larger solar field. Figure 4–5 illustrates the impacts of the SM and the thermal storage hours on the LCOE, which critically depends on a combination of these values [60]. The LCOE decreases with the increase of SM and number of storage hours, owing to a higher capacity utilization factor, until it reaches an optimum value before increasing again [60]. It is worth noting that the LCOE values shown on the *y*-axis were converted to USD from Indian rupees in the original study. IRENA estimates that the required SM for a system with no storage is 1.1–1.5, which is higher than the theoretical optimal value (i.e., SM = 1), in order to cope with thermal losses of power plants, while plants with storage may have SMs of 3–5 [100].

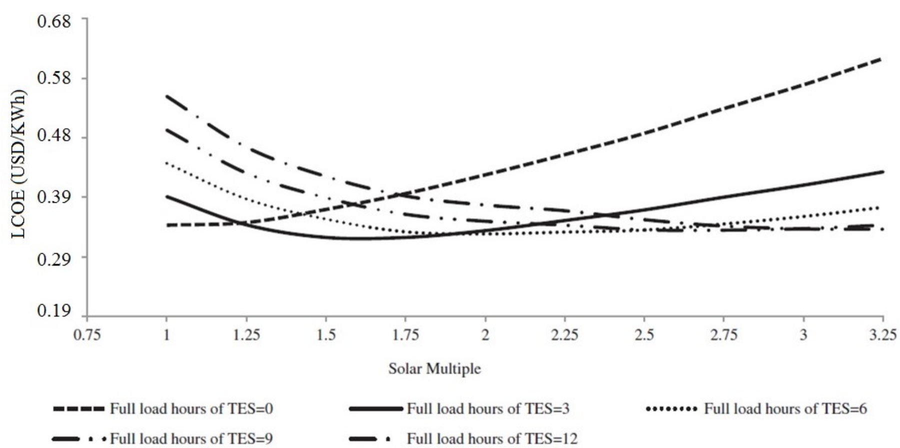



Figure 4-5: Impacts of SM and thermal storage on LCOE
*Source: Sundaray and Kandpal, 2014* [60]

For thermal storage dispatch control, two scenarios provided in the SAM library were investigated: the uniform dispatch and generic summer peak scenarios. The uniform dispatch scenario does not account for the different daily load periods. On the other hand, the generic summer peak scenario considers the peak load periods and directs the thermal storage accordingly to control when the thermal storage is charged or discharged. The time of power delivery is a vital parameter, illustrating the importance of energy storage associated with CSP; it reduces fluctuations and enhances the abilities of CSP systems with storage to cover peak demand after sunset or in cloudy weather. The time of power delivery is not considered in LCOE calculations [57]. Accordingly, although the generic summer model yields slightly lower annual energies, it was selected owing to the value of the energy it provides during high demand. Two peak demand periods occur in Saudi Arabia, both of which are related to the high usage of air conditioners that accounts for 70% of the residential electricity consumption in summer [125]. The first peak occurs around 3:00 pm, and the second occurs around 7:30 pm, according to the data obtained by the National Control Center of the Saudi Electricity Company during the summer of 2015, during which the load demand reached new records [144]. The two peak periods are accounted for in the generic summer peak dispatch control model.

The plant power-cycle capacity of each scenario is included in accordance with the defined scenarios. The estimation of parasitic losses depends on turbine selection. Lemmer [57] conducted market analysis and recommended Siemens turbine model SST-700 [145] as a suitable model for a PT project in Morocco. The same model was also considered by Guzman et al., [59] to simulate a PT facility in Colombia due to its flexibility to energy availability fluctuations and its high efficiency. The SST-700 model benefits from short start-up and shut-down times. It is also widely adopted in CSP plants in the US, Spain, Germany, and North Africa. In addition, several conventional power plants in Saudi Arabia utilize Siemens SST-series models. Subsequently, the estimated gross-to-net conversion factor was defined to be 90%.

#### *4.3.3.3. Financial parameters*

The LCOE was utilized to compare the financial performances of the different power plants and is defined as the ratio of the total life cycle cost of a plant to the amount of electricity produced over the plant's lifetime. The total life cycle cost can be calculated based on financial parameters that are divided into the following categories: direct capital costs, contingencies, O&M costs, and indirect capital costs such as the engineering, procurement, and construction (EPC) costs. The SAM performance model can be employed to calculate the annual energy output, and hence, the LCOE can be obtained. IRENA's renewable energy technologies cost analysis study associated with CSP [132] describes the LCOE formula and the associated parameters [132], [146]:

$$\text{LCOE} = \frac{Total\ lifecycle\ costs}{Produced\ electricity\ over\ life\ time} = \frac{\sum_{t=1}^{n} \ (C_t)\ /\ (1+r)^t}{\sum_{t=1}^{n} \ E_t/\ (1+r)^t} = \frac{\sum_{t=1}^{n} \ (I_t+OM_t+CO_t+S_t)/\ (1+r)^t}{\sum_{t=1}^{n} \ E_t/\ (1+r)^t} \quad (4\text{-}1)$$

where $I_t$ is the amount of investment expenditures in year t, $OM_t$ is the amount of operation and maintenance expenditures in year t, $CO_t$ is the amount of the contingency expenditures in year t, $S_t$ is the salvage value in year t, $E_t$ is the amount of electricity generated in year t, r is the discount rate, and n is the lifetime of the system.

### 4.4. Application of System Advisor Model (SAM)

After presenting the common design parameters associated with the different scenarios in Section 4.3.3, the following sections address the individual characteristics of the developed scenarios.

#### 4.4.1. Parameters of scenarios adopting PT collectors

For scenarios based on PTs, synthetic oil is the most commonly used as the HTF, as indicated in Table 4–2. PT systems using synthetic oil were compared with those using molten salt and DSG as the HTF, which are not employed in any operating PT power plant with a capacity of more than 9 MW. Therminol VP-1 is an ultra-high-temperature synthetic HTF that has been utilized in the majority of large PT power plants, and it was selected in this study for use in the PT scenarios [101].

Several types of solar collector assemblies (SCA) are commercially available since PT collectors are the most used collectors in CSP plants [79], [147]. These include the Luz (LS-1, LS-2, and LS-3), Abengoa (E2 and Astro), EuroTrough (ET150), Sener (SenerTrough), and Flagsol TSK (SKAL-ET and HelioTrough), models, among others. Some of these models are manufactured by solar thermal power plant developers who utilize their own collectors when commissioning CSP projects; for instance, Luz employed LS-1, LS-2, and LS-3 models in the SEGS complex, and Abengoa has utilized the E2 and Astro models in many projects, such as the Mojave Solar project in the US [101]. The Astro and ET150 models are based on the EuroTrough collectors with a central torque boxes design, which is considered to be an improvement on the Luz collectors. ET150 model is low-cost, easily installable, has rigid structure, and has high optical performance [59]. In addition, EuroTrough collectors benefit from reduced weights with proven performances [3], [148]. EuroTrough collectors are used in many projects in Spain (e.g., the 150 MW Solnova project), the US (e.g., the Solaben project), and India (e.g., the Gujarat Solar One project) [57], [101]. In the Arab world, EuroTrough collectors are used in the 20 MW ISCC Ain Beni Mathar project in Morocco, the 20 MW ISCC Kuraymat project in Egypt, and the 100 MW Shams 1 project. Shams 1 is the largest CSP plant on the Arabian Peninsula. It is located in Abu Dhabi, which is within 600 miles of Riyadh and is quite similar to Riyadh in terms of weather conditions. The EuroTrough ET150 model was subsequently selected for the PT scenarios.

A Schott PTR70 was chosen as the heat-collecting element (HCE) since it provides the required stable performance and robustness as well as low heat loss to improve efficiency. Guzman et al., [59] compared the receivers most commonly employed in the construction of CSP plants based on PT technology. They noted that the differences between the receivers were minimal and concluded with the selection of the Schott PTR70 model. Schott is the leading manufacturer of solar receiver tubes, and the PTR70 model is by far the most commonly used in major CSP plants such as the Mojave Solar project in the US, Andasol in Spain, and Shams 1 in the UAE [7], [101].;

The installed costs of CSP projects in general ranged from 3550 USD/kW to 11,311 USD/kW in 2013 and 2014 according to a comprehensive study concerning renewable power generation costs released by IRENA in 2014 [79], The significant variation originated mainly from the different plant capacities and thermal storage levels. In addition, the installed cost variation was influenced to a lesser extent by the differences between the cost structures in different countries. The financial parameters estimations differ for each of the scenarios. IRENA's study presents a thorough bottom-up engineering estimates of PT and ST projects costs based on the available literature. The traditional top-down learning curve analysis requires many data points to provide reliable results, whereas large-scale CSP is considered to be in the infancy of its deployment [79]. Bottom-up engineering evaluation is suitable for early-stage planning of technologies with limited operational projects data on which to base the calculations [58]. Accordingly, for the PT and ST scenarios, the total installed cost estimates and breakdowns, as well as the O&M costs, were mainly obtained for the defined scenarios from IRENA's study. For the PT scenarios, the installed capacities of the projects with no storage ranged from 4950 USD/kW to 7688 USD/kW, whereas the range was from 7936 USD/kW to 10,552 USD/kW for projects with storage systems. IRENA's study notes the scarcity of publicly available O&M cost data for recent CSP plants. However, a detailed assessment of the O&M costs of the SEGS plant led to the estimation of the O&M costs as being 0.02–0.04 USD/kWh, including fixed and variable costs. The cost was found to decrease with increasing installed capacity and storage level. The O&M costs when shifting the capacity from 50 MW to 100 MW appeared to offer a 7% reduction for PT plants and a 5% reduction for ST plants as a result of the economies of scale, whereas the installed cost reduction was found to be 10% for both technologies [79].

### 4.4.2. Parameters of scenarios adopting ST systems

ST systems utilize molten salts highly efficiently [149], [150], which is reflected by the existence of several large-scale operational, under-construction, and under-development molten salt ST facilities globally. In this approach, molten salt is adopted both as an HTF and for TES, which reduces thermal losses. It is heated in the tower receiver and directly stored in a hot tank. Accordingly, the defined ST scenarios in this study addressed the advantage of utilizing molten salt through two designs incorporating high storage capacities, which enhances the capacity factors [149].

The Solar Two plant was the first demonstration project to adopt 10 h of storage together with ST technology. The demonstration of this plant was conducted in the US between 1996 and 1999 [149], [150]. The project facilitated the reduction of the economic and technical risks of ST systems with nitrate salt for long thermal storage and stimulated this combination commercialization [151]. After successful demonstration, the Solar Tres project (later renamed Gemasolar) was developed in Spain and was the first operable commercial CSP plant capable of producing electricity for 15 h without solar radiation using the proven molten salt technology of the Solar Two plant together with increased installed and storage capacities [136], [150].

For solar receivers, there are two possible configurations: external cylindrical receives and cavity receivers. The external configuration includes a fully exposed cylindrical surface consisting of a number of individual panels arranged in a vertical cylinder at the top of the tower. The receiver in this configuration is exposed to the ambient weather conditions, and the heliostats are arranged circularly around the tower. In the second configuration, the receiver is situated inside a cavity, which offers the receiver more protection and also consists of multiple panels [139]. While each configuration has its merits and drawbacks, the external cylindrical configuration is often adopted since it is easier to design, operate, and repair, among other reasons [152]. Furthermore, external receivers can accommodate larger heliostat fields circumferentially surrounding the towers, whereas the cavity receivers have geometric limitations that require their heliostat fields to be situated entirely on the northern side of the towers [139]. Garg [152] stated that external receivers might be preferable, which is consistent with them being more frequently adopted than cavity receivers, including in several large-scale operational ST plants such as Gemasolar and Crescent Dunes.

Unlike other CSP technologies, ST systems require the solar rays reflected by their heliostats to travel significant distances (1 km or more) before reaching the receivers mounted to their towers. These extensive travel distances require adequate and precise field layouts to minimize the optical losses [139]; meanwhile, other technologies can be based on modular designs of individual components, as discussed in relation to the PT scenarios [146]. The required field precision increases the capital costs of the heliostat fields of ST plants, which represent 30–40% of the total capital cost of such plants [139]. Consequently, ST systems typically require solar field geometry optimization to ensure that their heliostat field layouts, receiver heights and diameters, and tower heights are optimized. These optimal values were obtained for the defined scenarios by using SAM's embedded optimization algorithm to meet the specified thermal point requirements of the power block and SM. Figure 4–6 illustrates the heliostat field layouts of scenarios 4 and 5.

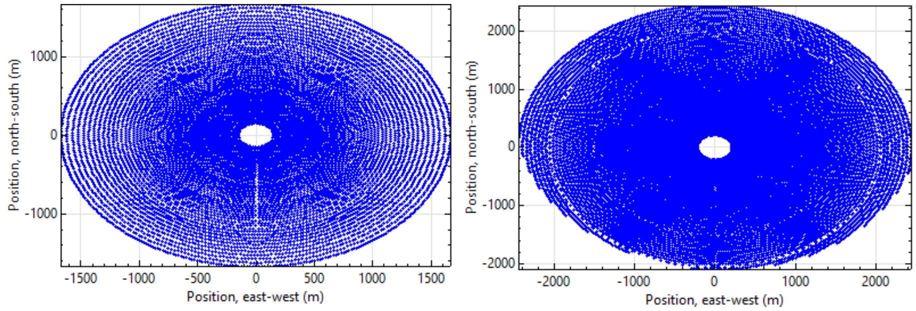



*Figure 4-6: Heliostat field layouts of scenario 4 (left), and scenario 5 (right)*

IRENA's study mentioned the scarcity of publicly available data on the installed costs of ST systems, which is associated with the short periods that large-scale ST plants have been operated. Nonetheless, IRENA's study provided cost estimates of different molten salt ST configurations according to bottom-up engineering analysis based on the available literature. Thus, the installed costs of ST projects using molten salt were found to range from 7825 USD/kW to 11,311 USD/kW, where the variations mainly originated from the differences between the storage levels and SMs of the different systems. Compared to PT systems, ST systems involve lower storage costs due to the improved efficiencies that result from their higher operating temperatures [79].

### 4.4.3. Parameters of scenarios adopting LF collectors

LF facilities are less complex and have lower costs than other types of CSP plants, with the tradeoff of lower efficiencies. LF systems are gaining more attention, although most of the existing plants are pilot projects. There are only two operational commercial LF plants, which are in India and Spain (i.e., Dhursar and Puerto Errado 2) and have installed capacities of 120 MW and 30 MW, respectively. It is important to note that the scarcity of large-scale reference operating projects leads to higher uncertainties. However, one LF scenario was simulated to exploit the obtained local weather data to generate an overview of the potential results. There is ongoing R&D associated with enhancing the efficiencies of LF systems so that they will become more competitive with the other technologies.

The steam flow in the solar field of an LF system may have a recirculated or once-through configuration. In the recirculated boiler configuration, the liquid phase is removed from the water-steam mixture exiting the boiler by a separator. The liquid is then recirculated back to the boiler inlet, and the saturated vapor is sent to the superheater and then to the turbine [153]. This configuration ensures consistent heat transfer from the absorber to the fluid, which prevents the tube walls from overheating [154], and is used in most current steam generator designs. The once-through configuration, on the other hand, involves a newer concept in which the water is heated to superheated steam in a single pass through the loop. This design does not require a steam separator, a recirculation pump, or transport equipment. However, the once-through configuration is still in the demonstration phase and has not been commercially adopted. There are concerns about the heat transfer stability and control complexity [154]. The recirculated boiler configuration was therefore selected in this scenario.

Zhu et al., [155] conducted a study of the history, current state, and future of LF technology in which they presented cost estimates of a state-of-the-art LF project. The estimates of the total installed costs and breakdowns for the LF scenarios defined in this study were based on their results. One of the main reasons to introduce LF technology is to reduce the cost, particularly that of the solar field; this effect can be observed by comparing this scenario with the PT scenario that has no storage. The SM increases compared to PT as a result of the decreased optical efficiency [153], [155]. Figure 4–7 illustrates the installed costs of several major CSP projects together with their gross capacities and storage hours based on data obtained from NREL [101]. The presented projects are from different countries, including the US, Spain, South Africa, Morocco, and the UAE. The ST projects have high levels of storage. Their high storage levels are not associated with significant installed cost increases since ST systems also have high operating temperatures, which enhance their efficiencies, increase their capacity factors, and decrease their thermal storage costs. Tables 4–5 and 4–6 summarize the technical and financial design parameters of the defined scenarios that were used in the SAM simulations. Parametric analyses were applied to evaluate the SMs for all of the scenarios to measure the impacts on the LCOEs; this ensured that optimal SM values were adopted for each scenario.

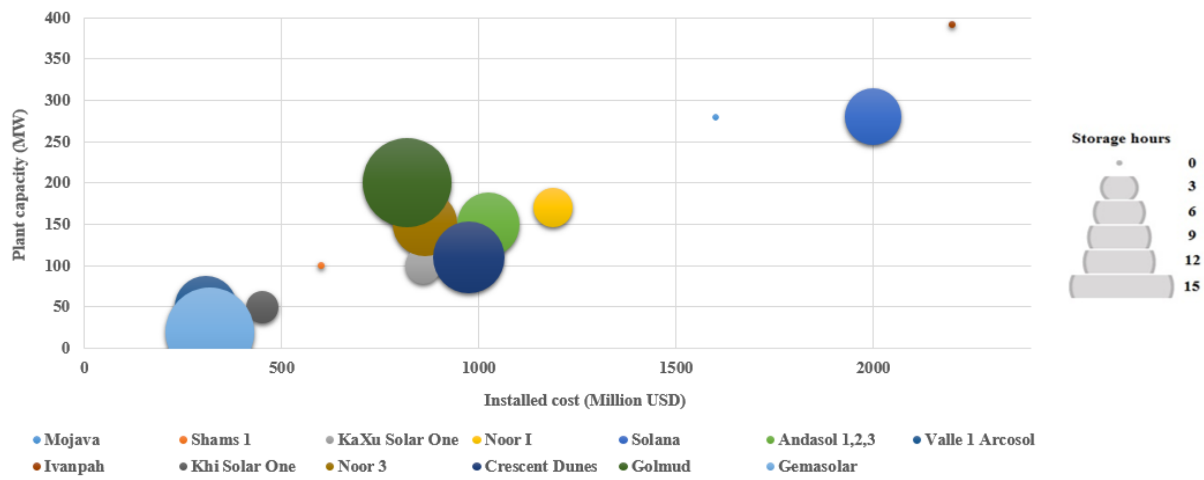



*Figure 4-7: Installed costs, gross capacities, and storage hours of major PT and ST projects*

| | Parabolic Trough | | | | | |
|---|---|---|---|---|---|---|
| | Scenario 1 | | Scenario 2 | | Scenario 3 | |
| Technical parameters | | | | | | |
| SM | 1.3 | | 1.7 | | 2.3 | |
| SCA | EuroTrough | | EuroTrough | | EuroTrough | |
| HCE | Schott PTR70 | | Schott PTR70 | | Schott PTR70 | |
| Plant gross capacity (MW) | 100 | | 170 | | 200 | |
| Cooling system | Dry cooling | | Dry cooling | | Dry cooling | |
| Thermal storage (h) | N/A | | 3 | | 6 | |
| Financial parameters | | | | | | |
| | Share (%) | Million USD | Share (%) | Million USD | Share (%) | Million USD |
| Site improvement | 5 | 25 | 4 | 53 | 3 | 58 |
| Solar field | 53 | 262 | 44 | 590 | 39 | 733 |
| HTF system | 9 | 45 | 10 | 134 | 12 | 217 |
| Storage | N/A | 0 | 9 | 107 | 16 | 310 |
| Power block | 20 | 99 | 21 | 249 | 14 | 258 |
| Indirect costs (EPC, contingencies, etc.) | 13 | 64 | 12 | 157 | 16 | 302 |
| Total estimated installed cost | 100 | 495 | 100 | 1290 | 100 | 1878 |
| | | | | | | |
| Cost in USD/kW | 4950 | | 7588 | | 9390 | |
| Reference plant | Shams 1 | | Noor 1 | | Noor 2 | |

*Table 4-5: Technical and financial modeling parameters for PT scenarios*

| | Solar Tower | | | | Linear Fresnel | |
|---|---|---|---|---|---|---|
| | Scenario 4 | | Scenario 5 | | Scenario 6 | |
| Technical parameters | | | | | | |
| SM | 2.9 | | 3 | | 1.9 | |
| Tower height (m) | 200 | | 287.6 | | N/A | |
| Receiver height (m) | 22.8 | | 23.8 | | N/A | |
| Receiver diameter (m) | 19.2 | | 37.9 | | N/A | |
| Plant gross capacity (MW) | 110 | | 200 | | 125 | |
| Cooling system | Dry cooling | | Dry cooling | | Dry cooling | |
| Thermal storage (h) | 10 | | 12 | | N/A | |
| Financial parameters | | | | | | |
| | Share (%) | Million USD | Share (%) | Million USD | Share (%) | Million USD |
| Site improvement | 3 | 32 | 3 | 58 | 5 | 20 |
| Solar field | 32 | 305 | 34 | 662 | 41 | 184 |
| HTF system | 17 | 158 | 17 | 331 | 8 | 36 |
| Storage | 8 | 70 | 9 | 175 | N/A | 0 |
| Power block | 15 | 139 | 18 | 351 | 27 | 118 |
| Indirect costs (EPC, contingencies, etc.) | 25 | 237 | 19 | 371 | 19 | 86 |
| Total estimated installed cost | 100 | 941 | 100 | 1948 | 100 | 444 |
| | | | | | | |
| Cost /kW | 8555 | | 9740 | | 3552 | |
| Reference plant | Crescent Dunes | | Golmud & Dubai solar | | Dhursar | |

*Table 4-6: Technical and financial modeling parameters for ST and LF scenarios*

### 4.5. Results and discussion

To evaluate the simulation results obtained using the different scenarios and compare them with each other, several performance and financial parameters, including the annual energy outputs, LCOEs, capacity factors, and initial costs, are discussed herein.

The capacity factor is defined as the ratio of the actual output of a power plant during a certain period to the potential output of the plant during the same period. Higher capacity factors enhance grid support, especially considering power availability during peak times. Table 4–7 lists the capacity factors and annual energy outputs for the first year in each of the proposed scenarios. The capacity factors obtained from the simulation are in agreement with the capacity factor ranges of CSP technologies that were provided by IRENA following the 2014 renewable power generation cost study [79], which are illustrated in Figure 4–8. Since the scenarios have different capabilities in terms of their gross and storage capacities as well as their SMs, their capacity factors and annual energy outputs cannot be compared directly, as will be discussed later in this section.

| Scenario | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Capacity factor (%) | 22.4 | 30 | 39.9 | 59.5 | 64.1 | 27.1 |
| Annual energy output (GWh) | 176.2 | 402.7 | 629.8 | 515.9 | 1010.9 | 266.7 |

*Table 4-7: Capacity factors and annual energy outputs for the first year for the simulated scenarios*

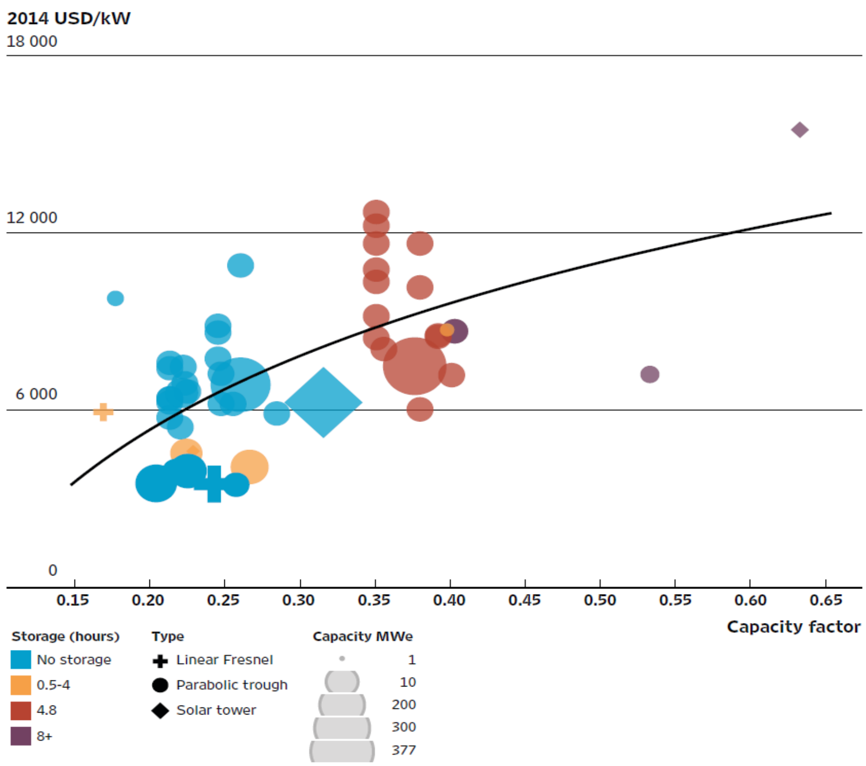



*Figure 4-8: CSP project capacity factors and installed costs based on thermal storage*
*Source: Taylor et al., 2014* [79]

Higher storage levels and SMs lead to higher capacity factors by enabling the plants' storage systems to provide electricity for longer periods and allowing for more radiation to be collected through the larger solar apertures. The tendencies of the capacity factors and annual energy output follow those of the installed capacity and storage level. This increase in capacity factors, however, comes with the compromise of higher costs for storage system and solar field. Accordingly, for comparison purposes, an index (the capacity factor per initial cost index, CFI) was defined as the ratio of the capacity factor during the first year to the initial cost of the plant;

the CFIs for the investigated scenarios are shown in Figure 4–9 The CFI represents the capacity factor per dollar and therefore indicates the ability of each technology combination in the defined scenarios to achieve a high capacity factor.

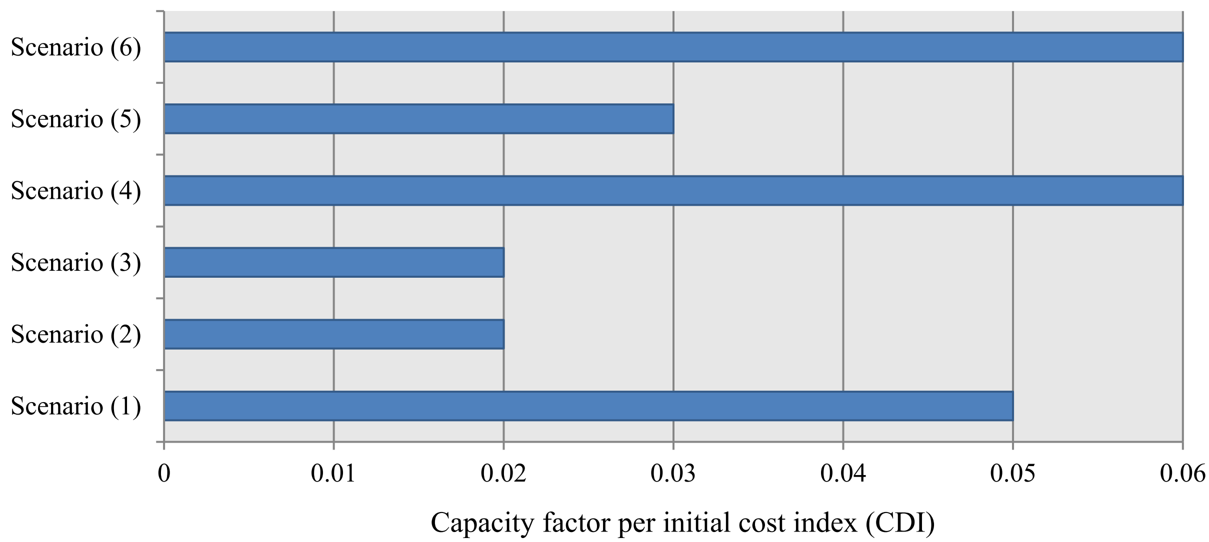



*Figure 4-9: Capacity factors during the first year per dollar invested*

Scenario 5 achieved the highest capacity factor, as shown in Table 4–7, since it had the highest combination of gross capacity and number of storage hours. However, considering the initial cost, scenarios 4 and 6 appear to achieve the highest capacity factors per dollar invested. This result reflects the vital merit of the low cost of thermal storage using molten salt coupled with ST technology, which helped scenario 4 achieve a high CFI. It also indicates the importance of optimizing the plant capacity and number of storage hours during the advanced stages of planning once the technologies to be employed have been selected. The CFI also reflects the importance of the reduced investment cost of LF technology and supports the high potential of LF technology following enhancements to its efficiency, thermal storage, and economies of scale as it becomes more widely adopted around the world. Scenarios 2 and 3 yielded acceptable capacity factors, higher than those of the LF scenarios, but low CFIs, which indicates considerably high initial costs for thermal storage incorporated with PT collectors relative to the gained increases in the plants' capacity factor.

The annual energy outputs are presented in Figure 4–10 by considering the net capacity of each scenario. This indicator reflects the capability of each kilowatt of installed capacity to generate energy throughout the year. It is important to consider the advantage of longer generation hours for systems with storage, which leads to greater annual energy output per unit of capacity.

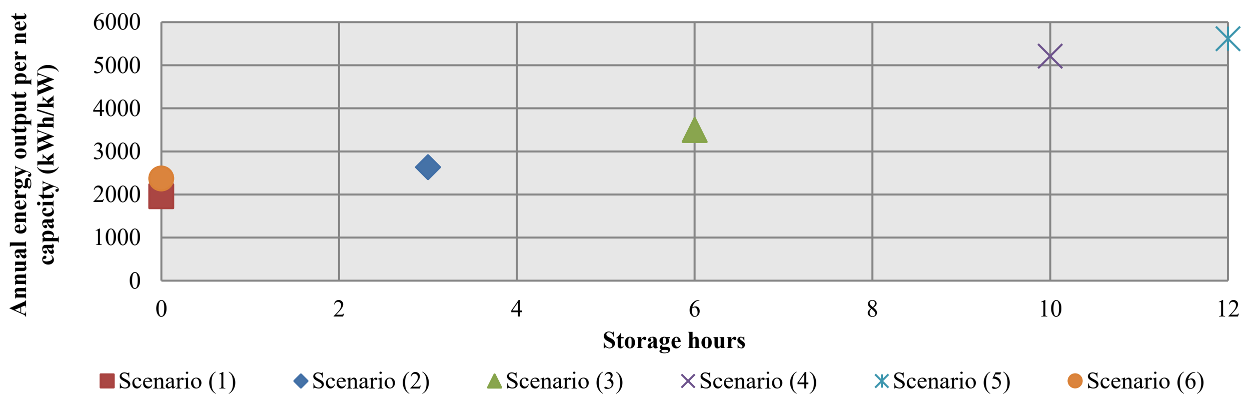



*Figure 4-10: Annual energy outputs per net capacity based on storage hours*

The scenarios with no storage yielded similar annual energy outputs per net capacity. However, the LF scenario generated a slightly higher amount of energy per kilowatt, which is significant considering that LF technology benefits from reduced costs at the expense of an optical efficiency that is lower than those of the other collection technologies. On the other hand, the tendency observed in the results for the scenarios with storage is as expected: increased storage corresponds to greater annual energy output per unit of capacity, this increase becomes more significant as the storage level increases. To determine the extent to which each additional storage hour in the simulated scenarios increased the annual energy output per net capacity, the value of this quantity for the LF scenario without storage was used as a reference. Accordingly, the percentage increases per storage hour were found to be 3.7%, 7.9%, 12%, and 11.4% for scenarios 2, 3, 4, and 5, respectively. This tendency reflects the fact that the increase in the annual energy output becomes greater toward the higher end of the proposed storage capacities and it maximizes at the 10 h storage level.

An essential indicator for the proposed scenarios is the LCOE, which reflects both the energy generated and the expenditures incurred over the lifetime of a power plant. Figure 4–11 shows the LCOEs for all of the scenarios. The LF scenario achieved the lowest cost, followed closely by scenarios 4 and 5, which were based on ST technology. The LF scenario has the advantage of low investment cost, which led to its low LCOE, whereas the ST scenarios have the merits of storage systems, which facilitated their achievement of low LCOEs. Further benefits of the ST scenarios are the ability to provide valuable power to cover peak periods and base load through storage as well as enhanced system stability, both of which are highly advantageous. These factors are not reflected by the LCOEs but necessary to be involved throughout the decision-making process along with all of the other factors that are important to stakeholders. The scenarios including PT collectors yielded higher LCOEs since they involved storage levels lower than those of the ST scenarios and installed costs higher than that of the LF scenario. Scenarios 1 and 3 achieved similar LCOEs, yet again one with the ability to generate electricity in the absence of solar radiation with the compromise of higher initial expenditures. Thus, the priorities should be determined according to stakeholders' preferences.

The obtained LCOEs were compared with those presented in the 2015 Global Status Report for validation [5]. Table 4–8 lists the global LCOE intervals presented in that report. The results shown in Figure 4–11 are mostly in agreement with these intervals, which indicates the accuracy of the simulations conducted in this study. The LCOEs of the PT scenarios are in the lower halves of the intervals for systems with and without storage, which reflects the fact that the accepted design led to moderate results. For the ST scenarios, the results are closer to the higher ends of the intervals (i.e., for systems with storage) because of the additional costs related to the storage systems and solar fields. For the LF scenario, the LCOE is slightly lower than the interval. This result is a positive indicator for LF technology and suggests that the high DNI in Saudi Arabia can compensate for the reduced optical efficiencies of LF collectors.

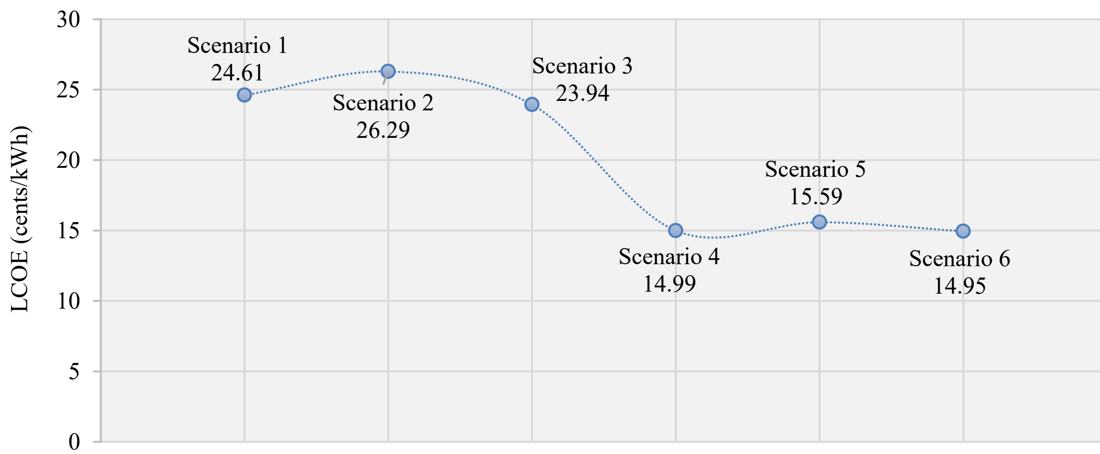



*Figure 4-11: Levelized costs of energy*

| Collecting technology | LCOE (cents/kWh) | |
|---|---|---|
| PT and LF | No storage: 19–38 | 6 h of storage: 17–37 |
| ST | 12.5–16.4 (high end of range is with storage) | |

*Table 4-8: Levelized costs of energy of CSP technologies*
*Source: Swin et al., 2015 [5]*

- **Sensitivity analysis**

Sensitivity analysis was performed to evaluate the impacts of the financial and weather inputs on the simulation results. The analysis was conducted using the parametric and macros tools in SAM. An uncertainty margin of 10% was considered for the main financial parameter estimations. The costs of the solar fields, HTFs, storage systems, and power blocks were assessed with ±10% uncertainty, and the LCOEs were observed.

Figure 4–12 presents tornado charts showing the influences of the uncertainties of the main financial parameters on the LCOEs. The left chart is associated with scenario 2, representing the

PT and LF scenarios. The uncertainty in the solar field cost has the highest impact on the LCOE since the solar field is the most expensive part of a plant. The tendency of uncertainty influence for the PT and LF scenarios reasonably corresponds to the breakdown percentage of the power plant parts costs, except for scenario 3 in which the storage level was increased and became in a greater influence. The right-hand chart in Figure 4–12 corresponds to scenario 4 representing ST scenarios. In the ST scenarios, the storage levels are high, again causing the storage cost to be the most influential parameter. Overall, in systems with more storage, the storage system cost uncertainty more strongly affects the LCOE. It is important to note, however, that the solar field costs of ST systems are divided into heliostat field, tower, and receiver costs and that if these values were added together, they would have a greater impact.

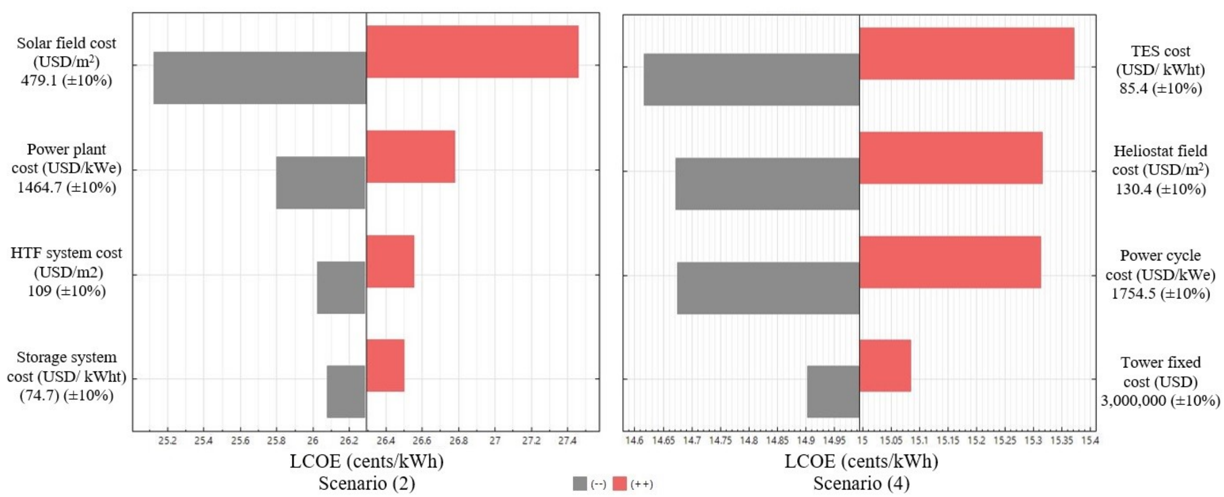



*Figure 4-12: Influences of financial parameter uncertainties on LCOEs*

To address the sensitivity to weather conditions, the ±17% DNI uncertainty that was calculated by Alyahya and Irfan [126] by combining modeled data with those measured by the measuring stations of the RRMM program in Saudi Arabia was employed. The TMY weather file was modified to account for the ±17% uncertainty, and three runs were conducted for each scenario. Accordingly, the impacts of this uncertainty on the annual energies, capacity factors, and LCOEs were assessed. Figure 4–13 depicts the monthly energy outputs of the three runs, which were performed using scenario 3, while the results for all of the scenarios are listed in Table 4–9.

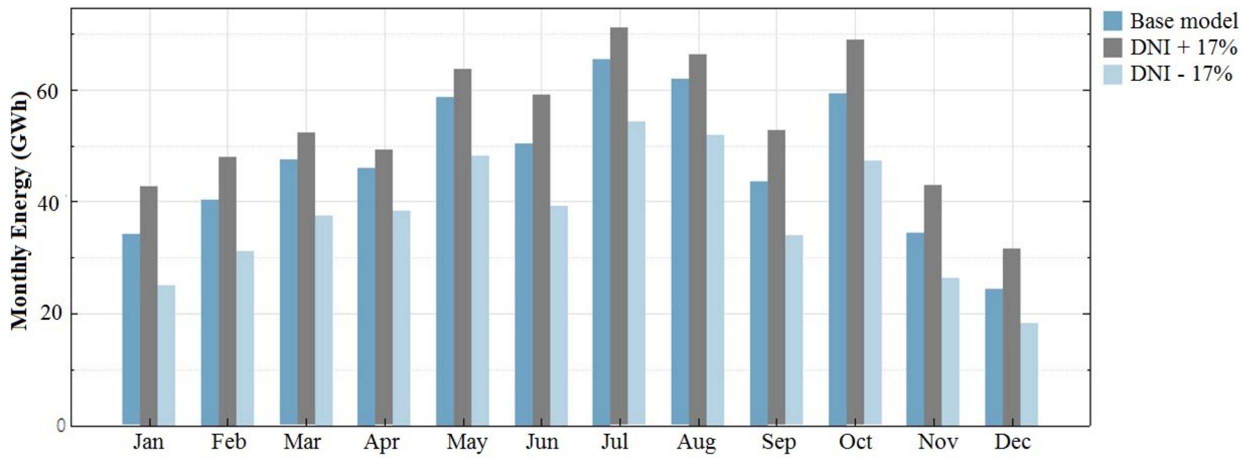



*Figure 4-13: Monthly energy outputs in base model, DNI +17 % model, and DNI –17% model of scenario 3*

As shown in Figure 4–13, the peak generation occurs between May and October, i.e., during the summer, when the solar radiation is high. The impact of the DNI uncertainty is reflected by the monthly energy output, where a higher DNI results in a higher output, and vice versa. However, the impact of a higher DNI is less than that of a lower DNI, especially in the hottest months. Considering August for instance, the energy output improvement resulting from the DNI increase of 17% compared to reference model is less than the energy output difference between the reference model and the DNI –17% model.

| Scenario | | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|
| Capacity factor (%) | Reference model | 22.4 | 26.5 | 35.9 | 51.3 | 64.1 | 25.3 |
| Variation from reference model (%) | DNI +17% | +13 | +16 | +14 | +18 | +10 | +11 |
| | DNI -17% | –18 | –20 | –20 | –22 | –20 | –16 |
| LCOE (cents/kWh) | Reference model | 24.61 | 27.68 | 24.6 | 16.31 | 15.59 | 15.07 |
| Variation from reference model (%) | DNI +17% | –12 | –13 | –13 | –14 | –9 | –10 |
| | DNI -17% | +21 | +24 | +25 | +27 | +25 | +19 |

*Table 4-9: Influences of the DNI uncertainty on the capacity factors and LCOEs*

Table 4–9 shows the impact of the DNI uncertainty on the capacity factors and LCOEs. An increase in the DNI increases the capacity factors and decreases the LCOEs, and vice versa. In general, again, the impact of a DNI decrease is greater than that of a DNI increase. This characteristic could result from the fact that higher temperatures affect systems efficiencies, causing less output enhancement. The annual energy outputs of all of the scenarios follow the same trend as their capacity factors. For the capacity factors and LCOEs, scenario 4 exhibits the greatest variations, which reflects the fact that the DNI level strongly affects ST systems due to the long travel distance between the heliostats and the receiver. Scenario 5 is less influenced by DNI variations, which may result from its higher storage level and higher SM. Scenario 6, meanwhile, shows the smallest capacity factor variations due to low optical efficiency of LF collectors which causes them to be less influenced by DNI variations. The impacts on the PT scenarios' capacity factors are moderate compared to those on the other scenarios' capacity factors. Finally, the LCOEs variations of the PT scenarios increase with higher installed capacities and storage levels.

### 4.6. Conclusions and implications

CSP has considerable potential to support the national grids in several developing countries that are exposed to high solar radiation levels. CSP plants come with a variety of available technologies, including solar thermal collectors, HTFs, storage levels, and installed capacities. In addition, solar energy companies that are interested in projects deployment in developing countries face challenges due to the lack of adequate long-term local solar data. Comprehensive assessment of the CSP technologies available for large-scale plants together with thorough knowledge of local energy sector requirements and weather conditions is therefore essential.

Such analysis can facilitate judicious decision-making by the planning bodies during the critical early stages of CSP development.

In this study, the SWOT of the CSP technologies usable in large-scale power plants were analyzed. The analysis results provide an overview of the features of the available CSP collection technologies, HTFs and storage systems, and cooling methods. Ample consideration was given to the characteristics of Saudi Arabia, such as its arid climate and abundance of land. The analysis outcomes were then obtained by taking the Saudi sector requirements and weather conditions into account. Furthermore, the technology combinations used in large-scale power plants worldwide, along with the available operational plants using each type of technology, were overviewed. Six potential CSP plant scenarios were defined based on the outcomes of this investigation, as well as the regionally and globally available CSP plants, for performance and financial analysis. The defined scenarios included three scenarios adopting PT collectors with different installed capacities and storage levels ranging from no storage to 6 h of storage and using synthetic oil as an HTF and molten salt as storage medium. In addition, two scenarios were defined in which ST technology was adopted with molten salt as an HTF and storage medium. These scenarios differed in their installed capacities and storage levels. Finally, one scenario was defined in which LF collection technology was adopted together with a DSG and no storage. In addition, it was decided not to define any scenarios using PD collectors at such early stages of renewable energy integration in Saudi Arabia because there are no large-scale operational PD facilities for reference.

To obtain sufficiently high time resolution and long-term weather profile, modeled and measured data were combined. The modeled data were obtained through satellites observations, while the measured data were obtained from local measuring stations in Riyadh through the

Saudi Renewable Resource Atlas. Subsequently, the technical and financial design parameters of the six scenarios were defined and simulations were performed. The technical parameters and cost estimations for the defined scenarios were thereafter derived from the literature and the IRENA study of renewable energy generation costs to calculate the financial parameters.

The capacity factors and annual energy outputs of the different scenarios increased as their storage levels and installed capacities increased. However, these advantages came at the expense of higher expenditures. The priorities should be therefore determined according to stakeholders' preferences during the decision-making process. The ratios of the capacity factors to the initial costs illustrated the high performances of the ST scenario with 10 h of storage and the LF scenario. The PT scenario with no storage, on the other hand, achieved a high capacity factor per dollar. Considering the annual energy output per net capacity, the LF scenario achieved a slightly higher level than the PT scenario without storage. This higher annual energy output per net capacity is an advantage of LF technology, which, on the other hand, still lacks operational projects with storage capacities. For the scenarios with storage, the annual energy output per net capacity increased with increasing storage level, this increase was more sensitive at higher storage levels. In terms of LCOE, the reduced expenditures associated with the LF scenario enabled it to achieve the lowest LCOE, followed closely by the ST scenarios because of their high levels of incorporated thermal storage. The PT scenarios achieved higher LCOEs, yet these were within the expected global intervals. The PT scenario that included 3 h of storage achieved a higher LCOE, whereas storage level increases beyond 3 h reduced the LCOE, and still higher storage levels are expected to decrease the LCOE further. Sensitivity analysis illustrated that the solar field and power block costs more strongly influenced the LCOEs of the PT and LF scenarios than the storage and HTF system costs did. In addition, the DNI uncertainty caused 9–

27% variations in the capacity factors and LCOEs. Overall, the simulations yielded outputs consistent with the data available in the literature.

The proposed scenarios will be advantageous for focusing the decision-making process during the early stages of CSP planning on practical scenarios capable of achieving competitive results. The methodology employed in this study could easily be adopted to other developing countries to define alternative scenarios based on their local weather conditions and energy sector requirements. The facts that large-scale plants using CSP technology are in their infancy and that there is a lack of experience in many developing countries in commissioning solar projects contribute to the uncertainty involved in energy projects. Therefore, such a structured methodology could facilitate energy portfolio planning.

The results of this research will help stakeholders develop roadmaps for CSP integration into national grids to support sustainability. In various developing countries, the state still owns the power plants. Consequently, it is vital to consider the fact that the scope for adopting renewable energy does not depend only upon technical and economic aspects. Rather, renewable energy adoption represents a segment of the future energy portfolio in consideration of sustainability goals including environmental condition improvement, societal prosperity, and political independence. Therefore, the outcomes of this research could be incorporated with all of the relevant criteria to prioritize the alternatives.

# Chapter 5: A Fuzzy Multi-Criteria Decision-Making Model for Assessing Concentrated Solar Thermal Power Alternatives in Developing Countries

## 5.1. Introduction

The planning for energy power plants is a complex process. Such projects are commonly classified under national development requirements that involve significant associated parameters, stakeholders, investments, and influenced consumers. In addition, RESs integration to national grids is a vital process facing tremendous challenges and unforeseen obstacles [22]. These projects require large amounts of capital, which is particularly critical for developing countries where it may be deviated from other development projects supporting the prosperity of society. Consequently, it is essential to carefully plan these plant projects and to assure that all relevant parameters and interests of stakeholders are addressed.

Consideration of all relevant criteria for assessment requires looking beyond the fundamentally important techno-economic aspects. The planning thus considers a large number of potentially conflicting parameters and stakeholders. Hence, an optimized solution that performs best in all aspects is practically not possible; instead, multi-criteria decision-making (MCDM) methods identify prioritized solutions. A key advantage of the MCDM methods is that they can evaluate several alternatives with consideration to various criteria that have different units. Traditional decision aiding methods, on the other hand, require the conversion of all criteria into a unified unit, such as monetary values.

As a value added to the literature, this study aimed to set a foundation for assessing practical alternatives for CSP plant technologies and deployment in developing countries. An evaluation of various CSP alternative scenarios was performed through applying MCDM in a fuzzy environment. Utilizing MCDM with fuzzy analytics overcomes associated uncertainty. The complexity of energy projects stems from multiple parameter and stakeholder involvement where the uncertainty and subjectivity cannot be reduced to zero. This study focused on potential developing countries where the lack of experience and sufficient data add uncertainties. The assessment process of this research considered a significant number of evaluation parameters. In relation to the assessed alternatives, instead of focusing only on the collection technologies, the study carried out an assessment of scenario-based alternatives. The research helps planners in developing countries focus on assessing practical solutions and enables them to identify CSP technologies and configurations that better promote sustainable development based on local requirements.

The remainder of this study is organized as follows: Section 5.2 introduces a background for CSP evaluation through developing a fuzzy analytic hierarchy process (FAHP) model. Section 5.3 presents the proposed methodological approach to the CSP evaluation. Section 5.4 illustrates a case study to validate the model which incorporates quantitative and qualitative data for assessing alternatives performances in accordance with the assessing parameters. Section 5.5 presents the results and interpretations, and Section 5.6 concludes the study.

### 5.2. CSP assessment background

There are several available MCDM methods for evaluation. No method is best suited for all problems, and each of them has its benefits and drawbacks. AHP was adopted in this research owing to its several features which are particularly suitable for CSP plants planning problem. First, AHP breaks down complex problems in a hierarchal manner to simplify the decision-making process. In our case, four-level hierarchy was constructed, and will be discussed in detail in Section 5.4. Second, AHP sets a baseline for the computational requirements of the quantitative data as well as the qualitative and intangible parameters involved; it provides the mathematical capability to integrate such inputs into one matrix to reach the final solution. Third, AHP includes a unique check which allows screen out inconsistent values in stakeholder inputs and helps in reaching accurate outputs. The decision criteria and sub-criteria weighting depends on stakeholders' interests associated with the energy sector and user requirements. AHP uses a crisp numerical scale, but it has been criticized in the literature for its inability to adequately deal with inherent ambiguity and imprecision in mapping human perceptions [156]. Accordingly, adopting AHP in a fuzzy environment enhances the evaluation accuracy by addressing the associated linguistic vagueness, uncertainty, and incomplete knowledge.

In this research, Chang extent [94], [157] was adopted which utilizes triangular fuzzy numbers (TFNs) instead of crisp values. Chang extent maintains the key advantages of the original AHP since it follows the same structure [96]. Chang extent also overcomes the tremendous computational requirements of some of the other methods, such as Van Laarhoven and Pedrycz [93] and Buckley [158]. In addition, Chang extent avoids pressuring questionnaire contributors by allowing them to leave blank answers when they have no opinion or knowledge of certain points.

Figure 5–1 illustrates the evaluation hierarchy that was constructed through the incorporation of the outputs of the previous phases of the thesis, which were presented in Chapters 3 and 4. In the sub-criteria level, minor changes were made to the parameters for evaluation as follows: Under the technical criterion, some parameters were combined together in one parameter due to the strong interrelation; namely, scalability and augmentation capability were combined as modularity and scalability. The modularity is defined as the ability of a system to be divided into smaller segments, while the scalability is the ability to enlarge the size of a power plant. In addition, experts' availability and key components' availability were combined as key components' and experts' availability. Under the economic criterion, the operational life was neglected, as most CSP plants are considered to be in the early stages of their operational life span [101], [132]. It is a common practice in the literature to assume a period of 25–35 years of operational life for CSP plants with less consideration toward collection technology type [5–9]. There is only one large-scale CSP project with some phases of the complex that have begun operation since the mid-1980s (i.e., SEGS PT complex), while all other projects have mostly been in operation for less than a decade.

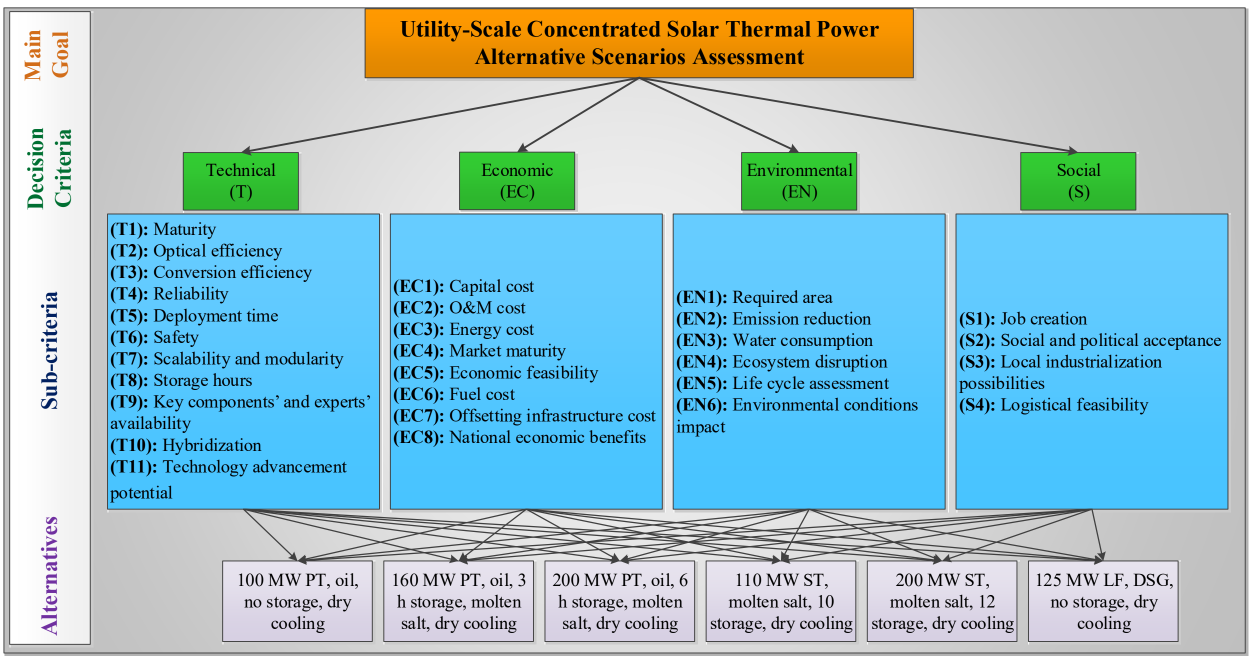



*Figure 5-1: CSP evaluation value tree in developing countries*

### 5.3. Methodology

The proposed methodology, as shown in Figure 5–2, aimed to assess potential CSP alternative scenarios with consideration to all relevant criteria in a hierarchal manner. The decision criteria and alternatives were defined based on previous research. Subsequently, the stakeholders' evaluations of decision criteria and sub-criteria were carried out through pairwise comparisons of TFNs. In addition, intensive research was conducted to obtain alternatives evaluations with consideration to quantitative and qualitative parameters. Accordingly, priority weights were calculated, degrees of possibilities were compared, and the weight vectors were determined. Parameter evaluations were checked to screen out inconsistent evaluations, and if identified, they were directed for re-evaluation through feedback reports to stakeholders. The model was therefore synthesized in which the evaluation matrix was obtained and results were presented. Sensitivity analysis was then conducted and final recommendations were made.

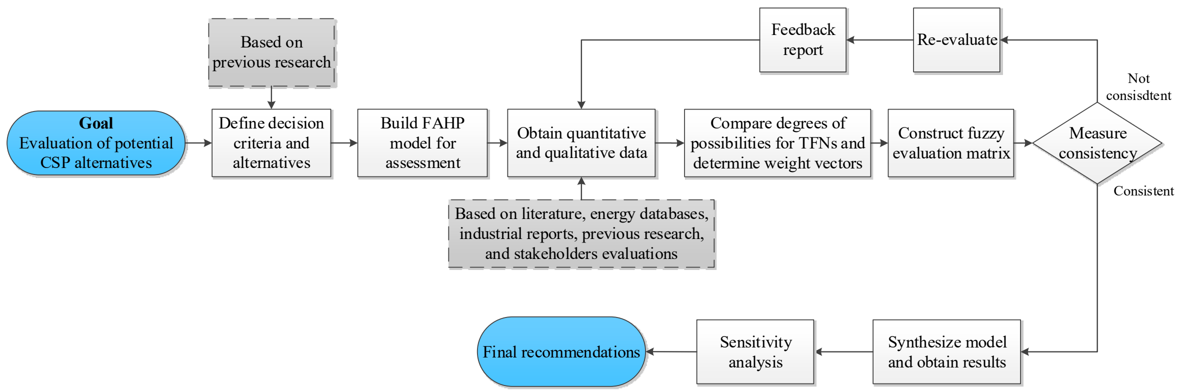



*Figure 5-2: Methodology of developing FAHP model for CSP assessment*

The AHP method was combined with fuzzy set theory to deal quantitatively with imprecision derived from vagueness in human thoughts and perception as well as uncertainty which is characteristic for the planning process of renewable energy projects in early stages [95], [156]. Chang extent analysis allows TFNs instead of crisp values to deal with imprecision and uncertainty through representation and processing in a fuzzy environment [159]. A TFN is defined as a triplet named *M,* which can be denoted by ($l, m, u$) in which ($l < m < u$). The greater the value of $u - l$, the fuzzier the degree, and if $l = m = u$, then $M$ is not a fuzzy number. Table 5–1 shows the TFN scale to convert participants' linguistic inputs through data elicitation.

| Linguistic scale | TFNs scale | TFNs reciprocal scale |
|---|---|---|
| Just equal | (1,1,1) | (1,1,1) |
| Equally important | (1/2,1,3/2) | (2/3,1,2) |
| Weakly important | (1,3/2,2) | (1/2,2/3,1) |
| Strongly more important | (3/2,2,5/2) | (2/5,1/2,2/3) |
| Very strongly more important | (2,5/2,3) | (1/3,2/5,1/2) |
| Absolutely more important | (5/2,3,7/2) | (2/7,1/3,2/5) |

*Table 5-1: Triangular fuzzy conversion scale*
*Source: Zheng et al., 2010* [75]

The mathematical basic operations of TFNs are implemented as follows:

- **Addition:** $M_1 \oplus M_2 = (l_1, m_1, u_1) \oplus (l_2, m_2, u_2) = (l_1 + l_2, m_1 + m_2, u_1 + u_2)$ *( 5-1 )*
- **Multiplication:** $M_1 \odot M_2 = (l_1, m_1, u_1) \odot (l_2, m_2, u_2) \approx (l_1 l_2, m_1 m_2, u_1 u_2)$ *( 5-2 )*
- **Inversion:** $(M_1)^{-1} = (l_1, m_1, u_1)^{-1} \approx (1/u_1, 1/m_1, 1/l_1)$ *( 5-3 )*

Chang extent analysis facilitates the comparison of fuzzy numbers for the prioritization of factors and alternatives. The following sections describe the methodological steps in detail.

### 5.3.1. Data collection

Prior to carrying out FAHP calculations, quantitative and qualitative data were obtained. Quantitative data were associated with measurable parameters. While reviewing previous studies analyzing RESs and solar technologies, it was noted that several technical and financial parameters were often weighted highly. These parameters include conversion efficiency, annual energy output, initial cost, and energy cost. Accordingly, an extended investigation was conducted in the previous phase of the thesis to obtain accurate data for these parameters. Further quantitative and qualitative data associated with the evaluation of tangible and intangible parameters with respect to sub-criteria were obtained in this study through an extensive research in the literature, industrial reports, and international databases. On the other hand, qualitative evaluations were associated with the assessment of criteria with respect to the main goal of prioritizing CSP alternatives and the evaluation of sub-criteria with respect to parent criteria. These qualitative data were extrapolated using a questionnaire presented to stakeholders from developing countries with potential for CSP. In the questionnaire, the participants were requested to weight high number of evaluating parameters in a linguistic scale. The linguistic values were then translated to TFNs. An advantage of the Chang extent is that it allows incomplete responses [159]. Participants were asked to skip questions that they have no opinion about to avoid making inappropriate decisions. Subsequently, quantitative and qualitative data were translated into pairwise comparisons of TFNs through the FAHP model.

### 5.3.2. Obtaining priority weight

In this step, TFNs were used for pairwise comparison instead of Saaty's nine-level scale provided in the original AHP. The application of AHP in the literature indicated that with higher numbers of decision criteria and sub-criteria, answers from participants were often inconsistent due to the complications resulting from a high number of pairwise comparisons. To avoid this issue, a scaling method was integrated into FAHP and used to collect participant responses. Subsequently, the responses were aggregated as rank numbers of alternatives (RNAs) and converted into pairwise comparisons that can be incorporated to the FAHP scale. A scoring value (SV) was introduced in Equation (5–4) to obtain a pairwise comparison of two alternatives (A and B) [160].

$$SV_{A\to B} = \begin{cases} \left(RNA_{(A)} - RNA_{(B)} + 1\right) & ,if \quad RNA_{(A)} - RNA_{(B)} \geq 0 \\ \left(1/(RNA_{(B)} - RNA_{(A)} + 1)\right) & ,if \quad RNA_{(A)} - RNA_{(B)} < 0 \end{cases} \tag{5-4}$$

The integration of the scaling method helped decrease the number of questions asked to participants, while reducing inconsistencies and eliminating complexity and confusion for contributors. The geometric means were taken for the triplets of TFNs in the ranking matrices to reach an individual matrix corresponding to each pairwise comparison representing participants' entries. On the other hand, for quantitative parameters, the values corresponding to alternatives with respect to sub-criteria were converted into TFNs using the definition of a step value (h) in the range from $K_{min}$ to $K_{max}$ using Equations (5–5) and (5–6) [160].

$$h = (K_{max} - K_{min}) / 5 \tag{5-5}$$

where $K_{max}$ and $K_{min}$ are the maximum and minimum values of alternative quantitative data associated with a specific parameter. Next, the RNAs were obtained as per Equation (5–6) and converted to TFNs through the mapping values provided in Table 5–1.

$$RNA_{(i)} = \begin{cases} INT\,(5 - \frac{K_{(i)} - K_{(min)}}{h})\ , & if \quad K_{(min)}\ is\ preferred \\ INT\,(\frac{K_{(i)} - K_{(min)}}{h})\ , & if \quad K_{(max)}\ is\ preferred \end{cases} \tag{5-6}$$

where $i$ =1, 2, …, $n$, and $n$ is the number of alternatives.

Subsequently, the values of priority weights were obtained through synthetic extent value $S$ with respect to the $i^{th}$ object, as shown in Equation (5–7) [161], [162].

$$S_i = \sum_{j=1}^{m} M_{g_i}^{j} \odot \left[ \sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{j} \right]^{-1} \tag{5-7}$$

where

$$\sum_{j=1}^{m} M_{g_i}^{j} = \left[ \sum_{j=1}^{n} l_j\ , \sum_{j=1}^{n} m_j\ , \sum_{j=1}^{n} u_j \right] \tag{5-8}$$

$$\left[ \sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^{j} \right]^{-1} = \left( \frac{1}{\sum_{i=1}^{n} u_i}, \frac{1}{\Sigma_{i=1}^{n} m_i}, \frac{1}{\Sigma_{i=1}^{n} l_i} \right) \tag{5-9}$$

### 5.3.3. Comparing degrees of possibility

In this step, fuzzy numbers were compared. The larger number in a set of two TFNs was defined for pairwise comparisons in order to calculate estimates for the sets of weight values. The degree of possibility was defined as follows:

$$V\,(M_1 \geq M_2) = sup_{x \geq y}\,[min\,(\mu_{M1}(x), \mu_{M2}(y))] \tag{5-10}$$

where *sup* represents the supremum, which is the least upper bound of a set, and $x$ and $y$ represent the values on the axis of the membership function [159], [163]. $M_1$ and $M_2$ are convex fuzzy numbers; for their comparisons:

$$V(M_2 \geq M_1) = \begin{cases} 1, & iff \;\; m_2 \geq m_1 \\ 0, & iff \;\; l_1 \geq u_2 \\ hgt\,(M_1 \cap M_2) = \mu_{M1}(d) = \frac{(l_1 - u_2)}{(m_2 - u_2) - (m_1 - l_1)} & Otherwise \end{cases} \quad (5\text{-}11)$$

where *iff* stands for if and only if, *hgt* represents the height, and *d* is thus the ordinate of the highest intersection point between $\mu_{M1}$ and $\mu_{M2}$; in other words, the highest intersection point between the two fuzzy numbers $M_1$ and $M_2$, as shown in Figure 5–3:

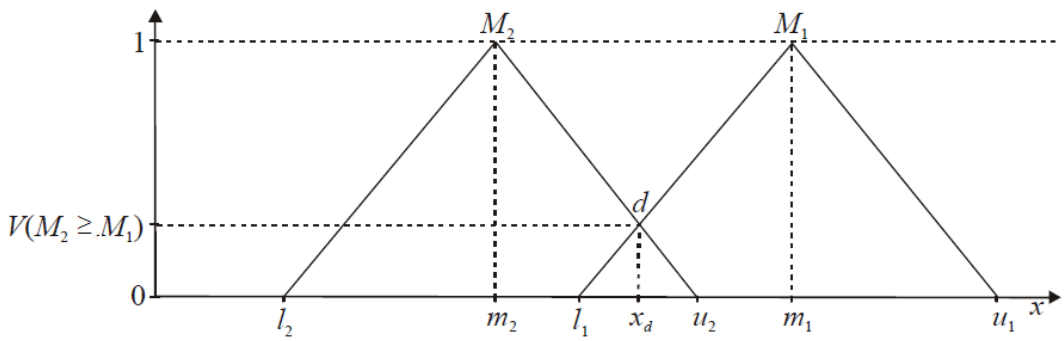



*Figure 5-3: The comparison of two fuzzy numbers $M_1$ and $M_2$*
*Source: Chang, 1996* [94]

### 5.3.4. Obtaining the weight vector

In this step, the weight vector *W'* was obtained in a non-fuzzy form and was given by:

$$W' = [d'(A_1), d'(A_2) \ldots d'(A_n)]^T \quad (5\text{-}12)$$

where $d'(A_i)$ is assumed to be

$$d'(A_i) = \min V(S_i \geq S_k), \qquad k=1, 2\ldots n \text{ and } k \neq I \quad (5\text{-}13)$$

The degree of possibility of a convex fuzzy number can be defined to be greater than *k* convex fuzzy number $M_i$ ($i = 1, 2\ldots k$) as per the following equation:

$$V(M \geq M_1, M_2 \ldots M_k) = V[(M \geq M_1), (M \geq M_2) \ldots (M \geq M_k)] \quad (5\text{-}14)$$

$$V = \min V(M \geq M_i) \qquad i=1, 2\ldots k \quad (5\text{-}15)$$

Subsequently, by normalizing $W'$, we get $W$ which is a non-fuzzy number that can be utilized for the evaluation of alternatives according to Saaty's main approach for AHP.

$$W = [d(A_1), d(A_2) \ldots d(A_n)]^T \qquad (5\text{-}16)$$

## 5.4. Case Study

The case study involving the selection of the CSP plant technologies in developing countries is presented for demonstration. Regardless, the proposed model is suitable for utilization with other technologies and regions as well. The hierarchy shown in Figure 5–1 is comprised of four levels. The first level covers the main goal of assessing CSP technologies for large-scale deployment in developing countries. The second level contains four evaluating criteria representing the main trajectories. These are divided to sub-criteria, which lie in the third level. The fourth level comprises six alternatives representing different configurations of CSP technologies. The following is an extended discussion of the assessment of each level of the hierarchy and the FAHP calculations.

### 5.4.1. Criteria and sub-criteria priority weights

In this section, the priority weights of the second and third levels of the hierarchy were calculated. The opinions of forty-four stakeholders from the renewable energy field from several developing countries with high potential for CSP were addressed through a questionnaire. Individual stakeholder scaling values were converted into a pairwise comparison based on TFNs through the application of Equation (5–4) and Table 5–1 conversions, after checking the consistencies. Table 5–2 is illustrative of the individual pairwise comparisons in which the entries of three stakeholders are represented by the three rows in each cell of the matrix for the evaluation of the main criteria with respect to the goal. Table 5–3, shows the aggregated pairwise comparison based on the geometric means of the TFNs of all participants for the decision criteria with respect to the goal.

| | Technical | Economic | Environmental | Social |
|---|---|---|---|---|
| Technical | (1,1,1) | (1/2,2/3,1)<br>(1/2,2/3,1)<br>(1/3,2/5,1/2) | -<br>(1/3,2/5,1/2)<br>(1/2,2/3,1) | (2,5/2,3)<br>(2/5,1/2,2/3)<br>- |
| Economic | (1,3/2,2)<br>(1,3/2,2)<br>(2,5/2,3) | (1,1,1) | -<br>(2/5,1/2,2/3)<br>(3/2,2,5/2) | (5/2,3,7/2)<br>(1/2,2/3,1)<br>- |
| Environmental | -<br>(2,5/2,3)<br>(1,3/2,2) | -<br>(3/2,2,5/2)<br>(2/5,1/2,2/3) | (1,1,1) | -<br>(1,3/2,2)<br>- |
| Social | (1/3,2/5,1/2)<br>(3/2,2,5/2)<br>- | (2/7,1/3,2/5)<br>(1,3/2,2)<br>- | -<br>(1/2,2/3,1)<br>- | (1,1,1) |

*Table 5-2: Individual pairwise comparison of decision criteria with respect to goal*

| | Technical | Economic | Environmental | Social |
|---|---|---|---|---|
| Technical | (1,1,1) | (0.54,0.95,1.39) | (0.77,1.22,1.70) | (0.98,1.46,1.94) |
| Economic | (0.72,1.05,1.85) | (1,1,1) | (0.801.28,1.77) | (1.01,1.53,2.04) |
| Environmental | (0.59,0.82,1.30) | (0.56,0.78,1.25) | (1,1,1) | (0.75,1.21,1.70) |
| Social | (0.52,0.69,1.02) | (0.49,0.65,0.99) | (0.59,0.82,1.34) | (1,1,1) |

*Table 5-3: Aggregated pairwise comparison of decision criteria with respect to goal*

Based on the aggregated pairwise comparison, the synthetic extents were found through Equations (5–7) to (5–9), and they are represented as follows:

$S_1 = (0.15,0.28,0.49)$, $S_2 = (0.16,0.30,0.54)$, $S_3 = (0.13,0.23,0.43)$, $S_4 = (0.12,0.19,0.35)$

Then, the degrees of possibilities were found through Equation (5–10) and (5–11):

$V(S_1 \geq S_2) = 0.96$, $V(S_1 \geq S_3) = 1$, $V(S_1 \geq S_4) = 1$ ➔ $V(S_1 \geq S_2, S_3, S_4) = 0.96$

$V(S_2 \geq S_1) = 1$, $V(S_2 \geq S_3) = 1$, $V(S_2 \geq S_4) = 1$ ➔ $V(S_2 \geq S_1, S_3, S_4) = 1$

$V(S_3 \geq S_1) = 0.85$, $V(S_3 \geq S_2) = 0.81$, $V(S_3 \geq S_4) = 1$ ➔ $V(S_3 \geq S_1, S_2, S_4) = 0.81$

$V(S_4 \geq S_1) = 0.70$, $V(S_4 \geq S_2) = 0.66$, $V(S_4 \geq S_1) = 0.85$ ➔ $V(S_4 \geq S_1, S_2, S_3) = 0.66$

Accordingly, the priority weights were found for the four decision criteria through Equations (5–12) to (5–16) to be:

W = (Technical: 0.28, Economic, 0.29, Environmental, 0.24, Social, 0.19). Similarly, the priority weights of the sub-criteria with respect to parent criteria were calculated.

### 5.4.2. Alternatives priority weights with respect to sub-criteria

In this section, the details of the alternatives evaluations with respect to the parent sub-criteria are presented. The evaluations of the alternatives were obtained through extensive research in the literature, industrial reports, international databases, and previous simulation results, which all contributed in determining the performance of the alternatives with respect to each sub-criterion. The pairwise comparisons calculations are illustrated in Appendix A.

#### *5.4.2.1. Technical*

The ***maturity*** of the alternatives was considered based on the overall installed capacities of each mix of technologies worldwide. The assessed six alternatives consisted mainly of four trajectories of mixed technology, if the installed and storage capacity levels were not considered. These trajectories consisted of PT with synthetic oil as HTF and without storage, PT with synthetic oil as HTF and molten salt for TES, ST with molten salt as HTF and for TES, and LF with DSG. All scenarios were coupled with Rankine cycle steam generators with dry cooling systems. Total installed capacities were calculated based on the NREL database for CSP projects [101]. All projects with operational power plants as well as projects under construction were considered. Accordingly, the PT collectors coupled with synthetic oil as HTF and with no storage were found to be the most common technology mix adopted with a total installed capacity of 2234 MW, followed by PT with synthetic oil and molten salt for TES with a total installed capacity of 1180 MW. The ST system with molten salt as HTF and for TES, and LF with DSG have total installed capacities of 640 MW and 181 MW, respectively. Subsequently, the consistency ratio was calculated to be at 1%, within the accepted range as defined by Saaty.

The calculations of the alternatives values were then translated into the FAHP scale following Equations (5–5) and (5–6) and the TFNs conversions as per Table 5–1. Table 5–4 shows the pairwise comparison of alternatives with respect to maturity.

| | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 | Alternative 5 | Alternative 6 |
|---|---|---|---|---|---|---|
| Alternative 1 | (1,1,1) | (2,5/2,3) | (2,5/2,3) | (5/2,3,7/2) | (5/2,3,7/2) | (5/2,3,7/2) |
| Alternative 2 | (1/3,2/5,1/2) | (1,1,1) | (1,1,1) | (1,3/2,2) | (1,3/2,2) | (1,3/2,2) |
| Alternative 3 | (1/3,2/5,1/2) | (1,1,1) | (1,1,1) | (1,3/2,2) | (1,3/2,2) | (1,3/2,2) |
| Alternative 4 | (2/7,1/3,2/5) | (1/2,2/3,1) | (1/2,2/3,1) | (1,1,1) | (1,1,1) | (1/2,1,3/2) |
| Alternative 5 | (2/7,1/3,2/5) | (1/2,2/3,1) | (1/2,2/3,1) | (1,1,1) | (1,1,1) | (1/2,1,3/2) |
| Alternative 6 | (2/7,1/3,2/5) | (1/2,2/3,1) | (1/2,2/3,1) | (2/3,1,2) | (2/3,1,2) | (1,1,1) |

*Table 5-4:Pairwise comparison of alternatives with respect to maturity*

The synthetic extents were subsequently calculated and found to be as follows:

$S_1$= (0.23,0.35,0.51), $S_2$= (0.1,0.16,0.25), $S_3$= (0.1,0.16,0.25), $S_4$= (0.07,0.11,0.17),

$S_5$= (0.07,0.11,0.17), $S_6$= (0.07,0.11,0.22).

Then through comparing the degrees of possibilities the weight vectors were obtained. The ***optical efficiencies*** of the alternatives depend on the type of solar collectors. The optical efficiency of the ST system is very high with a concentration level of up to 1000 suns compared to low optical efficiency for PT 70-80 suns, and very low for LF 60 suns [79]. Since all scenarios are assumed to be in the same location and benefit from the same input energy resource, their technical efficiencies differ mainly based on the selected technologies, SMs, and TES levels. All of which are reflected by the capacity factor, which was accordingly utilized as the measuring indicator for the evaluation of the ***conversion efficiency***. The capacity factor reflects the ratio of the actual output of a power plant to its potential maximum output in a given period. It increases depending on many parameters, including the plant installed and storage capacities, as well as the optical and conversion efficiencies. The capacity factors of alternatives 1 to 6, as obtained in the previous phase, were 22.4%, 30%, 39.9%, 59.5%, 64.1%, and 27.1%, respectively.

The ***reliability*** that CSP can support grid stability through TES is one of the key advantages of this technology compared to other RESs such as PV and wind. CSP can help reduce intermittency resulting from increased penetration of RESs to the grid, as well as partially contribute to the base load along with peak load. The reliability of different technology configurations is reflected through their ability to consistently meet electricity demand without interruption. The reliability of the assessed alternatives was considered to be related to the maturity of technology [23] and the grid stability that each alternative could provide, mainly through TES. Backup systems and hybridization with conventional plants are also influencing parameters, yet they were out of the scope of this study. In terms of technological credibility gained through experience, PT with synthetic oil has proved reliable for more than 25 years in the SEGS complex [57], [164]. PT was indicated to provide medium grid stability, which improves to high if coupled with TES or hybridized. ST provides high grid stability as a result of its inherent capability to be coupled with high capacity of TES. LF is not yet commercially coupled with TES, and hence it provides only medium grid stability [132]. Considering the storage level, a capacity credit parameter was discussed in literature. It reflects the fraction of the rated capacity of a plant that is considered firm for covering demand and ancillary services, including regulation, contingency reserves, and frequency response [165]–[167]. The capacity credit of CSP without TES, at low RESs penetration in the grid, was rated at 75% compared to 98% for CSP with TES, 70% for PV, and 100% for conventional plants where energy resources can be provided on demand [167]. This means that for scenario 1, for instance, 75 MW of its capacity is considered firm, and 25 MW should be backed up by the grid. As the RESs penetration level increases from 13% to 34%, the capacity credit of PV and CSP without TES decreases dramatically to 13% and 3%, respectively, because their production is limited to certain timeframes that was incrementally covered by previously installed capacity. The CSP with TES maintains a considerably higher capacity credit level of 78% owing to the capability of shifting production [167]. The capacity credits are discussed as monetary values later when considering offsetting infrastructure costs under the economic criterion (Section 5.4.2.2).

In establishing CSP commercial plants, the first step is the project development phase, followed by the construction and operation phases (Figure 5–4). The project development begins with defining the basic scope of the project through the decision-making processes associated with technical and economic feasibility studies, site selection, and financing opportunities. Thereafter, the conceptual engineering developments take place through proposing technical specifications, followed by permission processes and contract negotiations [164]. The ***deployment times*** of commercial CSP projects were noted to range from 1 to 3 years [100]. An indicative timeline for the deployment of a CSP plant estimated 18 months for development processes and a similar period for the construction [168]. While the development phase length is not expected to vary much based on the selected technologies, the construction phase is partially dependent on the technologies. Accordingly, the development time was considered as 18 months for all assessed scenarios while the construction phase varied between lower and higher end of the construction time in relation to plant capacity and solar multiple.

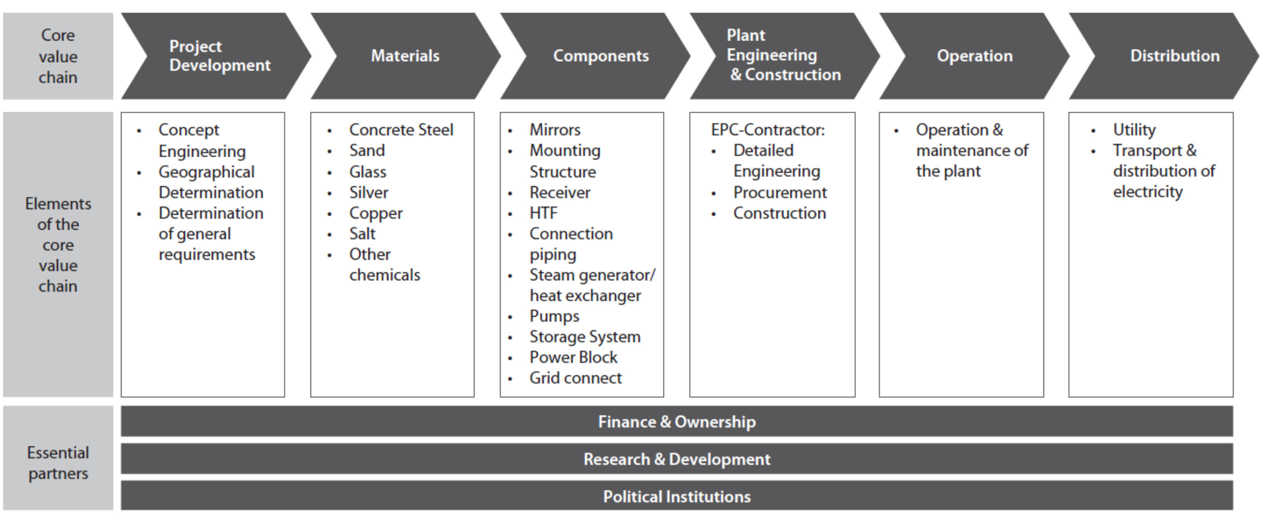



*Figure 5-4: Basic structure of the CSP value chain*
*Source: Gazzo et al., 2011* [164]

An analysis project concerned with the ***safety*** of power plants of different renewable and non-renewable technologies provided an energy-related severe accident database (ENSAD) [169]. In the ENSAD, a human fatality rate indicator was measured throughout the energy chain. The fatality rate was based on the annual production, but no studies found in the literature quantify the fatalities based on differing CSP technologies. The database assists industries, authorities, and policy makers by documenting the accidents resulting in severe injuries or fatalities. A considerably low rate was reported for solar thermal technology at $2\times10^{-4}$ fatalities/GWh per year compared to other RESs, including $2.45\times10^{-4}$ and $18.9\times10^{-4}$ annual fatalities/GWh for PV and onshore wind, respectively. Higher rates were reported for non-renewable technologies. Accordingly, the annual fatality rates for alternatives 1 to 6 were found to be 0.035, 0.081, 0.126, 0.103, 0.202, and 0.053 fatalities/GWh, respectively.

PT and LF systems are based on segmental designs of individual components and are more suitable for ***modularity and scalability*** compared to ST [37]. SEGS is a clear example of an augmented PT with total capacity of 354 GW composed of nine phase plants in which the first phase started operation in 1984 with a 13.8 GW capacity and the final phase started operation in 1990 with an 80 GW capacity [101]. The ST concept, on the other hand, is based on the central receiver system that leads to lower modularity and scalability. A 5 MW demonstrational ST project has adopted a modular concept based on standardized components (i.e., Sierra SunTower) [170]. Once proved on large-scale, this proposed concept could improve scalability for ST commercial projects through the replication of similar modules clustered together into a larger plant without the need for significant redesign.

Peterseim et al., [82], [171] discussed the suitability of CSP technologies for ***hybridization*** with conventional and renewable power plants. The hybridization can occur with a new plant or by retrofitting an existing plant. It helps maximize equipment utilization and saves fuel, thus further reducing emission intensity per generated energy if coupled with a conventional plant. Hybridization is considered a rapid way to decrease capital expenditures. This helps in early stages of CSP integration to national grids and aids operators and financiers to understand the different technologies and configurations, and it facilitates fast-tracking CSP implementation [171]. Peterseim et al., [82] assessed CSP for hybridization with technologies utilizing Ranking cycle turbines focusing on the temperature ranges of each technology. Their findings indicated that LF systems appeared to be the best technology for cold reheat steam, feedwater preheating, as well as < 450 °C steam boost applications. The PT with thermal oil ranked second for all CSP integration scenarios where the steam temperature is < 380 °C, while for applications requiring temperatures > 450 °C, ST with DSG performed the strongest followed by ST with molten salt. Focusing on the practical considerations of on-the-ground implemented configurations, Peterseim et al., [171] categorized hybridization concepts into light, medium, and strong hybrid synergy levels. These synergy levels begin with minimal sharing of infrastructure and move up to physical interconnection through the utilization of joint equipment including steam turbine, condenser, and building infrastructure. Hybridization subsequently facilitates substantial LCOEs reductions of up to 28% [82]. The hybridization options of CSP, considering plant configurations that utilize Rankine cycle steam turbines, include coal, gas, biomass and waste material, and geothermal. CSP plants with backup systems and/or production boosters can be considered under the strong synergy category. An example of a strong synergy model is Shams 1 CSP with two natural gas burners, one used continuously to raise steam temperature from 380 °C to 540 °C and accounts for 18% of the plant production, while the other gas burner is only used as backup for heating the HTF when there is a lack of sunshine [7].

A clear form of hybridization is in the medium category. In the medium synergy category, CSP is coupled to a host plant where it represents < 10% of the plant's total installed capacity. The dominant form of established CSP hybridization with conventional power plant adopts the integrated solar combined cycle (ISCC) concept, in which CSP is coupled to a combined cycle gas turbine (CCGT). Among the synergy options, the ISCC is considered the most practical matured configuration, in which PT solar field is commonly coupled to CCGT. Kuraymat (20 MW CSP), Ain Beni Mathar (20 MW CSP), and Martin Next Generation Solar (75 MW CSP) in Egypt, Morocco, and the US, respectively, are among the largest examples of CSP hybridization worldwide. The ISCCs are not commonly coupled with storage systems since the gas can compensate for solar radiation absence or insufficiency. Nevertheless, there is a small operational plant adopting the ISCC concept with an 8 h of storage (i.e., Archimede, 5 MW CSP). Archimede is the largest CSP operational plant utilizing molten salt as HTF instead of oil. ISCC is followed by CSP hybridization with a coal option. Liddell Power Station (9 MW CSP) and Kogan Creek Solar Boost (44 MW) are both operational plant examples of hybridization with coal coupled with LF solar fields [171]. There is not as of yet a large-scale reference hybridized plant including ST or PD.

***Technological advancements*** are crucial to support efficiency improvements and cost reductions of the different CSP plants' components. The potential for technical advancements and cost reductions for PT systems is associated with improvements in the HTFs (e.g., improved utilization of DSG and molten salt), collector designs (e.g., increased dimensions and lower weights), and absorbers tubes and mirrors (e.g., enhanced optical properties, new reflector materials development). In relation to ST systems the potential improvements are relevant to plant layout and design (e.g., enhanced aiming strategy and standardization of key components), receivers designs (e.g., development of new nickel alloys to allow higher solar fluxes), and heliostats designs (e.g., enhanced collectors structure) [21], [100]. For LF systems the potential enhancements are related to the collectors designs (e.g., Structural and collectors materials), HTF (e.g., use of superheated instead of saturated steam), and TES (e.g., development of storage systems based on phase-change materials to be coupled with DSG) [100]. The components showing the most potential for cost reduction are the reflectors for PT technology, mounting structures for PT, ST, and LF technologies, receivers for PT and LF technologies, and heat transfer mediums and molten salt systems for PT and ST technologies. The cost reduction potential range is 15–30% for PT technology with low development risk, 15–25% for ST technology with medium development risk, and 15–35% for LF technology with medium development risk. Accordingly, excluding PD systems, the LF systems show the highest potential for cost reduction through technological advancement followed by PT [11]. The outlook for improvements were noted as limited for PT [7], [77], significant for LF, and very significant for ST systems [77].

It is vital to consider monopolistic market situations as they relate to the complexity of some hardware and software factors, and may negatively influence the ***availability of experts and key components***, leading to artificial inflation. Experts' availability considers the required human expertise throughout the CSP value chain. Among the developing countries with the most potential for CSP, MENA and South Africa regions have been identified as having limited availability to the highly skilled workforce required for processes like project development and EPC [11]. However, low-skilled labor, which is needed in many stages such as civil works and installation works of solar fields, is available there at low cost. In addition, mass-production could reduce the need for highly skilled labor for CSP components assembly [11]. Receiver tubes associated with PT and LF require a highly specialized and accurate coating process, and the relevant is dominated by a few companies with relatively high earning margins around 20–25%. In addition, the production of the molten salt and synthetic oil associated with PT and ST alternatives requires an advanced chemical industry and has relatively limited production. Other components like reflecting mirrors also require a highly skilled workforce and advanced processes; yet they have the potential for local production in some developing countries such as in Egypt and Algeria, as there is a pre-existing advanced glass industry [11]. On another level, the configuration of the solar field in ST plants require advanced controlling capabilities as the concept depends on focusing the solar rays into a single focal point with a long traveling distance. Accordingly, the software for solar tracking and heliostat allocation is a major factor. Highly efficient algorithms are necessary, but are possessed by a limited number of organizations [172].

#### *5.4.2.2. Economic*

The ***initial costs*** of the alternative scenarios, as previously presented in Tables 4–3 and 4–4, were found to be 495, 1290, 1878, 941, 1948, and 444 MUSD, respectively. Financial and technical parameters were used to simulate the alternatives and to obtain the ***LCOEs*** for alternatives 1 to 6, which were found to be 24.61, 26.29, 23.94, 14.99, 15.59, and 14.95 cent/kWh, respectively (Section 4.5).

The ***O&M costs*** for PT and ST systems were estimated to be in the range of 0.02–0.04 USD/kWh, including fixed and variable costs based on the plant size and to lesser extent the storage level. Increasing the plant size from 50 MW to 100 MW results in a 7% reduction of O&M costs for PT, and 5% for ST, due to the economies of scale. Assuming similar reduction rates associated with the alternatives evaluated in this research, the O&M costs for alternatives 1 to 5 ranged between 0.023–0.032 USD/kWh [79]. LF systems offer lower O&M costs owing to lower design complexity as well as less water consumption for cleaning due to the availability of robot cleaning of mirrors. The O&M cost of the LF plant was thus estimated to be 0.015 USD/kWh [155]. Accordingly, the annual O&M costs of alternatives 1 to 6 were estimated to be 4.1, 12.9, 17, 16, 27.3, and 4 MUSD, respectively.

In relation to ***market maturity***, a study conducted by the World Bank has extensively covered the required regulations to support the development of CSP in the major emerging markets of India, South Africa, and the MENA by addressing the required incentive schemes, markets maturity, and local industrialization opportunities [11]. The number of technology providers reflects the market maturity of each technology. Accordingly, the market maturity was classified as high for PT, with more than ten companies commissioning PT projects, such as Abengoa Solar and Sener. ST with molten salt was indicated to have medium market maturity, with up to five companies, including SolarReserve and eSolar. Lastly, the market maturity was classified as medium for LF with up to four companies commissioning projects, such as Novatec and Sky Fuels [11], [61].

The net present value (NPV) of each alternative was calculated in association with the ***economic feasibility***. NPV calculates the expected net monetary gain or loss from a project by discounting all cash inflows and outflows during project's lifetime to the present point of time as per Equation (5–17).

$$\text{NPV} = \sum_{t=0}^{n} \frac{A_t}{(1+r)^t} \qquad (5\text{-}17)$$

where: $A_t$ is the cash flow in year t; r is the discount rate; and n is the lifetime of the system.

A NPV over zero reflects project financial feasibility while below zero means that an investor cannot recoup an investment from an economic viewpoint. The cash flows calculations include the expenditures and revenues throughout the systems lifetime, such as capital investments, O&M costs, as well as electricity sales. Assuming a 25 year operational lifetime and a discount rate of 8% [21], [132], the obtained NPVs of alternatives 1 to 6 were 36.9, 96.2, 140.2, 70.3, 145.4, and 33.1 MUSD, respectively.

The ***fuel cost*** parameter is dependent on freeze protection systems, the fuel consumed for the auxiliary boiling, and more significantly, the fuel consumed by the conventional power plant when the assessed alternatives are hybridized (which is beyond the scope of this research). The quantity of fossil fuel required by the auxiliary boiler is related to the time the auxiliary fossil system is utilized to supplement the thermal energy yielded from the solar field or storage system to generate steam [146]. Subsequently, fossil fuel quantity is associated with the solar field outlet temperature, the HTF and TES mediums' capabilities, and the plant capacity of each alternative. As a result, technology-wise the highest fossil fuel consumption was associated with alternative scenarios utilizing LF coupled with a DSG system with temperature gains of 250–350 °C, followed by alternatives utilizing PT coupled with synthetic oil as HTF with temperature gains of 350–400 °C [79]. The ST technology yields high temperature gains of up to 565 °C, given sufficient solar input, and the usable operating range of molten salt complementing the operating temperatures of Rankine cycle turbines [81]. Accordingly, ST systems coupled with molten salt, such as in Crescent Dunes Solar Energy Project, do not consume fossil fuel for backup. Yet, if the ST was coupled with a DSG system, then an auxiliary boiler would still be necessary for water preheating (e.g., largest CSP in the world, Ivanpah Solar) [101]. Systems with higher capacities require proportionally more fuel for energy generation. In relation to the freeze protection, the fuel consumption was neglected since the required quantities were minimal.

***Offsetting infrastructure costs*** are considered through the capability that the grid must have to maintain its stability for each alternative scenario under similar production levels compared to conventional fossil fuel generation. While LCOE is a key parameter in comparing energy sources, it does not consider the value of the produced energy as a function of time with relation to the demand. As intermittent RESs grid penetration increases, the value of the ability to shift production and to facilitate ancillary services increases. Subsequently, regulators sought scenario-based portfolio analysis in which net system costs-benefits were analyzed. The capacity values of RESs were calculated as the avoided costs of alternative capacity. In regions where increased solar radiation is in coincidence with higher demand, the capacity values of CSP with and without TES were high (i.e., 37–47 USD/MWh). This reflects the high value of the produced energy because it covers peak demand. As the penetration of solar capacity (both CSP and PV) increases, the incremental capacity of RESs requires a shift to evening demand. Therefore, at 30% RESs grid penetration, the capacity values were found to be around 15 USD/MWh for CSP with TES, and only 2 USD/MWh for CSP without TES (Figure 5–5) [165]. Accordingly, for alternatives 1 to 6 the annual capacity values were found to be 0.35, 6.04, 9.45, 7.76, 15.16, and 0.53 MUSD, respectively.

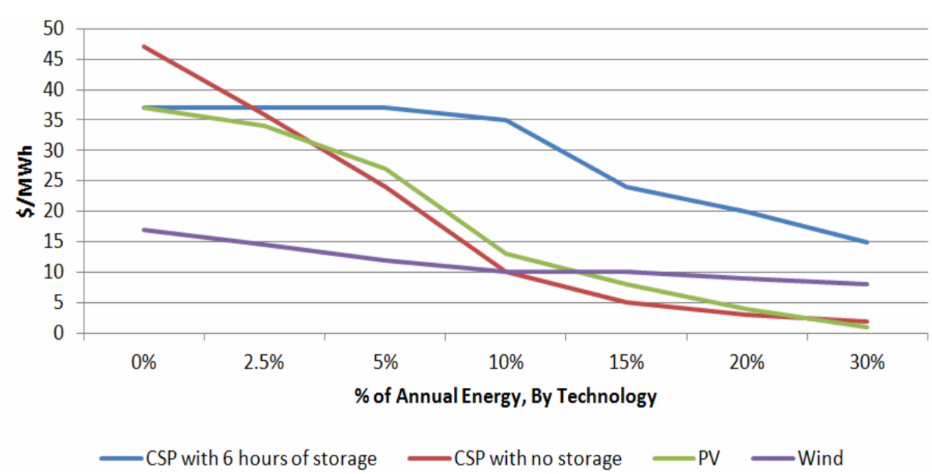



*Figure 5-5: Marginal capacity value by penetration of solar and wind technologies*
*Source: Forrester, 2013* [165]

The direct and indirect economic impacts of CSP power plants are associated with construction, O&M, and effects associated with increased demand in the supply value chain. Hence, the ***national economic benefit*** parameter is interrelated with the local industrialization and job opportunities generated by each alternative scenario and associated accordingly with the size of the power plant. The overall current proportion of local manufacturing of CSP projects is expected to be up to 60% [11]. Practically, Acwa Power, a Saudi energy company commissioned CSP projects in Morocco and South Africa, indicated that 45% of CSP plant manufacturing can be acquired locally in early stages of CSP integration wherein the total installed capacity of the country is between 100 MW and 500 MW [173]. This value is in agreement with the estimated economic impact provided by the World Bank study [11] for a 100 MW PT plant without storage. The economic impact was calculated to be 233 MUSD, which represents approximately 47% of the total installed cost of alternative scenario 1 in this study. In addition, 90% of the O&M costs can be covered from local resources. Accordingly, an index for the national economic benefit was calculated, considering local industrialization of 45% from initial cost of an alternative scenario and 90% O&M costs as well as the job opportunities created. The normalized values for national economic benefit index of alternatives 1 to 6 were found to be 0.07, 0.18, 0.27, 0.14, 0.28, and 0.06, respectively.

#### ***5.4.2.3. Environmental***

The evaluation of the alternative scenarios with consideration to environmental sub-criteria were investigated. Several studies in the literature discussed the ***land-use factor*** based on the collection technology of CSP projects [37], [125]. The land-use factor may be measured based on energy produced per unit of capacity or per unit of energy generation; however, it is more important to evaluate the land-use factor of CSP technologies based on annual energy generation of the power plant, and to consider effects of the different solar multiples and storage levels [174]. Peterseim et al., [82] provided an extended discussion of land-use factor considering plant configurations along with collection technologies. The data in the aforementioned studies indicated the direct area required for CSP technologies. In contrast, a comprehensive study carried out by Ong et al., [174] focused on the land-use factor of each technology with consideration to both direct and total area based on operational and under-construction plants of 25 CSP projects in the US. The direct area comprised of land occupied by solar fields, access roads, substations, and service buildings, while total area stemmed from empirical efforts to determine boundaries of the power plants based on blueprint drawings, fact sheets, and satellite imagery analysis. Accordingly, the total required areas for each of the plants were calculated based on the collection technology annual energy output of each alternative. The estimations for total land-use factor were found to be 15.8 $m^2$/MWh/year for systems using PT, 12.9 $m^2$/MWh/year for ST systems, and 16.2 $m^2$/MWh/year for systems using LF. Subsequently, by obtaining the annual energy output of each plant, the required areas of alternatives 1 to 6 were found to be 2.78, 6.36, 9.95, 6.66, 13.04, and 4.32 $km^2$, respectively.

In terms of the ***water consumption***, the Rankine cycles of the assessed alternatives were connected to dry cooling systems to overcome water scarcity. Therefore, only the cleaning water for the mirrors was considered. Dry cooling was selected since many potential locations for CSP plants are in arid lands. However, it is important to note that dry cooling has a performance penalty of 1–3% for ST systems and 4.5–5% for PT systems, as well as increased cost of 5% for ST systems and 2–9% for PT systems [11]. The design of LF results in a very low cleaning water requirement compared to other technologies. The mirrors linearity and flatness of LFs allow for robotic cleaning techniques, and thus the water consumption is 15 L/MWh. The parabolic shape of PTs prevents the utilization of the same technique which is used in LF. Thus, the water consumption of PT coupled with thermal oil increases to 75 L/MWh. Systems that depend on individual mirrors (i.e., ST and PD) result in higher water consumption. Thus, STs with molten salt require 114 L/MWh for cleaning [82]. The annual cleaning water consumption of alternatives 1 to 6 were found to be 13.2, 30.2, 47.2, 58.8, 115.2, and 4 ML, respectively.

In relation to ***ecosystem disruption***, LF and PT involve high numbers of widespread receiver pipes, fittings, and ball joints distributed in the solar field, which increases the risk of HTF leakage. For LF plants, the DSG system does not involve risks of environmental disruption. However, in the case of PT plants, leakage of synthetic oil results in an unavoidable odor and increases the environmental risks from the toxic nature of the synthetic oil as well as pollution to soil and surfaces. Additionally, in regions with vulnerable aquifers, there is a risk associated with oil passing rapidly into the water system. On the other hand, there are limited areas devoted to TES which reduces the risk of contamination especially with precautionary measures like wall surface proofing within the storage tanks. ST alternatives include a central piping system and utilize molten salt as HTF, which is less hazardous to the environment compared to oil. In terms of impact on flora and fauna associated with technology selections, there were minimal risks reported. These risks were related to bird mortalities from hitting mirrors as well as high towers of ST plants, and from flying within the high solar flux over the towers causing burns. CSP plants might result in a depopulation of some species, such as the relocation of desert tortoises reported during the construction of Ivanpah Solar plant. Furthermore, if the plant was built on former agriculture land, the existing soil nutrients might help vegetation growth which increases fire risk. The impacts of species relocation and agriculture lands, however, were not related to certain CSP technologies [172], [175], [176].

The ***life cycle assessment (LCA)*** is a holistic and systematic approach in which the environmental performance of power plants is analyzed from cradle to grave to quantify the environmental impact of the associated technologies. The LCA helps determine the environmental burdens by monitoring the activities from upstream to downstream during the life cycle phases of the plant including manufacturing, construction, O&M, dismantling, and disposal [177]. Figure 5–6 illustrates the processes modeled by Lechón et al., to obtain carry out LCA of CSP plants in Spain [178]. The energy payback time (EPBT) indicator was used to measure the LCA parameter for the evaluated alternative scenarios. EPBT represents the time it takes a plant to generate energy that equals its own cumulative energy demand (CED) throughout its entire life span. CED represents the sum of the primary energy supplied during the life cycle of the plant, including direct and indirect energy consumptions such as the energy consumed to manufacture plant components [179]. The EPBT values vary based on the technologies involved in the plant, since the components required and operational concepts are not the same. Yet, as the EPBT is calculated based on a ratio between the CED and the annual energy of the plant [177], it is less influenced by the installed capacity as the increased energy demand is proportionally compensated by higher energy generation. The EPBT was found to be 12.5 months for PT, 12.2 months for ST [178], and 8.2 months for LF [179]. In addition, the LCA facilitates the evaluation of the plants ***GHG emissions*** during the life cycle. While in conventional fossil fuel power plants most of the life cycle emissions are related to the operational phase, in CSP, it was found that 60–70% of the emissions were associated with the upstream phase whereas 21–26% and 5–20% were associated with the operation and downstream phases [178], [180]. The life cycle GHG emission intensities for the PT, ST, and LF were found to be 26 g-$CO_{2eq}$/kWh [177], 23 g-$CO_{2eq}$/kWh [181], and 31 g-$CO_{2eq}$/kWh, respectively [179]. The higher value emissions associated with LF were perhaps because it requires higher quantities of auxiliary gas combustions due to lower operational temperatures. Nevertheless, the emission values of different CSP technologies were considerably lower compared to other conventional and renewable electricity generation technologies including 975 g-$CO_{2eq}$/kWh for coal, 608 g-$CO_{2eq}$/kWh for gas, and 742 g-$CO_{2eq}$/kWh for oil [176]. The emissions of other RESs were estimated as 43 g-$CO_{2eq}$/kWh for the PV and 126 g-$CO_{2eq}$/kWh for wind [180]. Other emission potentials included acidification in sulfur dioxide $SO_2$ equivalent and land over-nitrification in phosphate $PO_4^{3-}$ equivalent, but were estimated to have negligible values [50], [182]. Accordingly, the annual GHG emission intensities for alternatives 1 to 6 were found to be 4581, 10470, 16375, 11866, 23251, and 8268 Mg-$CO_{2eq}$, respectively.

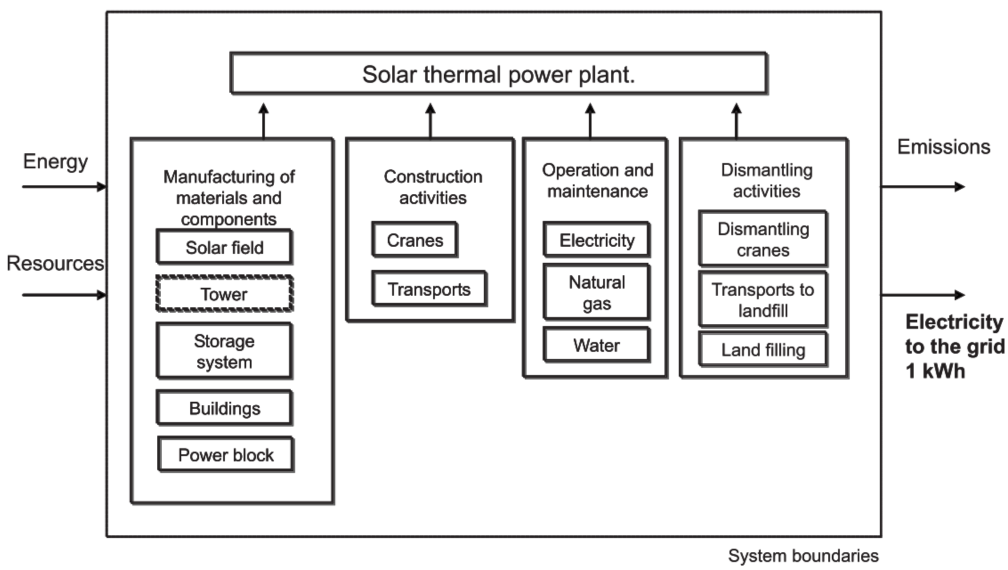



*Figure 5-6: Life cycle of a CSP plant*
*Source: Lechón et al., 2008* [178]

The ***environmental conditions*** impacting energy production involve soiling, temperature, humidity, and wind. The impact of soiling through accumulating dust is higher on the PT curved mirrors compared to heliostats and LF, but there are no studies yet quantifying the different impact rates of optical efficiency reduction based on CSP collecting technology [103]. In relation to wind loads impact, LF are constructed close to the ground and hence wind loads effect is reduced [21], [104], and found to be lower than the effect on PT [183]. The solar field of ST requires high accuracy of heliostats positions to reflect the sun's rays into a remote receiver resulting in solar radiation traveling 1 km or more [139]. ST systems are therefore more vulnerable to windy conditions and require precise operating [100]. Molten salt has a high freezing point (i.e., 120–220 °C). As a result, the alternatives that utilize molten salt as HTF and/or TES are more dependent on freeze protection compared to systems utilizing synthetic oil or DSG which have much lower freezing points at 12 °C and 0 °C, respectively [57]. With regard to humidity, it has a low impact on efficiency for all collectors, and is lower with flat mirrors in particular [172]. An innovative schematic involves glasshouses that contain the PTs has been embraced in an enhanced oil recovery plant in Oman to reduce the environmental conditions impact and allow the robotic cleaning technique (Figure 5–7) [184]. The concept is intended to be adopted in a large-scale project after the success of the 7 $MW_{th}$ pilot project [185].

*Figure 5-7: Innovative glasshouse scheme for CSP plant in Oman*
*Source: CSP World, 2015* [184]

#### *5.4.2.4. Social*

Both job creation and local industrialization are important to benefit national economies. In terms of ***job creation***, estimations of direct and indirect annual job opportunities throughout the value chain in association with CSP plants were discussed in a study conducted for the World Bank [164] as shown in Table 5–5. The averages of these values were utilized to estimate jobs created in association with the assessed alternatives. For a typical PT 50 MW plant, about 30 employees are required to operate the plant and 10 employees for field maintenance, while a 300 MW PT plant would still require 30 employees for operations and 20–30 employees for maintenance [7]. For TES, the most common structure depends on two thermal storage tanks which was estimated to create 500 jobs throughout the value chain [164]. Accordingly, the total job-year generated by alternatives 1 to 6 were calculated to be 1220, 2454, 2940, 1820, 2900, and 1500 jobs, respectively.

| Components | Civil work | installations | EPC | Assembling |
|---|---|---|---|---|
| One-year jobs/MW | 5–7 | 2 | 0.6-0.8 | 1–2 |
| Components | Receivers | Flat mirrors | Parabolic mirrors | Mounting structure |
| One-year jobs/MW | 0.3–0.7 | 0.6–1.2 | 0.7–1.5 | 0.3–0.5 |

*Table 5-5: Jobs created throughout CSP value chain*
*Source: Gazzo et al., 2011* [164]

The ***local industrialization*** issue for CSP development was extensively discussed in studies conducted by the World Bank for developing countries [11] and the MENA region in particular [164]. CSP plant components are classified as key components (mounting structures, mirrors, and receivers), key services (assembling, O&M, and EPC), secondary components (electronics, cables, and piping), and other components (e.g., trackers, HTF, and storage). The highest value-added returns are associated with key components such as parabolic mirrors and receivers, but they require high technological background and advanced manufacturing processes. MENA countries are aiming to shift their roles to become centers of excellence in production, and to support local economies. The production capability of such components is currently available in developed countries that are advanced in CSP technology. Market growth in developing countries is required in order to attain the desired capabilities. That said, there are other components such as piping and HTFs associated with other industries that require a lower technical knowledge level, and thus can be manufactured locally in the short-term. The prospect of local manufacturing includes production sectors that can be localized in short, medium, or long term with a low, medium, or high obstacle level. Activities like construction, assembly, and civil work can be localized in the short to medium term. The focus of this section will be on aspects that differ based on collection technology in the solar field, while other aspects associated with plant installed capacities were considered within the national economic benefit parameter in Section 5.4.2.2.

The mounting structure could also be adopted by local suppliers for the short to medium term, if local companies can meet the high accuracy mandatory for manufacturing. Mounting structure demand depends on the adopted collection technology and the solar field size. ST requires more mounting structure volume since they are utilized for each heliostat individually. In addition, heliostats direct solar rays on a focal point, and thus require a two-axis tracking system. Mirror and absorber manufacturing involves high levels of complexity and requires international collaborations to acquire the advanced technological knowledge. Float glass requires a coating process to produce flat mirrors used in LF and ST systems, while a more complex process is involved for the bending of PT collectors [164]. Absorbing pipes are utilized in PT and LF systems, while the ST systems depend on a receiver attached to the central tower instead. Storage tanks and pressure vessels have good local production potential, while synthetic oil and heliostat are produced within experienced chemical industries that can balance the capital-intensive requirements with high production [11].

The ***logistical feasibility*** of CSP technologies reflects the existence of supporting mechanisms through legislations and regulations. The introduction of new energy laws and policy guidelines played a vital role in enabling the CSP global market to develop since 2007 [186]. The current capital costs and energy costs of CSP are high compared to other conventional and renewable electrical generating technologies, and necessitates government financial support [164]. The support has been achieved through programs that incentivize companies to invest in CSP technology such as renewable portfolio standards (RPSs) that set mandatory targets of RESs, and power purchase agreements (PPAs) that guarantee the purchase of generated electricity at defined feed-in tariff (FiT). Such incentivizing programs facilitated CSP advancement in countries like US, Spain, and India in a relatively short timeframe [11]. More long-term R&D efforts support activities such as increasing operational temperatures and efficiencies, testing new storage options, and finding new plant concepts [164]. Logistical feasibilities are interrelated to several parameters and most importantly to technology maturity, reliability, capital cost, and energy cost. Long-term experience with the existence of several operational reference plants improve opportunities for obtaining administrative approval and financial support. Additionally, alternatives associated with lower capital costs and energy costs reduce the risk-driven financing of loans and incentives [82]. Table 5–6 depicts the quantitative and qualitative factors used to evaluate the alternative scenarios with respect to each sub-criterion.

| | Sub-criteria | Measuring indicator | Type | Unit |
|---|---|---|---|---|
| Technical | Maturity | Total installed capacity | Continuous | MW |
| | Optical efficiencies | Concentration level | Continuous | Suns |
| | Conversion efficiency | Capacity factor | Continuous | % |
| | Reliability | Ability to support grid stability | Discrete | 1–5 Likert-scale |
| | Deployment time | Required time for development and construction | Continuous | Months |
| | Safety | Sever accidents throughout energy chain | Continuous | Fatalities/GWh/y |
| | Scalability and modularity | Technology's capability to be scaled and augmented | Discrete | 1–5 Likert-scale |
| | Storage hours | Total time thermal energy can operate plant at rate capacity | Continuous | Hours |
| | Availability of key components and experts | Availability of crucial hardware, software, and human resources expertise | Discrete | 1–5 Likert-scale |
| | Hybridization | Suitability for hybridization | Discrete | 1–5 Likert-scale |
| | Technology advancement potential | Potential for efficiency increase and cost reduction | Discrete | 1–5 Likert-scale |
| Economic | Capital cost | Plant's initial cost | Continuous | MUSD |
| | O&M costs | Fixed and variable O&M costs | Continuous | USD/kWh |
| | Energy cost | Levelized cost of energy | Continuous | Cent/kWh |
| | Market maturity | Technology providers | Discrete | Number of companies |
| | Economic feasibility | Net present value | Continuous | M USD |
| | Fuel cost | Fuel consumption potential to operate plant | Discrete | 1–5 Likert-scale |
| | Offsetting infrastructure cost | Capacity value | Continuous | USD/MWh |
| | National economic benefit | Direct and indirect impact on national economic | Continuous | National economic benefit index |
| Environmental | Required area | Land-use factor | Continuous | $m^2$/MWh/y |
| | Emission reduction | Life cycle GHG emissions | Continuous | g-$CO_{2eq}$/kWh/y |
| | Water consumption | Cleaning water consumption | Continuous | L/MWh/y |
| | Ecosystem disruption | Impact on surrounding environment | Discrete | 1–5 Likert-scale |
| | Life cycle assessment | Energy payback time | Continuous | Months |
| | Environmental conditions impact | Impact of soiling, humidity, temperature, and wind on energy production | Discrete | 1–5 Likert-scale |
| Social | Job creation | Employment opportunities | Continuous | One-year jobs/MW |
| | Social and political acceptance | Community and politicians' attitudes toward alternatives (subjective via questionnaire) | Discrete | 1–5 Likert-scale |
| | Local industrialization possibilities | Potential for manufacturing CSP plant components locally | Discrete | 1–5 Likert-scale |
| | Logistical feasibility | Potential for supporting mechanisms and regulations | Discrete | 1–5 Likert-scale |

*Table 5-6: Measuring factors for alternatives evaluation with respect to sub-criteria*

## 5.5. Results and Discussion

The evaluation of the CSP alternatives with respect to the sub-criteria, criteria, and main goal was carried out through the FAHP model. The assessment was determined using quantitative and qualitative data available in the literature, simulation results, industrial reports, international databases, and stakeholders' evaluations. Subsequently, by aggregating all inputs and proceeding through the FAHP calculations, evaluations of the alternative scenarios were obtained to make recommendations.

Figure 5–8 illustrates the local evaluation of all sub-criteria with respect to parent nodes (sub-criteria codes were listed in Figure 5–1). Within the technical node, stakeholders' evaluations placed highest priority on reliability, followed closely by technology maturity and conversion efficiency. Developing countries seek reliable systems to support and enhance the stability of expanding national grids. Furthermore, technology maturity and conversion efficiency were highly valued owing to the need for assurances that such costly investments have considerable operational experience as well as high efficiency for electricity generation. Hybridization capability and deployment time obtained the lowest priority weights. Low priority for hybridization capability reflects stakeholders' consideration for stand-alone and grid connected CSP plants. The deployment time of plants was of low importance as it was considered more crucial to identify reliable and mature technologies with high efficiencies regardless of longer deployment time to support the sustainability of national grids. In terms of sub-criteria under the economic category, capital cost and energy cost obtained highest priority weights. This evaluation meets the expectation for all energy systems, as the initial cost and energy cost are the main drivers of such projects. Fuel cost and offsetting infrastructure cost obtained the lowest priority weights, as those were considered low in comparison to capital and energy costs. For the sub-criteria under the environmental category, the water consumption and emission reduction obtained the highest priority weights. Water consumption is well known as a vital concern for power plants, especially as most potential CSP locations are arid with high DNI levels and water scarcity. The required area for the plant got the lowest environmental priority weighting, which is again due to the expectation that potential locations will be essentially desert lands. With respect to sub-criteria under the social node, job opportunities created by each alternative scenario was considered the highest priority.

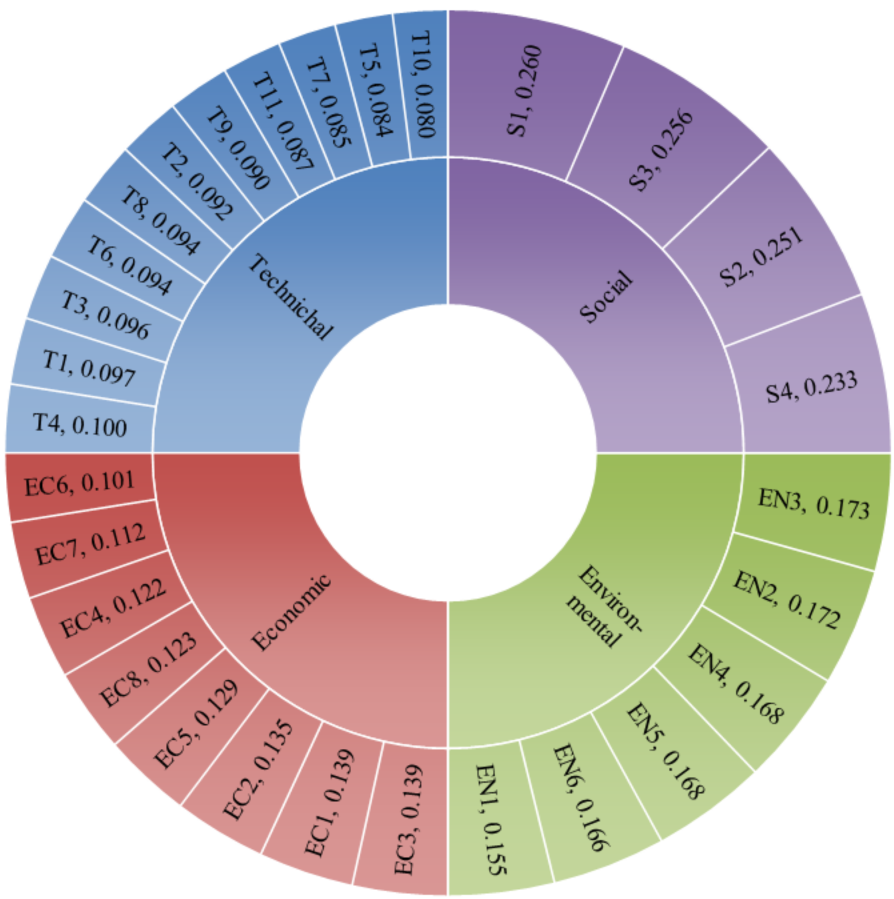



*Figure 5-8: Priority weights of sub-criteria with respect to parent nodes*

The local priority weights of the alternatives with respect to technical sub-criteria are illustrated in Figure 5–9. The highest priority was for alternative 1 at 0.24 followed by alternative 5 at 0.19. Alternative 1 performed exceptionally well in maturity as PT with no storage is by far the most mature technology. In addition, alternative 1 performed better than all other alternatives with respect to deployment time, safety, and hybridization capability. Alternative 1 also performed well in reliability, scalability and modularity, as well as key components and experts' availability. The aggregated evaluation of stakeholders regarding the sub-criteria under the technical criterion indicated highest local priority weight for reliability followed by maturity. Hence, the high performance of alternative 1 at these parameters significantly contributed to high overall evaluation with respect to technical aspects. Alternatives 4 and 5 have high priority weights second to alternative 1. They both benefited from good performance with respect to optical and conversion efficiency associated with high concentration levels of ST systems, and hence high operational temperatures. Moreover, the long TES added strength to those systems. In comparing the eleven sub-criteria under the technical category, the priority weights of conversion efficiency, storage hours, and optical efficiency were placed by stakeholders' evaluations in third, fifth, and sixth positions, respectively. It is vital to note that alternative 5 scored low in the deployment time, safety, and scalability and modularity parameters. Accordingly, if the priorities of stakeholders in a particular region did not emphasize these parameters, alternative 5 would have obtained higher priority in terms of technical aspects. Alternatives 2, 3, and 6 scored low overall priority weights technically. The three alternatives have low maturity, optical efficiency, and conversion efficiency. In terms of maturity, even though PT is the most mature collecting technology, it is less matured when integrated with molten salt for TES as indicated previously in Section 5.4.2.1. Such a configuration is yet promising with several operational plants predominantly in Spain, as well as ones under construction with up to 9 h of storage and ones under development with up to 16 h of storage [101].

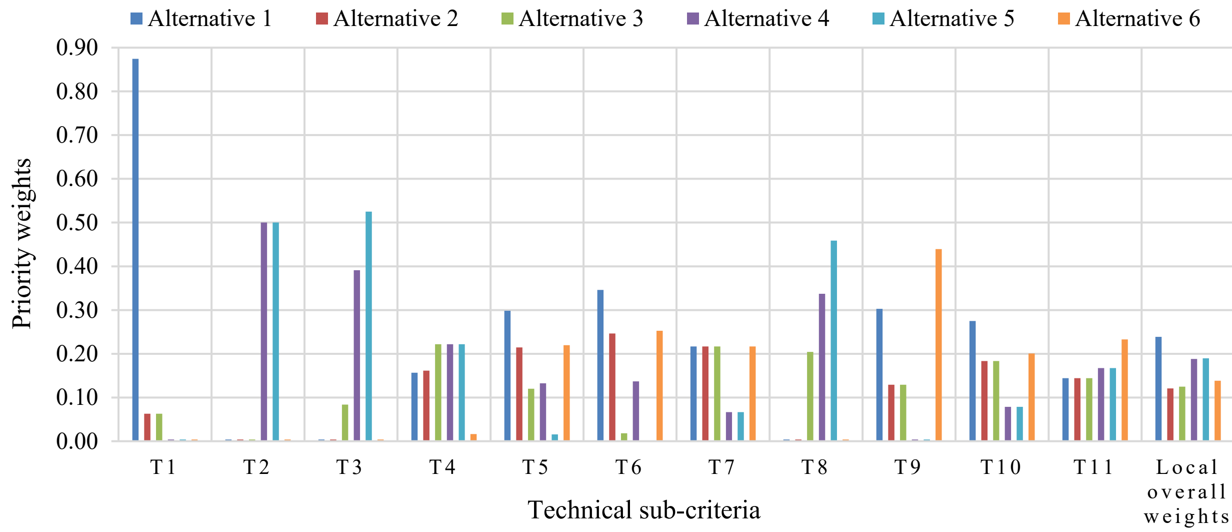



*Figure 5-9: Alternatives local priority weights with respect to technical decision criterion*

Figure 5–10 shows the local priority weights of the alternatives with respect to economic sub-criteria. Alternative 5 outperformed other alternatives with a priority weight of 0.24 even though it had the highest capital and O&M costs. This reflects an outstanding performance of alternative 5 by obtaining the highest priority weights in several aspects, either alone or with other alternatives. Alternative 5 benefited from low energy cost owing to high operating temperatures of the ST system and long TES leading to a high capacity factor. Hence, alternative 5 yielded high economic feasibility owing to high-energy production at low cost, which compensated for the large initial cost. In addition, both alternatives 3 and 5 strongly supported national economic benefit because they were associated with high local industrialization and jobs opportunities created by such massive investments. It is vital to note that the limitations of large monetary flows for certain countries can be a main barrier for the adoption of alternatives 3 and 5. In such cases, alternatives 1 and 6 using PT and LF could represent as suitable substitutes with economic concessions including low feasibility for both alternatives and low market maturity for LF. Overall, alternative 2 obtained the lowest priority weight with respect to the economic aspect. This resulted from low performance in several parameters including capital cost and high energy cost owing to a low capacity factor per initial cost, as well as low percentage of energy generation increase per unit of capacity for each additional storage hour. Alternatives 3, 4, and 6 obtained similar overall weights (i.e., 0.17, 0.15, and 0.15, respectively) with different performances at individual sub-criteria level. Hence, slight changes in the evaluation could lead to notable differences in their overall economic weights.

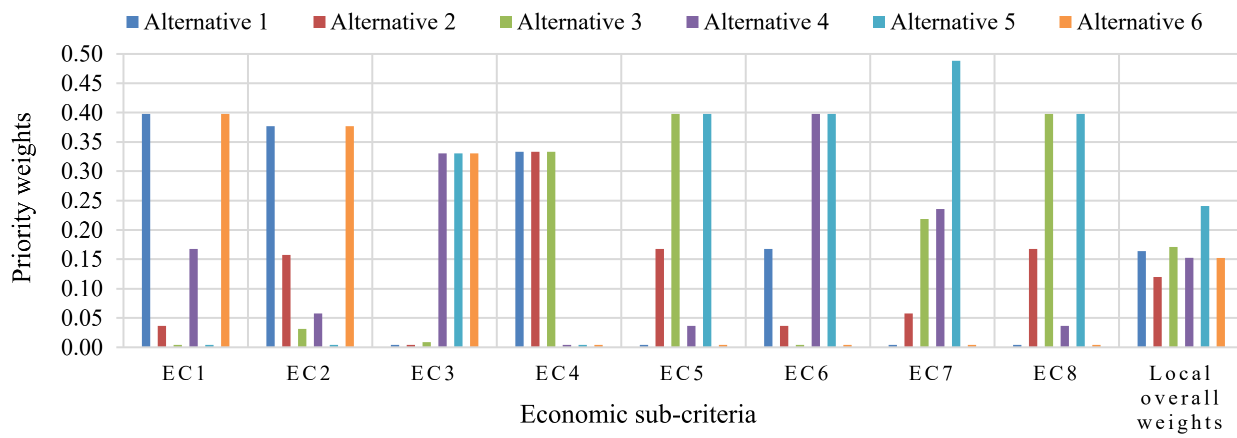



*Figure 5-10: Alternatives local priority weights with respect to economic decision criterion*

The local priority weights of the alternatives with respect to environmental sub-criteria are shown in Figure 5–11. Given stakeholders' aggregated evaluation of the assessment parameters, alternative 6 outweighed other scenarios with a priority weight of 0.34. Alternative 6's performance was the best with respect to ecosystem disruption and environmental conditions impact. This was a result of adopting DSG instead of synthetic oil and molten salt, utilizing linear flat mirrors set close to ground, and avoiding tracking systems. Furthermore, alternative 6 performed exceptionally well in LCA due to low material demand and a good level of annual energy production per net capacity if compared to similar PT plants with no storage at high DNI levels. Alternatives 3 and 5 obtained the lowest priority weights at 0.07 and 0.08, respectively. Both alternatives performed poorly with respect to required area and emission reduction owing to large installed capacities. In addition, alternative 5 scored lowest in the water consumption because of the large solar field and inherently separated heliostats.

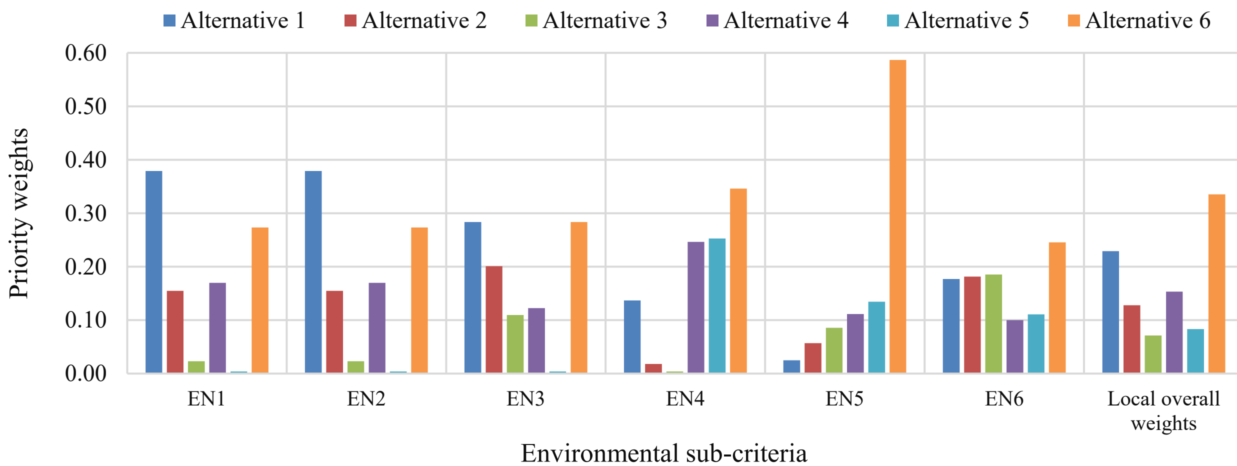



*Figure 5-11: Alternatives local priority weights with respect to environmental decision criterion*

Figure 5–12 presents the local priority weights of the alternatives with respect to social sub-criteria. In a social context, alternative 5 had a clear overall advantage compared to other alternatives with a priority weight of 0.28. Alternative 5's advantage was driven by a highest score in local industrialization possibilities, as well as scoring well in job creation, the most important social priority weighted by stakeholders. Alternatives 3 and 4 came in third and fourth places with priority weights of 0.18 and 0.17, respectively. Alternative 3 had an advantage of high job creation along with alternative 5, as they were the largest two projects. Alternative 4 strongly supported local industrialization with a priority weight second only to the larger ST system (i.e., alternative 5). They both had high material demands that can be met partly by local manufacturers. Alternative 1 obtained the lowest overall social priority weight at 0.10, as it performed poorly in all social sub-criteria except for logistical feasibility because of high maturity of PT with no storage. Yet, the logistical feasibility was evaluated as the lowest parameter by stakeholders, and subsequently has low influence on the overall weight.

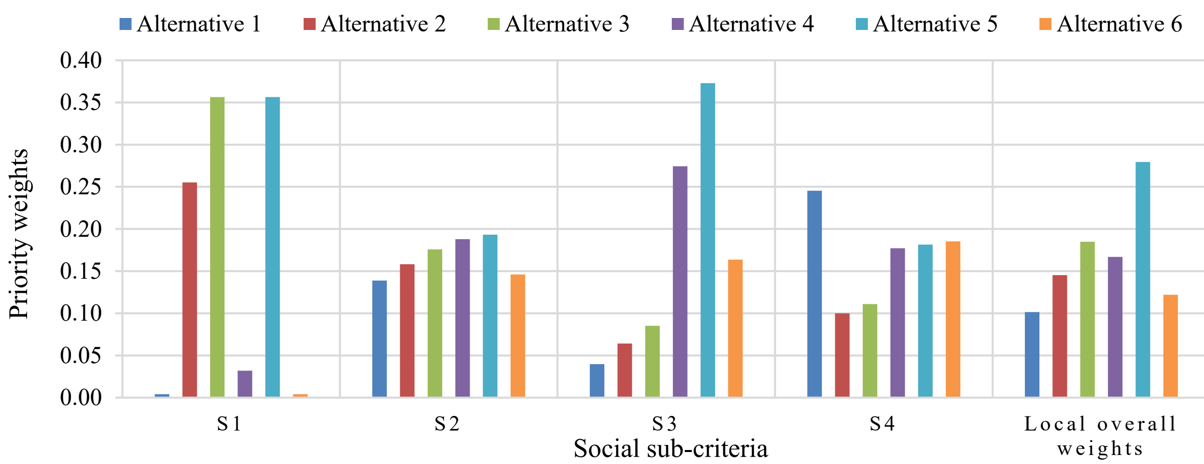



*Figure 5-12: Alternatives local priority weights with respect to social decision criterion*

The presented analysis aimed to make recommendations for adopting CSP projects based on local requirements and objectives. If technical aspects were the essential decision drivers, then PT with no storage had an overall advantage over other alternatives. However, it is vital to consider the breakdown of the technical sub-criteria in which stakeholders lay stress on the main parameters of interest in order to serve CSP integration goals. The same concept applies to other criteria in which alternative 5 outweighed other alternatives in economic and social aspects, while alternative 6 performed best in environmental aspects. Moreover, the other alternatives performances varied with regard to all sub-criteria, and subsequently the global priority weights depended on stakeholders' evaluations of the main criteria. Accordingly, this model with a clear vision of the decision maker can help set an early stage roadmap for the adoption of CSP technology.

Considering the stakeholders' judgments elicited in this study, the assessment of the main criteria obtained is shown in Figure 5–13. Highest priority was allocated to economic criterion. Second to economics was the technical criterion, with minimal differences in priority weight. This result is in line with the essentiality of techno-economic aspects as the main drivers for sustainable development. Environmental and social criteria came in third and fourth places, respectively. National electricity company owners and large energy plant projects initiators are the governments in many developing countries, which broadens the scope of such projects beyond merely the financial considerations. In Figures 5–9 to 5–12, the local overall weights denote the priority weights of alternatives with respect to each criterion. These weights were obtained from the evaluations of alternatives with respect to sub-criteria as well as the evaluation of sub-criteria with respect to parent nodes. In Figure 5–13, the overall global weights denote the priority weights with respect to the goal of prioritizing CSP alternatives to meet stakeholders' requirements, given their evaluation of the main criteria as per the FAHP matrix shown below.

Alternatives local weights to criteria — Criteria weights — Alternatives global weights

$$\begin{bmatrix} \text{Alternative 1} \\ \text{Alternative 2} \\ \text{Alternative 3} \\ \text{Alternative 4} \\ \text{Alternative 5} \\ \text{Alternative 6} \end{bmatrix} \begin{bmatrix} & T & EC & EN & S \\ & 0.24 & 0.16 & 023 & 0.10 \\ & 0.12 & 0.12 & 0.13 & 0.15 \\ & 0.12 & 0.17 & 0.07 & 0.18 \\ & 0.19 & 0.15 & 0.15 & 0.17 \\ & 0.19 & 0.24 & 0.08 & 0.28 \\ & 0.14 & 0.15 & 0.34 & 0.12 \end{bmatrix} * \begin{bmatrix} T \\ EC \\ EN \\ S \end{bmatrix} \begin{bmatrix} 0.28 \\ 0.29 \\ 0.24 \\ 0.19 \end{bmatrix} = \begin{bmatrix} 0.189 \\ 0.127 \\ 0.137 \\ 0.165 \\ 0.196 \\ 0.186 \end{bmatrix}$$

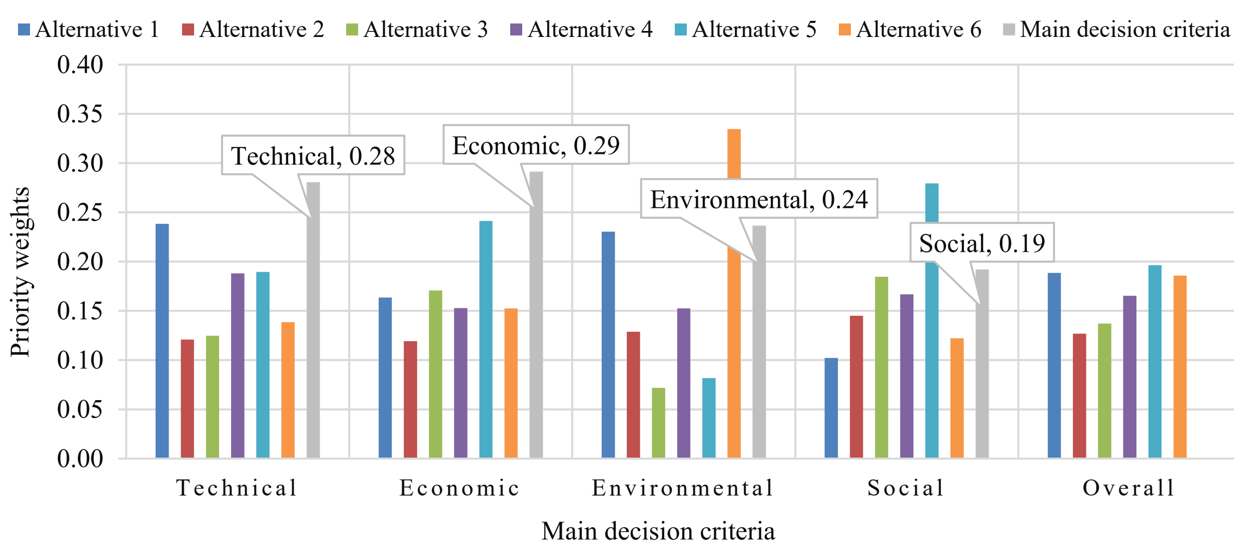



*Figure 5-13: Alternatives global priority weights with respect to goal*

Alternative 5 obtained the highest overall global priority weight, followed by alternatives 1 and 6 with only slight differences. The top alternatives adopted conceptually different technologies and configurations. Subsequently, focusing on the main objectives and barriers facilitates the decision-making process. The objective of this analysis was not to indicate one alternative as optimal in every aspect, but rather to help prioritize alternatives depending on strengths and weaknesses in accordance with stakeholders' and energy sector requirements. The high performance of alternative 5 in several parameters allocated it the highest overall global priority weight. Technically alternative 5 had the highest capacity factor, reliability, and storage hours, which is currently most appropriate with ST systems due to high optical efficiency leading to high operating temperatures. Given that alternatives 4 and 5 adopted similar technologies with different configurations in terms of installed capacity and storage hours indicates that larger plants and longer TESs supported stakeholders' requirements. Alternative 6 adopted LF as a promising technology that comes at low material demand, yet with lower strengths in the technical aspects in general. Economically, alternative 5 gained strength from low LCOE and national economic benefit, however at the expense of high capital cost, O&M cost, and low market maturity. Similarly, alternative 6 yielded low LCOE while also having strength from low capital cost and O&M cost. Environmentally, alternative 6 had a clear advantage over other options whereas alternative 5 was second to lowest. Therefore, the environmental parameter had a high impact on the scores for alternative 6, where a higher weight would lead to greater advantage, while a lower weight would support the priority of alternative 5. Alternative 1, which adopted PT with no storage, appeared to have higher weights in most main criteria compared to alternatives 2 and 3, which also adopted PT but with TESs and larger capacities. Alternative 3 derived strengths particularly from high reliability, as it had 6 h of storage as well as the mature PT technology. In addition, as a massive-scaled project, alternative 3 yielded high economic feasibility, job creation, and national economic benefit. These points of strengths enabled alternative 3 overcoming alternative 2, but it still came only second to last when considering global weights of all alternatives. As more operational PT with longer TESs come online comparable to ST plants (i.e., more than 9 h), points of strengths could shift to enhance the overall performance. Moreover, it is essential to observe whether the stakeholders of a particular region emphasize the parameters that are advantageous to alternative 3. Alternative 2 on the other hand, could not outweigh alternative 1 or 3, as they provided the two PT configurations that could better meet requirements based on the defined objectives.

To validate the calculations and the results of the case study, the acquired quantitative data and stakeholders' inputs were utilized in Expert Choice software. The existence of supporting software solutions is among the strengths of the AHP method. Expert Choice is a decision-making facilitator, which follows the original AHP calculations. The quantitative and qualitative data were also utilized to perform a multi-criteria evaluation (MCE) method, which was proposed by Kaldellis et al, [24] (MCE calculations are demonstrated in Appendix B). The two considered tools for validation do not explicitly address uncertainty and ambiguity of data and elicitation compared to the fuzzy methods. Thus, they result in more deviated and sensitive results illustrated in the alternatives and sub-criteria priority weights. More importantly in this context, the alternatives evaluations obtained through Expert Choice and MCE illustrate similar trends to the FAHP results indicating valid and legit data tackling in this study as shown in Figure 5–14.

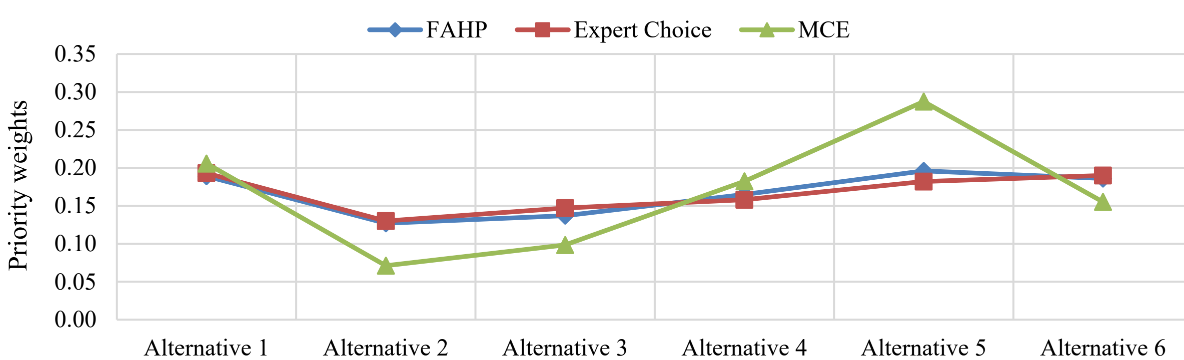



*Figure 5-14: Alternatives evaluations through Expert Choice and MCE for validation*

- **Sensitivity analysis**

Sensitivity analysis was conducted as uncertainty and subjectivity cannot be reduced to zero in early stages of the planning process for large-scale CSP projects in developing countries. It revealed the effect of parameters weights changes on alternatives evaluation results. Several scenarios were considered focusing on the techno-economic aspects with no consideration to other criteria, equal priority weights for the main criteria, and biased scenarios towards each criterion. Figure 5–15 depicts the results of the sensitivity analysis with comparison to the reference scenario that was presented in Figure 5–13 in the results (Section 5.5).

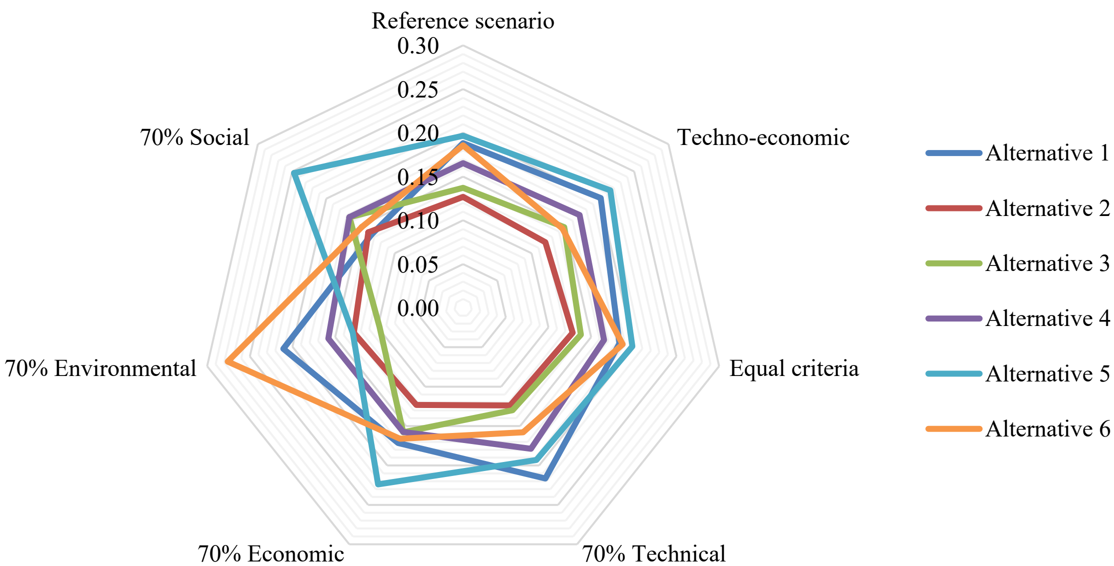



*Figure 5-15: Alternatives priority weights for different scenarios*

In the case of considering only the technical and economic criteria, each was assigned a priority weight of 50%, while environmental and social criteria were disregarded. If the technical and economic criteria were the mere drivers for adopting CSP, then ST appeared to be advantageous if storage was required, which is similar to the reference scenario. PT became advantageous if storage was not required, and the clearest impact was on alternative 6 as its strength was mostly in the environmental category. This interpretation highlighted the impact of the main criteria weights changes. It demonstrated the importance of conducting a deep analysis into the sub-criteria based on local requirements in order to make accurate recommendations. The four biased scenarios included assigning 70% weight to one criterion while the other criteria share the remaining 30% equally. Subsequently, stressing the technical aspect benefitted alternative 1 to outweigh alternative 5. Stressing economic or social aspects furthered the advantage of alternative 5 as the highest weighted alternative, and stressing environmental aspect highly benefitted alternative 6.

As a part of the sensitivity analysis, regional stakeholders' evaluations were investigated to observe their impact on the assessment. The inputs of stakeholders were categorized based on their regions in order to interpret the impact on the criteria compared to the aggregated case as illustrated in Figure 5–16. Regional categories derived from the World Bank study [11] were India, South Africa, and MENA, while the Gulf Cooperation Council (GCC) countries were classified separately with focus on Saudi Arabia. Divergence of the regional evaluations was based on local requirements and characteristics in accordance with the assessing parameters. Economic and technical criteria obtained highest priority weights in all cases either equally or with a slight advantage for the economic criterion. This emphasized the significance of the technical and economic aspects as the driving factors for CSP projects with respect to all different regions. India and South Africa are considered among the newly industrialized countries with operational CSP projects. Indian and South African stakeholders stressed on the local industrialization possibilities as well as job creation and logistical feasibility, which led the social criterion to slightly outweigh environmental criterion in these countries. Stakeholders in the MENA GCC region emphasized the environmental conditions impact as this region witnesses harsh weather conditions with concerns of the impact of sandstorms on the solar radiation reflections. In addition, MENA GCC stakeholders focused on offsetting infrastructure costs, which reflected the importance of electrical energy security and commerce objectives in these countries through the immense GCC interconnection initiative. Stakeholders in the MENA region outside the GCC emphasized hybridization, which led to approximately equal weights for technical and economic criteria. This indicated the need for more experience of smaller CSP segments hybridized with conventional plants, and it also reflected the successful experiences in Egypt and Algeria through the Kuraymat and Ain Beni Mathar hybrid projects.

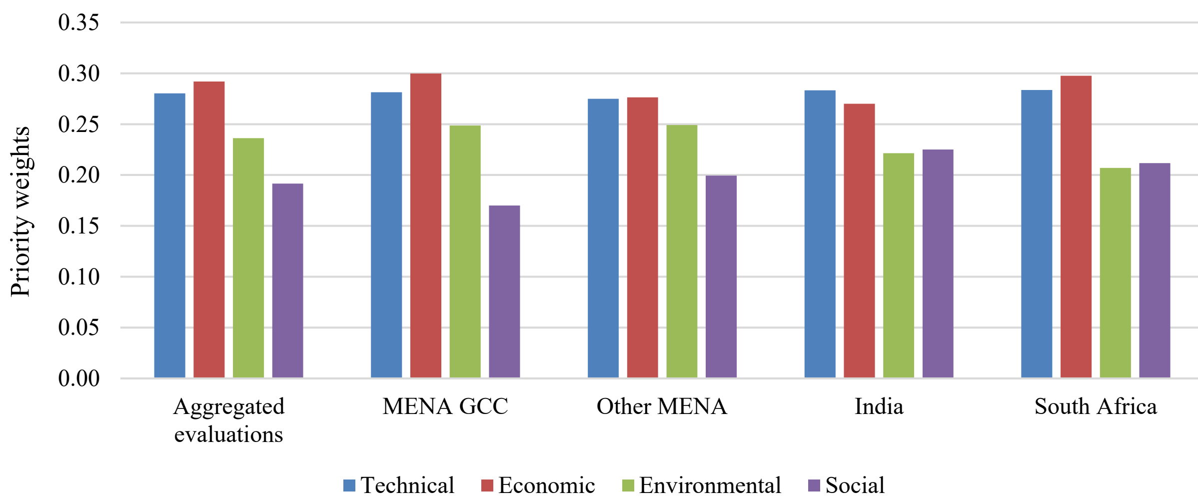



*Figure 5-16: Priority weights of evaluation criteria based on regional stakeholders' evaluation*

## 5.6. Conclusion and Implications

The growing awareness of the important need to adopt RESs is reflected by the ever-increasing capacities of these various technologies. CSP has significant potential to be allocated in large segments in several developing countries, and to be integrated to their national electric power generation schemes. However, CSP is in its infancy for large-scale power plants deployment. In addition, with varied configurations of CSP plants and their supporting technologies, coupled with the lack of sufficient data and experience of some developing countries, the inherent complexity of the planning process for RESs plants is increased.

This study aimed to set a foundation for evaluating practical alternative scenarios for potential early integration of CSP plants in suitable developing countries. An MCDM model was developed in a fuzzy environment to address the various quantitative and qualitative parameters that were involved in the evaluation process. A four-level processing hierarchy was adopted: the first level represented the goal of prioritizing CSP alternatives; the second level contained the four main criteria for the assessment; the third level contained 29 sub-criteria derived from the main trajectories; and the fourth level contained six alternatives including different potential configurations of CSP power plants. An evaluation was carried out through a questionnaire with the participation of forty-four heterogeneous stakeholder panelists from South Africa, India, and the MENA region. Their inputs evaluated the main criteria with respect to the goal, and the sub-criteria with respect to the parent criteria. Moreover, the evaluation of alternatives with respect to each sub-criterion was conducted through extensive investigation in the literature, industrial reports, international databases, and previous simulation results. The developed model adequately handled the uncertainty and ambiguity associated with human judgments in addition to quantitative and qualitative data in order to approach robust decisions.

The six evaluated alternatives involved three PT plants with synthetic oil of which two included molten salts for three and six hours of storage, two ST plants with molten salt as HTF and for ten and twelve hours of storage, and one LF plant with DSG and no TES. The main criteria for evaluation included technical, economic, environmental, and social aspects. Stakeholders' aggregated evaluations indicated the highest priorities as economic and technical aspects, with only slight differences in their rank. Considering the priority weights for the sub-criteria, highest priorities were allocated to reliability, maturity, and conversion efficiency under technical aspects, energy cost and capital cost under economic aspects, water consumption and emission reduction under environmental aspects, and job creation and local industrialization possibilities under social aspects.

Alternative 5 (i.e., 200 MW, ST with 12 h of TES) proved excellent overall performance given stakeholders aggregated priorities. Its strong performance in influencing parameters including reliability, conversion efficiency, energy cost, job creation, and local industrialization greatly contributed to such a high score. However, key possible barriers this option could entail are the required massive capital investment, which was the highest among all options, and the low maturity compared to PT options. Considering the three PT alternatives, the results indicated that alternative 2, which had midrange for installed capacity and TES level, did not outweigh the other two PT alternatives in any of the assessing parameters. This result reflects that PT preferences are toward the periphery for solutions, by means of longer or no TES and larger capacity, depending on the energy sector requirements and priorities of the stakeholders. Considering the overall evaluation, the options with no storage (i.e., alternatives 1 and 6) obtained second and third priorities, with only slight differences between them. Alternative 1, adopting PT with synthetic oil as HTF, had an outstanding maturity, low water consumption, and low GHG emission intensity compared to all other options. Alternative 6, adopting LF with DSG, yielded the lowest energy cost and performs well in all environmental parameters. Moreover, both of these alternatives require low capital costs. Overall, it is vital to be vigilant when reviewing options to consider strengths and weaknesses in accordance with requirements and obstacles.

The proposed methodology helps directing the decision-making process towards narrowing the solutions to better serve the needs of early stage integration of CSP. It enables stakeholders to better understand and analyze the areas of strengths and weaknesses of each solution in accordance with local energy sector requirements, weather characteristics, stakeholders' motivations, and barriers for CSP integration. The employed model focused on CSP alternatives evaluations in developing countries. However, it could be applied to assessing different technologies in different regions if the problem is of similar characteristics in terms of uncertainty and involvement of various criteria and stakeholders.

# Chapter 6: Conclusions and Implications

## 6.1. Summary

Electric power plays a vital role in the prosperity of society. It has a critical impact on the development process. Increasing urbanization and electrification require large-scale investment in electrical energy infrastructure, especially in developing economies. Today, most electricity generated around the globe is based on finite energy sources. Many developing countries raised their attention to RESs to facilitate the sustainability and diversification of energy resources.

When power plants are primarily owned by the private sector, the focus of the development process is more towards technical and economic feasibility. This situation is common in developed countries where governmental legislations are applied to support less established technologies through financial incentives to catch up with the more mature ones. This promotes energy diversifications towards more sustainable options within the electric energy sector. In contrast, it is more common in developing countries for power plants to be owned by the state, which enlarges the scope of electric power projects beyond the techno-economic drivers to include environmental, social, and political aspects, and accordingly increases the planning process complexity.

The presented research in this thesis aimed to facilitate the decision-making process through the proposed methodology, which included three main phases. In the first phase, an identification of the evaluation criteria of CSP technologies for large-scale deployment in developing countries was carried out. The study was conducted through a structured ADP with the participation of 140 experts from multidisciplinary fields related to solar thermal power following the Delphi method in two rounds of questionnaires. A trigger value tree was derived from literature as a starting point. The expert elicitation was then performed to evaluate the importance of each criterion for the assessment process and to add more required parameters. Individual value trees were subsequently combined and analyzed by measuring degrees of importance, consensus, and stability to proceed to the next round of deliberation. The outcomes of this phase were represented in an aggregated value tree with a consensus rate for each parameter of > 50%.

The second phase of the thesis aimed to analyze alternative CSP scenarios with consideration of local requirements in order to focus on more practical options and obtain accurate results. The alternatives were defined based on comprehensive research into the merits of different technologies involved in CSP power plants through SWOT analysis. Subsequently, Saudi Arabia's weather data were synthesized, and local energy sector requirements were incorporated into the analysis to make recommendations for the definition of alternative scenarios. Simulations were then carried out on the alternative scenarios to evaluate largely influencing technical and economic parameters.

In the third phase of the thesis, a fuzzy MCDM model was developed to evaluate the defined alternatives with respect to the goal of assessing large-scale CSP plants given the aggregated value tree. The different capabilities of alternative scenarios require the consideration of all related criteria and the stakeholders' evaluations for criteria and sub-criteria weights. This helps avoid the shortcoming of a mere techno-economic evaluation. Quantitative and qualitative data were obtained through extensive research in the literature, industrial reports, international databases, and previous simulation results. Accordingly, degrees of possibilities were compared for pairwise comparisons of TFNs in accordance with the alternatives to reach the fuzzy evaluation matrix. Finally, a sensitivity analysis was carried out due to the subjectivity and uncertainty involved in CSP planning.

In summary, the proposed hybrid ADP and fuzzy MCDM methodology ensures the involvement of worldwide CSP experts and local energy stakeholders in the decision-making process in a structured framework to support increased acceptability and credibility of results. In addition, it supports higher objectivity and wisdom, involvement of different perspectives, as well as the assignment of a fair share of responsibility.

### 6.2. Contributions

The original contributions of this thesis can be highlighted as follows:

- Integration of a deliberation-based model (i.e., ADP) to structurally tackle human perspectives with an equation-based model (i.e., FAHP) to tackle calculations. This integration helps to propose a framework for the decision-making of technology planning with various options and uncertainty. The hybrid model addresses the evaluations of global experts, with their knowledge and experience in the CSP sector, and the evaluations of local stakeholders, with their knowledge of local energy sectors requirements.
- Development of a unique generic value tree for the evaluation of large-scale CSP deployment in developing countries. This work sets the foundation for the solicitation of worldwide experts to obtain aggregated perspectives, improve consensus, and explicitly formulate the evaluation parameters combination for the first time in the context of CSP plants planning.
- This work proposed a constructed analysis for the definition of practical alternative scenarios consisting of various combinations of technologies involved in CSP plants with the incorporation of local energy sector requirements. In addition, the local weather data profile of Saudi Arabia was synthesized by integrating satellite observations and on-the-ground stations measurements in order to obtain data with high accuracy for simulations.

- An MCDM model was developed in a fuzzy environment to conduct a scenario-based alternatives evaluation. TFNs were utilized to overcome uncertainty and subjectivity. The model addresses alternative assessments with respect to 29 sub-criteria obtained from the aggregated value tree under technical, economic, environmental, and social criteria. The model tackles both quantitative and qualitative data and provides crucial information for early stage planning for the integration of CSP plants to national grids. Qualitative input data were obtained from heterogeneous energy stakeholder panelists from potential developing countries for CSP deployment. The model produces insight into the evaluation of alternatives subjected as package options to legal decision makers in a transparent and structured hierarchical manner instead of a black box process in which a decision is unveiled as the final solution. Consequently, political bodies can make the final selection to meet legitimate rules and institutional arrangements.

### 6.3. Limitations and future work

In order to involve data providers from solar thermal power community around the world to bring together their experience and vision, it was not possible to obtain higher level of commitment from participants at the current level of capabilities. This shortcoming could be overcome in future work through involving higher number of respondents for enhanced results impact. Moreover, this work could be improved through extended research into the definition of importance and consensus thresholds. It could also be improved by further researching the design parameters for alternative simulations, which is required for the advanced planning stages. In addition, it will be possible over time to obtain long-term field weather data to enhance the simulation accuracy.

Future research could carry out analysis extension to include alternatives involving water desalination, hybridization with conventional and renewable power plants, as well as the requirements for integration with local grids. In addition, the impact of local differences such as interest rates, lifetime expectations, and geopolitical aspects can be investigated further. A broader scope for future research can incorporate the complex adaptive system (CAS) and complexity theory through tackling the behavior dynamics and interactions between the different elements of the system.

### 6.4. List of publications

#### Journal papers

- **A. Kassem**, K. Al-Haddad, D. Komljenovic, and A. Schiffauerova. Assessment of concentrated solar thermal power alternatives in developing countries: A fuzzy multi-criteria decision-making model. *Journal of cleaner production* **(Submitted).**
- **A. Kassem**, K. Al-Haddad, and D. Komljenovic, "Concentrated solar thermal power in Saudi Arabia: Definition and simulation of alternative scenarios," *Renewable and. Sustainable. Energy Reviews*., vol. 80, pp. 75–91, Dec. 2017 **(Published).**
- **A. Kassem**, K. Al-Haddad, D. Komljenovic, and A. Schiffauerova, "A value tree for identification of evaluation criteria for solar thermal power technologies in developing countries," Sustainable Energy Technology Assessments, vol. 16, pp. 18–32, Aug. 2016. **(Published).**
- H. Al Garni, **A. Kassem**, A. Awasthi, D. Komljenovic, and K. Al-Haddad, "A multicriteria decision making approach for evaluating renewable power generation sources in Saudi Arabia," Sustainable Energy Technology Assessments, vol. 16, 2016 **(Published).**

**Conferences papers and presentations**

- **A. Kassem**, K. Al-Haddad, and D. Komljenovic, "Techno-economic analysis for concentrated solar thermal power in developing countries" in International Energy & Environment Summit, Dubai, Mar 2017.
- **A. Kassem**, K. Al-Haddad, and D. Komljenovic, "Weather data influence on concentrated solar thermal power plants simulation in Saudi Arabia." in International Conference and Exhibition on Clean Energy (ICCE), Montreal, Aug 2016.
- **A. Kassem**, K. Al-Haddad, D. Komljenovic, and A. Schiffauerova, "A comparison of two multiple criteria decision methods for solar thermal power collecting technologies evaluation." in International Conference on Modern Engineering and Technological Advances, Toronto, Sep 2016, pp. 29-38.

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# Appendix A: Pairwise Comparison Calculations of the Fuzzy Analytic Hierarchy Process (FAHP) Model

This Appendix presents the calculations of the Fuzzy AHP model. The pairwise comparison matrices for evaluating the decision criteria, sub-criteria, and alternatives are illustrated.

## A.1. Criteria and sub-criteria priority weights

In this section, the calculation of the decision criteria evaluation with respect to the main goal and the sub-criteria with respect to the parent criteria are demonstrated. The pairwise comparisons of the decision criteria and the sub-criteria were applied through stakeholders' aggregated evaluations as shown in Tables A–1 to A–5. Stakeholders' aggregated evaluations were also applied to perform the pairwise comparisons of the alternatives with respect to the social and political acceptance sub-criterion as shown in Table A–32. The remaining pairwise comparisons are applied based on the triangular fuzzy conversion scale which was illustrated in Chapter 5 (Table 5–1).

### A.1.1. Decision criteria to the main goal

| | Technical | Economic | Environmental | Social |
|---|---|---|---|---|
| Technical | (1,1,1) | (0.55,0.95,1.39) | (0.76,1.22,1.70) | (0.98,1.46,1.94) |
| Economic | (0.72,1.05,1.83) | (1,1,1) | (0.80,1.27,1.76) | (1,1.52,2.03) |
| Environmental | (0.59,0.82,1.31) | (0.57,0.79,1.24) | (1,1,1) | (0.75,1.21,1.70) |
| Social | (0.51,0.69,1.02) | (0.49,0.66,1) | (0.59,0.82,1.34) | (1,1,1) |

*Table A-1: Pairwise comparison of decision criteria with respect to goal*

The synthetic extents were subsequently calculated and found to be as follows:

$S_1$= (0.15,0.28,0.49), $S_2$= (0.16,0.29,0.54), $S_3$= (0.13,0.23,0.43), $S_4$= (0.12,0.19,0.35).

Then, the degrees of possibilities were found as follows:

$V(S_1 \geq S_2)$= 0.96, $V(S_1 \geq S_3)$= 1, $V(S_1 \geq S_4)$= 1 ➔ $V(S_1 \geq S_2, S_3, S_4)$= 0.96

$V(S_2 \geq S_1)$= 1, $V(S_2 \geq S_3)$= 1, $V(S_2 \geq S_4)$= 1 ➔ $V(S_2 \geq S_1, S_3, S_4)$= 1

$V(S_3 \geq S_1)$= 0.85, $V(S_3 \geq S_2)$= 0.81, $V(S_3 \geq S_4)$= 1 ➔ $V(S_3 \geq S_1, S_2, S_4)$= 0.81

$V(S_4 \geq S_1)$= 0.70, $V(S_4 \geq S_2)$= 0.66, $V(S_4 \geq S_4)$= 0.85 ➔ $V(S_4 \geq S_1, S_2, S_3)$= 0.66

Therefore, W'= $[0.96,1,0.81,0.66]^T$, and hence W= $[0.28,0.29,0.24,0.19]^T$.

## A.1.2. Sub-criteria to parent criteria

| | T 1 | T 2 | T 3 | T 4 | T 5 | T 6 | T 7 | T 8 | T 9 | T 10 | T 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| T 1 | (1,1,1) | (0.64,1.08,1.56) | (0.61,1.02,1.47) | (0.60,0.96,1.38) | (0.75,1.23,1.71) | (0.65,1.03,1.47) | (0.72,1.21,1.71) | (0.63,1.05,1.52) | (0.66,1.13,1.62) | (0.85,1.32,1.81) | (0.73,1.17,1.64) |
| T 2 | (0.64,0.92,1.57) | (1,1,1) | (0.52,0.94,1.40) | (0.55,0.89,1.29) | (0.72,1.14,1.60) | (0.60,0.96,1.38) | (0.69,1.13,1.61) | (0.60,0.98,1.42) | (0.61,1.05,1.52) | (0.72,1.23,1.73) | (0.66,1.08,1.54) |
| T 3 | (0.68,0.98,1.63) | (0.72,1.07,1.94) | (1,1,1) | (0.57,0.94,1.37) | (0.76,1.22,1.71) | (0.62,1.02,1.47) | (0.74,1.21,1.70) | (0.63,1.04,1.50) | (0.64,1.11,1.60) | (0.79,1.30,1.81) | (0.69,1.16,1.65) |
| T 4 | (0.73,1.05,1.67) | (0.78,1.13,1.83) | (0.73,1.07,1.77) | (1,1,1) | (0.82,1.09,1.78) | (0.67,1.10,1.55) | (0.80,1.28,1.77) | (0.67,1.11,1.58) | (0.72,1.19,1.68) | (0.87,1.34,1.84) | (0.78,1.23,1.70) |
| T 5 | (0.58,0.81,1.33) | (0.62,0.88,1.39) | (0.59,0.82,1.32) | (0.56,0.77,1.22) | (1,1,1) | (0.55,0.84,1.21) | (0.59,1,1.45) | (0.55,0.86,1.24) | (0.57,0.91,1.32) | (0.67,1.06,1.51) | (0.59,0.96,1.38) |
| T 6 | (0.68,0.94,1.54) | (0.72,1.04,1.66) | (0.68,0.98,1.62) | (0.64,0.91,1.49) | (0.83,1.18,1.83) | (1,1,1) | (0.71,1.18,1.66) | (0.64,1.01,1.44) | (0.65,1.09,1.55) | (0.79,1.24,1.72) | (0.74,1.12,1.56) |
| T7 | (0.58,0.82,1.39) | (0.62,0.88,1.46) | (0.59,0.82,1.36) | (0.56,0.78,1.26) | (0.69,1,1.69) | (0.60,0.85,1.41) | (1,1,1) | (0.55,0.86,1.25) | (0.56,0.92,1.34) | (0.65,1.08,1.54) | (0.60,0.96,1.37) |
| T 8 | (0.66,0.95,1.58) | (0.71,1.02,1.67) | (0.67,0.96,1.60) | (0.63,0.90,1.50) | (0.81,1.17,1.80) | (0.70,0.99,1.57) | (0.80,1.16,1.83) | (1,1,1) | (0.62,1.07,1.54) | (0.80,1.26,1.74) | (0.67,1.12,1.59) |
| T9 | (0.62,0.89,1.51) | (0.66,0.95,1.64) | (0.62,0.90,1.57) | (0.59,0.84,1.39) | (0.76,1.10,1.77) | (0.65,0.92,1.53) | (0.75,1.09,1.78) | (0.65,0.93,1.61) | (1,1,1) | (0.73,1.18,1.65) | (0.65,1.05,1.49) |
| T 10 | (0.55,0.76,1.18) | (0.58,0.82,1.38) | (0.55,0.77,1.27) | (0.54,0.74,1.14) | (0.66,0.94,1.48) | (0.58,0.81,1.27) | (0.65,0.92,1.53) | (0.85,0.80,1.26) | (0.61,0.85,1.38) | (1,1,1) | (0.54,0.89,1.29) |
| T 11 | (0.61,0.85,1.37) | (0.65,0.93,1.52) | (0.61,0.86,1.54) | (0.59,0.82,1.29) | (0.72,1.04,1.71) | (0.64,0.89,1.35) | (0.73,1.04,1.64) | (0.63,0.89,1.48) | (0.64,0.95,1.54) | (0.78,1.12,1.85) | (1,1,1) |

*Table A-2: Pairwise comparison of decision sub-criteria with respect to technical criterion*

The synthetic extents were subsequently calculated and found to be as follows:

$S_1$= (0.04,0.10,0.20), $S_2$= (0.04,0.09,0.19), $S_3$= (0.04,0.10,0.21), $S_4$= (0.05,0.10,0.22), $S_5$= (0.04,0.08,0.17), $S_6$= (0.04,0.10,0.20), $S_7$= (0.04,0.08,0.18), $S_8$= (0.04,0.09,0.21), $S_9$= (0.04,0.09,0.20), $S_{10}$= (0.04,0.08,0.17), $S_{11}$= (0.04,0.09,0.19).

After calculating the degrees of possibilities, the priority weight vectors were found to be:

$W= [0.097,0.092,0.096,0.100,0.084,0.094,0.085,0.094,0.090,0.081,0.087]^T$.

| | EC 1 | EC 2 | EC 3 | EC 4 | EC 5 | EC 6 | EC 7 | EC 8 |
|---|---|---|---|---|---|---|---|---|
| EC 1 | (1,1,1) | (0.60,1.05,1.52) | (0.65,0.99,1.45) | (0.76,1.24,1.73) | (0.66,1.13,1.61) | (0.99,1.50,2.01) | (0.89,1.37,1.85) | (0.77,1.24,1.71) |
| EC 2 | (0.66,0.95,1.66) | (1,1,1) | (0.54,0.97,1.41) | (0.72,1.19,1.68) | (0.65,1.09,1.55) | (0.95,1.47,1.99) | (0.83,1.32,1.81) | (0.67,1.15,1.64) |
| EC 3 | (0.69,1.01,1.77) | (0.71,1.04,1.85) | (1,1,1) | (0.73,1.25,1.75) | (0.65,1.13,1.62) | (0.98,1.52,2.04) | (0.85,1.37,1.88) | (0.75,1.22,1.71) |
| EC 4 | (0.58,0.80,1.32) | (0.60,0.84,1.38) | (0.57,0.80,1.36) | (1,1,1) | (0.55,0.91,1.33) | (0.78,1.26,1.74) | (0.67,1.12,1.60) | (0.59,0.99,1.43) |
| EC 5 | (0.62,0.89,1.52) | (0.65,0.92,1.54) | (0.62,0.88,1.55) | (0.75,1.10,1.82) | (1,1,1) | (0.84,1.35,1.86) | (0.74,1.22,1.72) | (0.66,1.09,1.55) |
| EC 6 | (0.50,0.67,1.01) | (0.50,0.68,1.05) | (0.49,0.66,1.02) | (0.57,0.79,1.28) | (0.54,0.74,1.19) | (1,1,1) | (0.51,0.88,1.30) | (0.51,0.79,1.13) |
| EC 7 | (0.54,0.73,1.12) | (0.55,0.76,1.20) | (0.53,0.73,1.18) | (0.63,0.89,1.50) | (0.58,0.82,1.34) | (0.77,1.13,1.94) | (1,1,1) | (0.54,0.89,1.29) |
| EC 8 | (0.58,0.81,1.30) | (0.61,0.87,1.49) | (0.58,0.82,1.33) | (0.70,1.01,1.70) | (0.64,0.92,1.52) | (0.88,1.27,1.97) | (0.77,1.13,1.85) | (1,1,1) |

*Table A-3: Pairwise comparison of decision sub-criteria with respect to economic criterion*

The synthetic extents were subsequently calculated and found to be as follows:

$S_1$= (0.07,0.15,0.28), $S_2$= (0.06,0.14,0.28), $S_3$= (0.07,0.15,0.30), $S_4$= (0.06,0.12,0.25), $S_5$= (0.06,0.13,0.28), $S_6$= (0.05,0.10,0.20), $S_7$= (0.05,0.11,0.23), $S_8$= (0.06,0.12,0.27).

After calculating the degrees of possibilities, the priority weight vectors were found to be as follows:

W= $[0.139,0.135,0.139,0.122,0.129,0.101,0.112,0.123]^T$.

| | EN 1 | EN 2 | EN 3 | EN 4 | EN 5 | EN 6 |
|---|---|---|---|---|---|---|
| EN 1 | (1,1,1) | (0.57,0.90,1.28) | (0.57,0.87,1.23) | (0.67,0.96,1.35) | (0.61,0.93,1.33) | (0.62,0.95,1.34) |
| EN 2 | (0.78,1.12,1.75) | (1,1,1) | (0.61,1,1.42) | (0.69,1.16,1.65) | (0.65,1.07,1.52) | (0.68,1.08,1.52) |
| EN 3 | (0.81,1.15,1.74) | (0.71,1,1.65) | (1,1,1) | (0.62,1,1.45) | (0.63,1.08,1.55) | (0.67,1.09,1.54) |
| EN 4 | (0.74,1.04,1.49) | (0.61,0.86,1.46) | (0.69,1,1.62) | (1,1,1) | (0.50,0.92,1.38) | (0.54,0.89,1.13) |
| EN 5 | (0.75,1.07,1.64) | (0.66,0.93,1.53) | (0.65,0.93,1.58) | (0.72,1.08,2) | (1,1,1) | (0.58,1.01,1.47) |
| EN 6 | (0.75,1.05,1.60) | (0.66,0.92,1.46) | (0.65,0.92,1.50) | (0.76,1.13,1.87) | (0.680.99,1.72) | (1,1,1) |

*Table A- 4: Pairwise comparison of decision sub-criteria with respect to environmental criterion*

The synthetic extents were subsequently calculated and found to be as follows:

$S_1$= (0.08,0.16,0.29), $S_2$= (0.08,0.16,0.29), $S_3$= (0.09,0.18,0.35), $S_4$= (0.08,0.16,0.32),

$S_5$= (0.08,0.17,0.36), $S_6$= (0.09,0.17,0.35),

After calculating the degrees of possibilities, the priority weight vectors were found to be as follows:

W= $[0.155,0.172,0.173,0.168,0.168,0.166]^T$.

| | S 1 | S 2 | S 3 | S 4 |
|---|---|---|---|---|
| S 1 | (1,1,1) | (0.62,1.06,1.53) | (0.61,1.03,1.49) | (0.72,1.14,1.60) |
| S 2 | (0.65,0.94,1.61) | (1,1,1) | (0.57,0.98,1.43) | (0.68,1.08,1.54) |
| S 3 | (0.67,0.97,1.65) | (0.70,1.02,1.76) | (1,1,1) | (0.69,1.14,1.62) |
| S 4 | (0.62,0.88,1.38) | (0.65,0.92,1.47) | (0.62,0.88,1.46) | (1,1,1) |

*Table A-5: Pairwise comparison of decision sub-criteria with respect to social criterion*

The synthetic extents were subsequently calculated and found to be as follows:

$S_1$= (0.13,0.26,0.48), $S_2$= (0.13,0.25,0.47), $S_3$= (0.14,0.26,0.51), $S_4$= (0.13,0.23,0.45).

After calculating the degrees of possibilities, the priority weight vectors were found to be as follows:

W= $[0.260,0.251,0.256,0.233]^T$.

## A.2. Alternatives priority weights with respect to sub-criteria

In this section, the calculation of the alternatives evaluation with respect to sub-criteria under the four main criteria are demonstrated.

### A.2.1. Alternatives to sub-criteria under technical

| Maturity | Alt 1 | Alt 2 | Alt 3 | Alt 4 | Alt 5 | Alt 6 |
|---|---|---|---|---|---|---|
| Alt 1 | (1,1,1) | (2,5/2,3) | (2,5/2,3) | (5/2,3,7/2) | (5/2,3,7/2) | (5/2,3,7/2) |
| Alt 2 | (1/3,2/5,1/2) | (1,1,1) | (1,1,1) | (1,3/2,2) | (1,3/2,2) | (1,3/2,2) |
| Alt 3 | (1/3,2/5,1/2) | (1,1,1) | (1,1,1) | (1,3/2,2) | (1,3/2,2) | (1,3/2,2) |
| Alt 4 | (2/7,1/3,2/5) | (1/2,2/3,1) | (1/2,2/3,1) | (1,1,1) | (1,1,1) | (1/2,1,3/2) |
| Alt 5 | (2/7,1/3,2/5) | (1/2,2/3,1) | (1/2,2/3,1) | (1,1,1) | (1,1,1) | (1/2,1,3/2) |
| Alt 6 | (2/7,1/3,2/5) | (1/2,2/3,1) | (1/2,2/3,1) | (2/3,1,2) | (2/3,1,2) | (1,1,1) |

*Table A-6: Pairwise comparison of alternatives with respect to maturity*

The synthetic extents were subsequently calculated and found to be as follows:

$S_1$= (0.22,0.35,0.54), $S_2$= (0.09,0.16,0.28), $S_3$= (0.09,0.16,0.29), $S_4$= (0.06,0.11,0.20),

$S_5$= (0.06,0.11,0.21), $S_6$= (0.06,0.11,0.23).

Then, the degrees of possibilities were found as follow:

$V(S_1 \geq S_2)$= 1, $V(S_1 \geq S_3)$= 1, $V(S_1 \geq S_4)$= 1, $V(S_1 \geq S_5)$= 1, $V(S_1 \geq S_6)$= 1 ➔ $V(S_1 \geq S_2, S_3, S_4, S_5, S_6)$= 1

$V(S_2 \geq S_1)$= 0.07, $V(S_2 \geq S_3)$= 1, $V(S_2 \geq S_4)$= 1, $V(S_2 \geq S_5)$= 1, $V(S_2 \geq S_6)$= 1➔ $V(S_2 \geq S_1, S_3, S_4, S_5, S_6)$= 0.07

$V(S_3 \geq S_1)$= 0.07, $V(S_3 \geq S_2)$= 1, $V(S_3 \geq S_4)$= 1, $V(S_3 \geq S_5)$= 1, $V(S_3 \geq S_6)$= 1➔ $V(S_3 \geq S_1, S_2, S_4, S_5, S_6)$= 0.07

$V(S_4 \geq S_1)$= 0, $V(S_4 \geq S_2)$= 0.58, $V(S_4 \geq S_4)$= 0.58, $V(S_4 \geq S_5)$= 1, $V(S_4 \geq S_6)$= 1➔ $V(S_4 \geq S_1, S_2, S_3, S_5, S_6)$= 0

$V(S_5 \geq S_1)$= 0, $V(S_5 \geq S_2)$= 0.58, $V(S_5 \geq S_3)$= 0.58, $V(S_5 \geq S_4)$= 1, $V(S_5 \geq S_6)$= 1➔ $V(S_5 \geq S_1, S_2, S_3, S_4, S_6)$= 0

$V(S_6 \geq S_1)$= 0, $V(S_6 \geq S_2)$= 0.69, $V(S_6 \geq S_3)$= 0.69, $V(S_6 \geq S_4)$= 1, $V(S_6 \geq S_5)$= 1➔ $V(S_6 \geq S_1, S_2, S_3, S_4, S_5)$= 0

Therefore, W'= $[1,0.07,0.07,0,0,0]^T$, and hence W= $[0.87,0.06,0.06,0,0,0]^T$.

| Optical efficiency | Alt 1 | Alt 2 | Alt 3 | Alt 4 | Alt 5 | Alt 6 |
|---|---|---|---|---|---|---|
| Alt 1 | (1,1,1) | (1,1,1) | (1,1,1) | (1/3,2/5,1/2) | (1/3,2/5,1/2) | (1,3/2,2) |
| Alt 2 | (1,1,1) | (1,1,1) | (1,1,1) | (1/3,2/5,1/2) | (1/3,2/5,1/2) | (1,3/2,2) |
| Alt 3 | (1,1,1) | (1,1,1) | (1,1,1) | (1/3,2/5,1/2) | (1/3,2/5,1/2) | (1,3/2,2) |
| Alt 4 | (2,5/2,3) | (2,5/2,3) | (2,5/2,3) | (1,1,1) | (1,1,1) | (5/2,3,7/2) |
| Alt 5 | (2,5/2,3) | (2,5/2,3) | (2,5/2,3) | (1,1,1) | (1,1,1) | (5/2,3,7/2) |
| Alt 6 | (1/2,2/3,1) | (1/2,2/3,1) | (1/2,2/3,1) | (2/7,1/3,2/5) | (2/7,1/3,2/5) | (1,1,1) |

*Table A-7: Pairwise comparison of alternatives with respect to optical efficiency*

The synthetic extents were subsequently calculated and found to be as follow:

$S_1$= (0.09,0.12,0.16), $S_2$= (0.09,0.12,0.16), $S_3$= (0.09,0.12,0.16), $S_4$= (0.2,0.28,0.38),

$S_5$= (0.2,0.28,0.38), $S_6$= (0.06,0.08,0.13).

After calculating the degrees of possibilities, the priority weight vectors were found to be as follows:

W= $[0,0,0,0.5,0.5,0]^T$.

| Conversion efficiency | Alt 1 | Alt 2 | Alt 3 | Alt 4 | Alt 5 | Alt 6 |
|---|---|---|---|---|---|---|
| Alt 1 | (1,1,1) | (1/2,1,3/2) | (1/2,2/3,1) | (1/3,2/5,1/2) | (2/7,1/3,2/5) | (1/2,1,3/2) |
| Alt 2 | (2/3,1, 2) | (1,1,1) | (1/2,2/3,1) | (1/3,2/5,1/2) | (2/7,1/3,2/5) | (1/2,1,3/2) |
| Alt 3 | (1,3/2,2) | (1,3/2,2) | (1,1,1) | (2/5,1/2,2/3) | (1/3,2/5,1/2) | (1,3/2,2) |
| Alt 4 | (2,5/2,3) | (2,5/2,3) | (3/2,2,5/2) | (1,1,1) | (1/2,2/3,1) | (2,5/2,3) |
| Alt 5 | (5/2,3,7/2) | (5/2,3,7/2) | (2,5/2,3) | (1,3/2,2) | (1,1,1) | (5/2,3,7/2) |
| Alt 6 | (2/3,1,2) | (2/3,1,2) | (1/2,2/3,1) | (1/3,2/5,1/2) | (2/7,1/3,2/5) | (1,1,1) |

*Table A- 8: Pairwise comparison of alternatives with respect to conversion efficiency*

The synthetic extents were subsequently calculated and found to be as follow:

$S_1$= (0.05,01,0.17), $S_2$= (0.06,0.1,0.18), $S_3$= (0.08,0.14,0.23), $S_4$= (0.16,0.25,0.38),

$S_5$= (0.2,0.31,0.47), $S_6$= (0.06,0.1,0.2).

After calculating the degrees of possibilities, the priority weight vectors were found to be as follows:

W= $[0,0,0.08,0.39,0.53,0]^T$.

| Reliability | Alt 1 | Alt 2 | Alt 3 | Alt 4 | Alt 5 | Alt 6 |
|---|---|---|---|---|---|---|
| Alt 1 | (1,1,1) | (1/2,1,3/2) | (1/2,2/3,1) | (1/2,2/3,1) | (1/2,2/3,1) | (3/2,2,5/2) |
| Alt 2 | (2/3,1,2) | (1,1,1) | (1/2,2/3,1) | (1/2,2/3,1) | (1/2,2/3,1) | (3/2,2,5/2) |
| Alt 3 | (1,3/2,2) | (1,3/2,2) | (1,1,1) | (1/2,1,3/2) | (1/2,1,3/2) | (2,5/2,3) |
| Alt 4 | (1,3/2,2) | (1,3/2,2) | (2/3,1,2) | (1,1,1) | (1/2,1,3/2) | (2,5/2,3) |
| Alt 5 | (1,3/2,2) | (1,3/2,2) | (2/3,1,2) | (2/3,1,2) | (1,1,1) | (2,5/2,3) |
| Alt 6 | (2/5,1/2,2/3) | (2/5,1/2,2/3) | (1/3,2/5,1/2) | (1/3,2/5,1/2) | (1/3,2/5,1/2) | (1,1,1) |

*Table A-9: Pairwise comparison of alternatives with respect to reliability*

The synthetic extents were subsequently calculated and found to be as follow:

$S_1$= (0.08,0.15,0.26), $S_2$= (0.09,0.15,0.28), $S_3$= (0.11,0.21,0.36), $S_4$= (0.11,0.21,0.38),

$S_5$= (0.12,0.21,0.39), $S_6$= (0.05,0.08,0.13).

After calculating the degrees of possibilities, the priority weight vectors were found to be as follows:

W= $[0.16,0.16,0.22,0.22,0.22,0.02]^T$.

| Deployment time | Alt 1 | Alt 2 | Alt 3 | Alt 4 | Alt 5 | Alt 6 |
|---|---|---|---|---|---|---|
| Alt 1 | (1,1,1) | (1,3/2,2) | (3/2,2,5/2) | (3/2,2,5/2) | (2,5/2,3) | (1,3/2,2) |
| Alt 2 | (1/2,2/3,1) | (1,1,1) | (1,3/2,2) | (1,3/2,2) | (3/2,2,5/2) | (1/2,1,3/2) |
| Alt 3 | (2/5,1/2,2/3) | (1/2,2/3,1) | (1,1,1) | (1/2,1,3/2) | (1,3/2,2) | (1/2,2/3,1) |
| Alt 4 | (2/5,1/2,2/3) | (1/2,2/3,1) | | (1,1,1) | (1,3/2,2) | (1/2,2/3,1) |
| Alt 5 | (2/5,1/2,2/3) | (2/5,1/2,2/3) | (1/2,2/3,1) | (1/2,2/3,1) | (1,1,1) | (2/5,1/2,2/3) |
| Alt 6 | (1/2,2/3,1) | (2/3,1,2) | (1,3/2,2) | (1,3/2,2) | (3/2,2,5/2) | (1,1,1) |

*Table A-10: Pairwise comparison of alternatives with respect to deployment time*

The synthetic extents were subsequently calculated and found to be as follow:

$S_1$= (0.15,0.26,0.43), $S_2$= (0.10,0.19,0.33), $S_3$= (0.07,0.13,0.24), $S_4$= (0.16,0.25,0.38),

$S_5$= (0.06,0.09,0.16), $S_6$= (0.11,0.19,0.35).

After calculating the degrees of possibilities, the priority weight vectors were found to be as follows:

W= $[0.3,0.21,0.12,0.13,0.02,0.22]^T$.

| Safety | Alt 1 | Alt 2 | Alt 3 | Alt 4 | Alt 5 | Alt 6 |
|---|---|---|---|---|---|---|
| Alt 1 | (1,1,1) | (1,3/2,2) | (2,5/2,3) | (3/2,2,5/2) | (5/2,3,7/2) | (1,3/2,2) |
| Alt 2 | (1/2,2/3,1) | (1,1,1) | (3/2,2,5/2) | (1,3/2,2) | (2,5/2,3) | (1/2,1,3/2) |
| Alt 3 | (1/3,2/5,1/2) | (2/5,1/2,2/3) | (1,1,1) | (1/2,2/3,1) | (1,3/2,2) | (2/5,1/2,2/3) |
| Alt 4 | (2/5,1/2,2/3) | (1/2,2/3,1) | (1,3/2,2) | (1,1,1) | (3/2,2,5/2) | (1/2,2/3,1) |
| Alt 5 | (2/7,1/3,2/5) | (1/3,2/5,1/2) | (1/2,2/3,1) | (2/5,1/2,2/3) | (1,1,1) | (1/3,2/5,1/2) |
| Alt 6 | (1/2,2/3,1) | (2/3,1,2) | (3/2,2,5/2) | (1,3/2,2) | (2,5/2,3) | (1,1,1) |

*Table A-11: Pairwise comparison of alternatives with respect to safety*

The synthetic extents were subsequently calculated and found to be as follow:

$S_1$= (0.16,0.27,0.42), $S_2$= (0.12,0.20,0.33), $S_3$= (0.07,0.11,0.17), $S_4$= (0.09,0.15,0.24),

$S_5$= (0.05,0.08,0.12), $S_6$= (0.12,0.20,0.34).

After calculating the degrees of possibilities, the priority weight vectors were found to be as follows:

W= $[0.35,0.25,0.02,0.14,0,0.25]^T$.

| Scalability and modularity | Alt 1 | Alt 2 | Alt 3 | Alt 4 | Alt 5 | Alt 6 |
|---|---|---|---|---|---|---|
| Alt 1 | (1,1,1) | (1/2,1,3/2) | (1/2,1,3/2) | (3/2,2,5/2) | (3/2,2,5/2) | (1/2,1,3/2) |
| Alt 2 | (2/3,1,2) | (1,1,1) | (1/2,1,3/2) | (3/2,2,5/2) | (3/2,2,5/2) | (1/2,1,3/2) |
| Alt 3 | (2/3,1,2) | (2/3,1,2) | (1,1,1) | (3/2,2,5/2) | (3/2,2,5/2) | (1/2,1,3/2) |
| Alt 4 | (2/5,1/2,2/3) | (2/5,1/2,2/3) | (2/5,1/2,2/3) | (1,1,1) | (1,1,1) | (2/5,1/2,2/3) |
| Alt 5 | (2/5,1/2,2/3) | (2/5,1/2,2/3) | (2/5,1/2,2/3) | (1,1,1) | (1,1,1) | (2/5,1/2,2/3) |
| Alt 6 | (2/3,1,2) | (2/3,1,2) | (2/3,1,2) | (3/2,2,5/2) | (3/2,2,5/2) | (1,1,1) |

*Table A-12: Pairwise comparison of alternatives with respect to Scalability and modularity*

The synthetic extents were subsequently calculated and found to be as follow:

$S_1$= (0.10,0.20,0.35), $S_2$= (0.10,0.20,0.36), $S_3$= (0.11,0.20,0.38), $S_4$= (0.07,0.10,0.15),

$S_5$= (0.07,0.10,0.15), $S_6$= (0.11,0.20,0.40).

After calculating the degrees of possibilities, the priority weight vectors were found to be as follows:

W= $[0.22,0.22,0.22,0.07,0.07,0.22]^T$.

| Storage hours | Alt 1 | Alt 2 | Alt 3 | Alt 4 | Alt 5 | Alt 6 |
|---|---|---|---|---|---|---|
| Alt 1 | (1,1,1) | (1/2,1,3/2) | (2/5,1/2,2/3) | (1/3,2/5,1/2) | (2/7,1/3,2/5) | (1/2,1,3/2) |
| Alt 2 | (2/3,1,2) | (1,1,1) | (2/5,1/2,2/3) | (1/3,2/5,1/2) | (2/7,1/3,2/5) | (1/2,1,3/2) |
| Alt 3 | (3/2,2,5/2) | (3/2,2,5/2) | (1,1,1) | (1/2,2/3,1) | (2/5,1/2,2/3) | (3/2,2,5/2) |
| Alt 4 | (2,5/2,3) | (2,5/2,3) | (1,3/2,2) | (1,1,1) | (1/2,2/3,1) | (2,5/2,3) |
| Alt 5 | (5/2,3,7/2) | (5/2,3,7/2) | (3/2,2,5/2) | (1,3/2,2) | (1,1,1) | (5/2,3,7/2) |
| Alt 6 | (2/3,1,2) | (2/3,1,2) | (2/5,1/2,2/3) | (1/3,2/5,1/2) | (2/7,1/3,2/5) | (1,1,1) |

*Table A-13: Pairwise comparison of alternatives with respect to conversion storage hours*

The synthetic extents were subsequently calculated and found to be as follow:

$S_1$= (0.05,0.09,0.16), $S_2$= (0.06,0.09,0.17), $S_3$= (0.11,0.18,0.29), $S_4$= (0.15,0.24,0.37),

$S_5$= (0.19,0.03,0.45), $S_6$= (0.06,0.09,0.19).

After calculating the degrees of possibilities, the priority weight vectors were found to be as follows:

W= $[0,0,0.2,0,34,0.46,0]^T$.

| Hybridization | Alt 1 | Alt 2 | Alt 3 | Alt 4 | Alt 5 | Alt 6 |
|---|---|---|---|---|---|---|
| Alt 1 | (1,1,1) | (1,3/2,2) | (1,3/2,2) | (3/2,2,5/2) | (3/2,2,5/2) | (1,3/2,2) |
| Alt 2 | (1/2,2/3,1) | (1,1,1) | (1,1,1) | (1,3/2,2) | (1,3/2,2) | (1/2,1,3/2) |
| Alt 3 | (1/2,2/3,1) | (1,1,1) | (1,1,1) | (1,3/2,2) | (1,3/2,2) | (1/2,1,3/2) |
| Alt 4 | (2/5,1/2,2/3) | (1/2,2/3,1) | (1/2,2/3,1) | (1,1,1) | (1,1,1) | (1/2,2/3,1) |
| Alt 5 | (2/5,1/2,2/3) | (1/2,2/3,1) | (1/2,2/3,1) | (1,1,1) | (1,1,1) | (1/2,2/3,1) |
| Alt 6 | (1/2,2/3,1) | (2/3,1,2) | (2/3,1,2) | (1,3/2,2) | (1,3/2,2) | (1,1,1) |

*Table A-14: Pairwise comparison of alternatives with respect to hybridization*

The synthetic extents were subsequently calculated and found to be as follow:

$S_1$= (0.14,0.25,0.40), $S_2$= (0.1,0.17,0.29), $S_3$= (0.10,0.17,0.29), $S_4$= (0.08,0.12,0.19),

$S_5$= (0.08,0.12,0.19), $S_6$= (0.1,0.17,0.34).

After calculating the degrees of possibilities, the priority weight vectors were found to be as follows:

W= $[0.27,0.18,0.18,0.08,0.08,0.2]^T$.

| Technology advancement potential | Alt 1 | Alt 2 | Alt 3 | Alt 4 | Alt 5 | Alt 6 |
|---|---|---|---|---|---|---|
| Alt 1 | (1,1,1) | (1,1,1) | (1,1,1) | (1/2,1,3/2) | (1/2,1,3/2) | (1/2,2/3,1) |
| Alt 2 | (1,1,1) | (1,1,1) | (1,1,1) | (1/2,1,3/2) | (1/2,1,3/2) | (1/2,2/3,1) |
| Alt 3 | (1,1,1) | (1,1,1) | (1,1,1) | (1/2,1,3/2) | (1/2,1,3/2) | (1/2,2/3,1) |
| Alt 4 | (2/3,1,2) | (2/3,1,2) | (2/3,1,2) | (1,1,1) | (1,1,1) | (1/2,2/3,1) |
| Alt 5 | (2/3,1,2) | (2/3,1,2) | (2/3,1,2) | (1,1,1) | (1,1,1) | (1/2,2/3,1) |
| Alt 6 | (1,3/2,2) | (1,3/2,2) | (1,3/2,2) | (1,3/2,2) | (1,3/2,2) | (1,1,1) |

*Table A-15: Pairwise comparison of alternatives with respect to technology advancement potential*

The synthetic extents were subsequently calculated and found to be as follow:

$S_1$= (0.09,0.15,0.25), $S_2$= (0.09,0.15,0.25), $S_3$= (0.09,0.15,0.25), $S_4$= (0.09,0.15,0.32),

$S_5$= (0.09,0.15,0.32), $S_6$= (0.12,0.23,0.39).

After calculating the degrees of possibilities, the priority weight vectors were found to be as follows:

W= $[0.14,0.14,0.14,0.17,0.17,0.23]^T$.

| Key components' and experts' availability | Alt 1 | Alt 2 | Alt 3 | Alt 4 | Alt 5 | Alt 6 |
|---|---|---|---|---|---|---|
| Alt 1 | (1,1,1) | (1,3/2,2) | (1,3/2,2) | (2,5/2,3) | (2,5/2,3) | (1/2,2/3,1) |
| Alt 2 | (1/2,2/3,1) | (1,1,1) | (1,1,1) | (3/2,2,5/2) | (3/2,2,5/2) | (2/5,1/2,2/3) |
| Alt 3 | (1/2,2/3,1) | (1,1,1) | (1,1,1) | (3/2,2,5/2) | (3/2,2,5/2) | (2/5,1/2,2/3) |
| Alt 4 | (1/3,2/5,1/2) | (2/5,1/2,2/3) | (2/5,1/2,2/3) | (1,1,1) | (1,1,1) | (2/7,1/3,2/5) |
| Alt 5 | (1/3,2/5,1/2) | (2/5,1/2,2/3) | (2/5,1/2,2/3) | (1,1,1) | (1,1,1) | (2/7,1/3,2/5) |
| Alt 6 | (1,3/2,2) | (3/2,2,5/2) | (3/2,2,5/2) | (5/2,3,7/2) | (5/2,3,7/2) | (1,1,1) |

*Table A-16: Pairwise comparison of alternatives with respect to key components' and experts' availability*

The synthetic extents were subsequently calculated and found to be as follow:

$S_1$= (0.14,0.22,0.33), $S_2$= (0.11,0.16,0.24), $S_3$= (0.11,0.16,0.24), $S_4$= (0.06,0.08,0.12),

$S_5$= (0.06,0.08,0.12), $S_6$= (0.19,0.28,0.42).

After calculating the degrees of possibilities, the priority weight vectors were found to be as follows:

W= $[0.3,0.13,0.13,0,0,0.44]^T$.

### A.2.2. Alternatives to sub-criteria under economic

| Capital cost | Alt 1 | Alt 2 | Alt 3 | Alt 4 | Alt 5 | Alt 6 |
|---|---|---|---|---|---|---|
| Alt 1 | (1,1,1) | (2,5/2,3) | (5/2,3,7/2) | (3/2,2,5/2) | (5/2,3,7/2) | (1/2,1,3/2) |
| Alt 2 | (1/3,2/5,1/2) | (1,1,1) | (1,3/2,2) | (1/2,2/3,1) | (1,3/2,2) | (1/3,2/5,1/2) |
| Alt 3 | (2/7,1/3,2/5) | (1/2,2/3,1) | (1,1,1) | (2/5,1/2,2/3) | (1/2,1,3/2) | (2/7,1/3,2/5) |
| Alt 4 | (2/5,1/2,2/3) | (1,3/2,2) | (3/2,2,5/2) | (1,1,1) | (3/2,2,5/2) | (2/5,1/2,2/3) |
| Alt 5 | (2/7,1/3,2/5) | (1/2,2/3,1) | (2/3,1,2) | (2/5,1/2,2/3) | (1,1,1) | (2/7,1/3,2/5) |
| Alt 6 | (2/3,1,2) | (2,5/2,3) | (5/2,3,7/2) | (3/2,2,5/2) | (5/2,3,7/2) | (1,1,1) |

*Table A-17: Pairwise comparison of alternatives with respect to capital cost*

The synthetic extents were subsequently calculated and found to be as follow:

$S_1$= (0.17,0.27,0.41), $S_2$= (0.07,0.12,0.19), $S_3$= (0.05,0.08,0.14), $S_4$= (0.1,0.16,0.26),

$S_5$= (0.05,0.08,0.15), $S_6$= (0.18,0.27,0.43).

After calculating the degrees of possibilities, the priority weight vectors were found to be as follows:

W= $[0.4,0.04,0,0.17,0,0.4]^T$.

| O&M costs | Alt 1 | Alt 2 | Alt 3 | Alt 4 | Alt 5 | Alt 6 |
|---|---|---|---|---|---|---|
| Alt 1 | (1,1,1) | (3/2,2,5/2) | (2,5/2,3) | (2,5/2,3) | (5/2,3,7/2) | (1/2,1,3/2) |
| Alt 2 | (2/5,1/2,2/3) | (1,1,1) | (3/2,2,5/2) | (3/2,2,5/2) | (3/2,2,5/2) | (2/5,1/2,2/3) |
| Alt 3 | (1/3,2/5,1/2) | (1/2,2/3,1) | (1,1,1) | (1/2,1,3/2) | (1,3/2,2) | (1/3,2/5,1/2) |
| Alt 4 | (1/3,2/5,1/2) | (1/2,2/3,1) | (2/3,1,2) | (1,1,1) | (1,3/2,2) | (1/3,2/5,1/2) |
| Alt 5 | (2/7,1/3,2/5) | (2/5,1/2,2/3) | (1/2,2/3,1) | (1/2,2/3,1) | (1,1,1) | (2/7,1/3,2/5) |
| Alt 6 | (2/3,1,2) | (3/2,2,5/2) | (2,5/2,3) | (2,5/2,3) | (5/2,3,7/2) | (1,1,1) |

*Table A-18: Pairwise comparison of alternatives with respect to O&M costs*

The synthetic extents were subsequently calculated and found to be as follow:

$S_1$= (0.17,0.27,0.42), $S_2$= (0.09,0.16,0.25), $S_3$= (0.07,0.11,0.19), $S_4$= (0.07,0.11,0.20),

$S_5$= (0.05,0.08,0.13), $S_6$= (0.17,0.27,0.43).

After calculating the degrees of possibilities, the priority weight vectors were found to be as follows:

W= $[0.38,0.16,0.03,0.06,0,0.38]^T$.

| Energy cost | Alt 1 | Alt 2 | Alt 3 | Alt 4 | Alt 5 | Alt 6 |
|---|---|---|---|---|---|---|
| Alt 1 | (1,1,1) | (1/2,1,3/2) | (1/2,1,3/2) | (2/7,1/3,2/5) | (2/7,1/3,2/5) | (2/7,1/3,2/5) |
| Alt 2 | (2/3,1,2) | (1,1,1) | (1/2,1,3/2) | (2/7,1/3,2/5) | (2/7,1/3,2/5) | (2/7,1/3,2/5) |
| Alt 3 | (2/3,1,2) | (2/3,1,2) | (1,1,1) | (2/7,1/3,2/5) | (2/7,1/3,2/5) | (2/7,1/3,2/5) |
| Alt 4 | (5/2,3,7/2) | (5/2,3,7/2) | (5/2,3,7/2) | (1,1,1) | (1/2,1,3/2) | (1/2,1,3/2) |
| Alt 5 | (5/2,3,7/2) | (5/2,3,7/2) | (5/2,3,7/2) | (2/3,1,2) | (1,1,1) | (1/2,1,3/2) |
| Alt 6 | (5/2,3,7/2) | (5/2,3,7/2) | (5/2,3,7/2) | (2/3,1,2) | (2/3,1,2) | (1,1,1) |

*Table A-19: Pairwise comparison of alternatives with respect to energy cost*

The synthetic extents were subsequently calculated and found to be as follow:

$S_1$= (0.05,0.08,0.14), $S_2$= (0.05,0.08,0.15), $S_3$= (0.05,0.08,0.16), $S_4$= (0.15,0.25,0.38),

$S_5$= (0.15,0.25,0.39), $S_6$= (0.16,0.25,0.41).

After calculating the degrees of possibilities, the priority weight vectors were found to be as follows:

W= $[0,0,0.01,0.33,0.33,0.33]^T$.

| Market maturity | Alt 1 | Alt 2 | Alt 3 | Alt 4 | Alt 5 | Alt 6 |
|---|---|---|---|---|---|---|
| Alt 1 | (1,1,1) | (1,1,1) | (1,1,1) | (5/2,3,7/2) | (5/2,3,7/2) | (5/2,3,7/2) |
| Alt 2 | (1,1,1) | (1,1,1) | (1,1,1) | (5/2,3,7/2) | (5/2,3,7/2) | (5/2,3,7/2) |
| Alt 3 | (1,1,1) | (1,1,1) | (1,1,1) | (5/2,3,7/2) | (5/2,3,7/2) | (5/2,3,7/2) |
| Alt 4 | (2/7,1/3,2/5) | (2/7,1/3,2/5) | (2/7,1/3,2/5) | (1,1,1) | (1,1,1) | (1/2,1,3/2) |
| Alt 5 | (2/7,1/3,2/5) | (2/7,1/3,2/5) | (2/7,1/3,2/5) | (1,1,1) | (1,1,1) | (1/2,1,3/2) |
| Alt 6 | (2/7,1/3,2/5) | (2/7,1/3,2/5) | (2/7,1/3,2/5) | (2/3,1,2) | (2/3,1,2) | (1,1,1) |

*Table A-20: Pairwise comparison of alternatives with respect to market maturity*

The synthetic extents were subsequently calculated and found to be as follow:

$S_1$= (0.19,0.25,0.33), $S_2$= (0.19,0.25,0.33), $S_3$= (0.19,0.25,0.33), $S_4$= (0.06,0.08,0.11),

$S_5$= (0.06,0.08,0.11), $S_6$= (0.06,0.08,0.15).

After calculating the degrees of possibilities, the priority weight vectors were found to be as follows:

W= $[0.33,0.33,0.33,0,0,0]^T$.

| Economic feasibility | Alt 1 | Alt 2 | Alt 3 | Alt 4 | Alt 5 | Alt 6 |
|---|---|---|---|---|---|---|
| Alt 1 | (1,1,1) | (2/5,1/2,2/3) | (2/7,1/3,2/5) | (1/2,2/3,1) | (2/7,1/3,2/5) | (1/2,1,3/2) |
| Alt 2 | (3/2,2,5/2) | (1,1,1) | (2/5,1/2,2/3) | (1,3/2,2) | (2/5,1/2,2/3) | (3/2,2,5/2) |
| Alt 3 | (5/2,3,7/2) | (3/2,2,5/2) | (1,1,1) | (2,5/2,3) | (1/2,1,3/2) | (5/2,3,7/2) |
| Alt 4 | (1,3/2,2) | (1/2,2/3,1) | (1/3,2/5,1/2) | (1,1,1) | (1/3,2/5,1/2) | (1,3/2,2) |
| Alt 5 | (5/2,3,7/2) | (3/2,2,5/2) | (2/3,1,2) | (2,5/2,3) | (1,1,1) | (5/2,3,7/2) |
| Alt 6 | (2/3,1,2) | (2/5,1/2,2/3) | (2/7,1/3,2/5) | (1/2,2/3,1) | (2/7,1/3,2/5) | (1,1,1) |

*Table A-21: Pairwise comparison of alternatives with respect to economic feasibility*

The synthetic extents were subsequently calculated and found to be as follow:

$S_1$= (0.05,0.08,0.14), $S_2$= (0.10,0.16,0.26), $S_3$= (0.17,0.27,0.41), $S_4$= (0.07,0.12,0.19),

$S_5$= (0.18,0.27,0.43), $S_6$= (0.05,0.08,0.15).

After calculating the degrees of possibilities, the priority weight vectors were found to be as follows:

$W= [0,0.17,0.40,0.04,0.40,0]^T$.

| Fuel cost | Alt 1 | Alt 2 | Alt 3 | Alt 4 | Alt 5 | Alt 6 |
|---|---|---|---|---|---|---|
| Alt 1 | (1,1,1) | (1,3/2,2) | (3/2,2,5/2) | (2/5,1/2,2/3) | (2/5,1/2,2/3) | (3/2,2,5/2) |
| Alt 2 | (1/2,2/3,1) | (1,1,1) | (1,3/2,2) | (1/3,2/5,1/2) | (1/3,2/5,1/2) | (1,3/2,2) |
| Alt 3 | (2/5,1/2,2/3) | (1/2,2/3,1) | (1,1,1) | (2/7,1/3,2/5) | (2/7,1/3,2/5) | (1/2,1,3/2) |
| Alt 4 | (3/2,2,5/2) | (2,5/2,3) | (5/2,3,7/2) | (1,1,1) | (1/2,1,3/2) | (5/2,3,7/2) |
| Alt 5 | (3/2,2,5/2) | (2,5/2,3) | (5/2,3,7/2) | (2/3,1,2) | (1,1,1) | (5/2,3,7/2) |
| Alt 6 | (2/5,1/2,2/3) | (1/2,2/3,1) | (2/3,1,2) | (2/7,1/3,2/5) | (2/7,1/3,2/5) | (1,1,1) |

*Table A-22: Pairwise comparison of alternatives with respect to fuel cost*

The synthetic extents were subsequently calculated and found to be as follow:

$S_1$= (0.10.0.16.0.26), $S_2$= (0.07.0.12.0.19), $S_3$= (0.05.0.08.0.14), $S_4$= (0.17.0.27.0.41),

$S_5$= (0.18.0.27.0.43), $S_6$= (0.05.0.08.0.15).

After calculating the degrees of possibilities, the priority weight vectors were found to be as follows:

$W= [0.17,0.04,0,0.40,0.40,0]^T$.

| Offsetting infrastructure cost | Alt 1 | Alt 2 | Alt 3 | Alt 4 | Alt 5 | Alt 6 |
|---|---|---|---|---|---|---|
| Alt 1 | (1,1,1) | (1/2,2/3,1) | (2/5,1/2,2/3) | (2/5,1/2,2/3) | (2/7,1/3,2/5) | (1/2,1,3/2) |
| Alt 2 | (1,3/2,2) | (1,1,1) | (1/2,2/3,1) | (1/2,2/3,1) | (1/3,2/5,1/2) | (1,3/2,2) |
| Alt 3 | (3/2,2,5/2) | (1,3/2,2) | (1,1,1) | (1/2,1,3/2) | (2/5,1/2,2/3) | (3/2,2,5/2) |
| Alt 4 | (3/2,2,5/2) | (1,3/2,2) | (2/3,1,2) | (1,1,1) | (2/5,1/2,2/3) | (3/2,2,5/2) |
| Alt 5 | (5/2,3,7/2) | (2,5/2,3) | (3/2,2,5/2) | (3/2,2,5/2) | (1,1,1) | (5/2,3,7/2) |
| Alt 6 | (2/3,1,2) | (1/2,2/3,1) | (2/5,1/2,2/3) | (2/5,1/2,2/3) | (2/7,1/3,2/5) | (1,1,1) |

*Table A-23: Pairwise comparison of alternatives with respect to offsetting infrastructure cost*

The synthetic extents were subsequently calculated and found to be as follow:

$S_1$= (0.06,0.09,0.16), $S_2$= (0.08,0.13,0.22), $S_3$= (0.11,0.19,0.30), $S_4$= (0.11,0.19,0.32),

$S_5$= (0.20,0.31,0.48), $S_6$= (0.06,0.09,0.17).

After calculating the degrees of possibilities, the priority weight vectors were found to be as follows:

$W= [0,0.06,0.22,0.24,0.49,0]^T$.

| National economic benefit | Alt 1 | Alt 2 | Alt 3 | Alt 4 | Alt 5 | Alt 6 |
|---|---|---|---|---|---|---|
| Alt 1 | (1,1,1) | (2/5,1/2,2/3) | (2/7,1/3,2/5) | (1/2,2/3,1) | (2/7,1/3,2/5) | (1/2,1,3/2) |
| Alt 2 | (3/2,2,5/2) | (1,1,1) | (2/5,1/2,2/3) | (1,3/2,2) | (2/5,1/2,2/3) | (3/2,2,5/2) |
| Alt 3 | (5/2,3,7/2) | (3/2,2,5/2) | (1,1,1) | (2,5/2,3) | (1/2,1,3/2) | (5/2,3,7/2) |
| Alt 4 | (1,3/2,2) | (1/2,2/3,1) | (1/3,2/5,1/2) | (1,1,1) | (1/3,2/5,1/2) | (1,3/2,2) |
| Alt 5 | (5/2,3,7/2) | (3/2,2,5/2) | (2/3,1,2) | (2,5/2,3) | (1,1,1) | (5/2,3,7/2) |
| Alt 6 | (2/3,1,2) | (2/5,1/2,2/3) | (2/7,1/3,2/5) | (1/2,2/3,1) | (2/7,1/3,2/5) | (1,1,1) |

*Table A-24: Pairwise comparison of alternatives with respect to national economic benefit*

The synthetic extents were subsequently calculated and found to be as follow:

$S_1$= (0.05,0.08,0.14), $S_2$= (0.10,0.16,0.26), $S_3$= (0.17,0.27,0.41), $S_4$= (0.07,0.12,0.19),

$S_5$= (0.18,0.27,0.43), $S_6$= (0.05,0.08,0.15).

After calculating the degrees of possibilities, the priority weight vectors were found to be as follows:

$W= [0,0.17,0.40,0.04,0.40,0]^T$.

### A.2.3. Alternatives to sub-criteria under environmental

| Required land | Alt 1 | Alt 2 | Alt 3 | Alt 4 | Alt 5 | Alt 6 |
|---|---|---|---|---|---|---|
| Alt 1 | (1,1,1) | (3/2,2,5/2) | (2,5/2,3) | (3/2,2,5/2) | (5/2,3,7/2) | (1,3/2,2) |
| Alt 2 | (2/5,1/2,2/3) | (1,1,1) | (1,3/2,2) | (1/2,1,3/2) | (3/2,2,5/2) | (1/2,2/3,1) |
| Alt 3 | (1/3,2/5,1/2) | (1/2,2/3,1) | (1,1,1) | (1/2,2/3,1) | (1,3/2,2) | (2/5,1/2,2/3) |
| Alt 4 | (2/5,1/2,2/3) | (2/3,1,2) | (1,3/2,2) | (1,1,1) | (3/2,2,5/2) | (1/2,2/3,1) |
| Alt 5 | (2/7,1/3,2/5) | (2/5,1/2,2/3) | (1/2,2/3,1) | (2/5,1/2,2/3) | (1,1,1) | (1/3,2/5,1/2) |
| Alt 6 | (1/2,2/3,1) | (1,3/2,2) | (2/5,1/2,2/3) | (1,3/2,2) | (2,5/2,3) | (1,1,1) |

*Table A-25: Pairwise comparison of alternatives with respect to national required land*

The synthetic extents were subsequently calculated and found to be as follow:

$S_1$= (0.18,0.28,0.44), $S_2$= (0.09,0.16,0.26), $S_3$= (0.07,0.11,0.19), $S_4$= (0.09,0.16,0.28),

$S_5$= (0.05,0.08,0.13), $S_6$= (0.13,0.22,0.35).

After calculating the degrees of possibilities, the priority weight vectors were found to be as follows:

$W= [0.38,0.15,0.02,0.17,0,0.27]^T$.

| GHG emissions | Alt 1 | Alt 2 | Alt 3 | Alt 4 | Alt 5 | Alt 6 |
|---|---|---|---|---|---|---|
| Alt 1 | (1,1,1) | (3/2,2,5/2) | (2,5/2,3) | (3/2,2,5/2) | (5/2,3,7/2) | (1,3/2,2) |
| Alt 2 | (2/5,1/2,2/3) | (1,1,1) | (1,3/2,2) | (1/2,1,3/2) | (3/2,2,5/2) | (1/2,2/3,1) |
| Alt 3 | (1/3,2/5,1/2) | (1/2,2/3,1) | (1,1,1) | (1/2,2/3,1) | (1,3/2,2) | (2/5,1/2,2/3) |
| Alt 4 | (2/5,1/2,2/3) | (2/3,1,2) | (1,3/2,2) | (1,1,1) | (3/2,2,5/2) | (2/7,1/3,2/5) |
| Alt 5 | (2/7,1/3,2/5) | (2/5,1/2,2/3) | (1/2,2/3,1) | (2/5,1/2,2/3) | (1,1,1) | (1/3,2/5,1/2) |
| Alt 6 | (1/2,2/3,1) | (1,3/2,2) | (3/2,2,5/2) | (1,3/2,2) | (2,5/2,3) | (1,1,1) |

*Table A-26: Pairwise comparison of alternatives with respect to GHG emission*

The synthetic extents were subsequently calculated and found to be as follow:

$S_1$= (0.18,0.28,0.44), $S_2$= (0.09,0.16,0.26), $S_3$= (0.07,0.11,0.19), $S_4$= (0.09,0.16,0.28),

$S_5$= (0.05,0.08,0.13), $S_6$= (0.13,0.22,0.35).

After calculating the degrees of possibilities, the priority weight vectors were found to be as follows:

$W= [0.38,0.15,0.02,0.17,0,0.27]^T$.

| Water consumption | Alt 1 | Alt 2 | Alt 3 | Alt 4 | Alt 5 | Alt 6 |
|---|---|---|---|---|---|---|
| Alt 1 | (1,1,1) | (1,3/2,2) | (3/2,2,5/2) | (3/2,2,5/2) | (5/2,3,7/2) | (1/2,1,3/2) |
| Alt 2 | (1/2,2/3,1) | (1,1,1) | (1,3/2,2) | (1,3/2,2) | (2,5/2,3) | (1/2,2/3,1) |
| Alt 3 | (2/5,1/2,2/3) | (1/2,2/3,1) | (1,1,1) | (1/2,1,3/2) | (3/2,2,5/2) | (2/5,1/2,2/3) |
| Alt 4 | (2/5,1/2,2/3) | (1/2,2/3,1) | (2/3,1,2) | (1,1,1) | (3/2,2,5/2) | (2/5,1/2,2/3) |
| Alt 5 | (2/7,1/3,2/5) | (1/3,2/5,1/2) | (2/5,1/2,2/3) | (2/5,1/2,2/3) | (1,1,1) | (2/7,1/3,2/5) |
| Alt 6 | (2/3,1,2) | (1,3/2,2) | (3/2,2,5/2) | (3/2,2,5/2) | (5/2,3,7/2) | (1,1,1) |

*Table A-27: Pairwise comparison of alternatives with respect to water consumption*

The synthetic extents were subsequently calculated and found to be as follow:

$S_1$= (0.14,0.24,0.39), $S_2$= (0.11,0.18,0.30), $S_3$= (0.08,0.13,0.22), $S_4$= (0.08,0.13,0.23),

$S_5$= (0.05,0.07,0.11), $S_6$= (0.15,0.24,0.40).

After calculating the degrees of possibilities, the priority weight vectors were found to be as follows:

W= $[0.28,0.20,0.11,0.12,0,0.28]^T$.

| Ecosystem disruption | Alt 1 | Alt 2 | Alt 3 | Alt 4 | Alt 5 | Alt 6 |
|---|---|---|---|---|---|---|
| Alt 1 | (1,1,1) | (1,3/2,2) | (3/2,2,5/2) | (1/2,2/3,1) | (1/2,2/3,1) | (2/5,1/2,2/3) |
| Alt 2 | (1/2,2/3,1) | (1,1,1) | (1,3/2,2) | (2/5,1/2,2/3) | (2/5,1/2,2/3) | (1/3,2/5,1/2) |
| Alt 3 | (2/5,1/2,2/3) | (1/2,2/3,1) | (1,1,1) | (1/3,2/5,1/2) | (1/3,2/5,1/2) | (2/7,1/3,2/5) |
| Alt 4 | (1,3/2,2) | (3/2,2,5/2) | (2,5/2,3) | (1,1,1) | (1/2,1,3/2) | (1/2,2/3,1) |
| Alt 5 | (1,3/2,2) | (3/2,2,5/2) | (2,5/2,3) | (2/3,1,2) | (1,1,1) | (1/2,2/3,1) |
| Alt 6 | (3/2,2,5/2) | (2,5/2,3) | (5/2,3,7/2) | (1,3/2,2) | (1,3/2,2) | (1,1,1) |

*Table A-28: Pairwise comparison of alternatives with respect to ecosystem disruption*

The synthetic extents were subsequently calculated and found to be as follow:

$S_1$= (0.09,0.15,0.24), $S_2$= (0.07,0.11,0.17), $S_3$= (0.05,0.08,0.12), $S_4$= (0.12,0.20,0.33),

$S_5$= (0.12,0.20,0.34), $S_6$= (0.16,0.27,0.42).

After calculating the degrees of possibilities, the priority weight vectors were found to be as follows:

W= $[0.14,0.02,0,0.25,0.25,0.35]^T$.

| Life cycle assessment | Alt 1 | Alt 2 | Alt 3 | Alt 4 | Alt 5 | Alt 6 |
|---|---|---|---|---|---|---|
| Alt 1 | (1,1,1) | (1/2,1,3/2) | (1/2,1,3/2) | (1/2,1,3/2) | (1/2,1,3/2) | (2/7,1/3,2/5) |
| Alt 2 | (2/3,1,2) | (1,1,1) | (1/2,1,3/2) | (1/2,1,3/2) | (1/2,1,3/2) | (2/7,1/3,2/5) |
| Alt 3 | (2/3,1,2) | (2/3,1,2) | (1,1,1) | (1/2,1,3/2) | (1/2,1,3/2) | (2/7,1/3,2/5) |
| Alt 4 | (2/3,1,2) | (2/3,1,2) | (2/3,1,2) | (1,1,1) | (1/2,1,3/2) | (2/7,1/3,2/5) |
| Alt 5 | (2/3,1,2) | (2/3,1,2) | (2/3,1,2) | (2/3,1,2) | (1,1,1) | (2/7,1/3,2/5) |
| Alt 6 | (5/2,3,7/2) | (5/2,3,7/2) | (5/2,3,7/2) | (5/2,3,7/2) | (5/2,3,7/2) | (1,1,1) |

*Table A-29: Pairwise comparison of alternatives with respect to life cycle assessment*

The synthetic extents were subsequently calculated and found to be as follow:

$S_1$= (0.05,0.13,0.23), $S_2$= (0.06,0.13,0.25), $S_3$= (0.06,0.13,0.27), $S_4$= (0.06,0.13,0.28),

$S_5$= (0.07,0.13,0.30), $S_6$= (0.22,0.38,0.59).

After calculating the degrees of possibilities, the priority weight vectors were found to be as follows:

W= $[0.02,0.06,0.09,0.11,0.13,0.59]^T$.

| Environmental conditions impact | Alt 1 | Alt 2 | Alt 3 | Alt 4 | Alt 5 | Alt 6 |
|---|---|---|---|---|---|---|
| Alt 1 | (1,1,1) | (1/2,1,3/2) | (1/2,1,3/2) | (1,3/2,2) | (1,3/2,2) | (1/2,2/3,1) |
| Alt 2 | (2/3,1,2) | (1,1,1) | (1/2,1,3/2) | (1,3/2,2) | (1,3/2,2) | (1/2,2/3,1) |
| Alt 3 | (2/3,1,2) | (2/3,1,2) | (1,1,1) | (1,3/2,2) | (1,3/2,2) | (1/2,2/3,1) |
| Alt 4 | (1/2,2/3,1) | (1/2,2/3,1) | (1/2,2/3,1) | (1,1,1) | (1/2,1,3/2) | (2/5,1/2,2/3) |
| Alt 5 | (1/2,2/3,1) | (1/2,2/3,1) | (1/2,2/3,1) | (2/3,1,2) | (1,1,1) | (2/5,1/2,2/3) |
| Alt 6 | (1,3/2,2) | (1,3/2,2) | (1,3/2,2) | (3/2,2,5/2) | (3/2,2,5/2) | (1,1,1) |

*Table A-30: Pairwise comparison of alternatives with respect to environmental conditions impact*

The synthetic extents were subsequently calculated and found to be as follow:

$S_1$= (0.08,0.17,0.32), $S_2$= (0.09,0.17,0.34), $S_3$= (0.09,0.17,0.36), $S_4$= (0.06,0.12,0.22),

$S_5$= (0.07,0.12,0.24), $S_6$= (0.13,0.25,0.43).

After calculating the degrees of possibilities, the priority weight vectors were found to be as follows:

W= $[0.18,0.18,0.19,0.10,0.11,0.25]^T$.

### A.2.4. Alternatives to sub-criteria under social

| Jobs creation | Alt 1 | Alt 2 | Alt 3 | Alt 4 | Alt 5 | Alt 6 |
|---|---|---|---|---|---|---|
| Alt 1 | (1,1,1) | (1/3,2/5,1/2) | (2/7,1/3,2/5) | (1/2,2/3,1) | (2/7,1/3,2/5) | (1/2,1,3/2) |
| Alt 2 | (2,5/2,3) | (1,1,1) | (1/2,2/3,1) | (3/2,2,5/2) | (1/2,2/3,1) | (2,5/2,3) |
| Alt 3 | (5/2,3,7/2) | (1,3/2,2) | (1,1,1) | (2,5/2,3) | (1/2,1,3/2) | (5/2,3,7/2) |
| Alt 4 | (1,3/2,2) | (2/5,1/2,2/3) | (1/3,2/5,1/2) | (1,1,1) | (1/3,2/5,1/2) | (1,3/2,2) |
| Alt 5 | (5/2,3,7/2) | (1,3/2,2) | (2/3,1,2) | (2,5/2,3) | (1,1,1) | (5/2,3,7/2) |
| Alt 6 | (2/3,1,2) | (1/3,2/5,1/2) | (2/7,1/3,2/5) | (1/2,2/3,1) | (2/7,1/3,2/5) | (1,1,1) |

*Table A-31: Pairwise comparison of alternatives with respect to jobs creation*

The synthetic extents were subsequently calculated and found to be as follow:

$S_1$= (0.05,0.08,0.13), $S_2$= (0.13,0.2,0.31), $S_3$= (0.16,0.26,0.39), $S_4$= (0.07,0.11,0.18),

$S_5$= (0.17,0.26,0.41), $S_6$= (0.05,0.08,0.14).

After calculating the degrees of possibilities, the priority weight vectors were found to be as follows:

W= $[0,0.26,0.36,0.03,0.36,0]^T$.

| Soc. & pol. acceptance | Alt 1 | Alt 2 | Alt 3 | Alt 4 | Alt 5 | Alt 6 |
|---|---|---|---|---|---|---|
| Alt 1 | (1,1,1) | (0.56,0.89,1.30) | (0.53,0.80,1.12) | (0.52,0.74,1.02) | (0.47,0.69,0.94) | (0.56,0.94,1.42) |
| Alt 2 | (0.77,1.12,1.80) | (1,1,1) | (0.50,0.86,1.27) | (0.51,0.80,1.16) | (0.49,0.74,1.05) | (0.71,1.11,1.54) |
| Alt 3 | (0.90,1.25,1.88) | (0.79,1.16,1.99) | (1,1,1) | (0.57,0.93,1.34) | (0.54,0.87,1.27) | (0.84,1.26,1.71) |
| Alt 4 | (0.98,1.35,1.94) | (0.87,1.25,1.97) | (0.47,1.07,1.74) | (1,1,1) | (0.56,0.94,1.39) | (0.88,1.32,1.79) |
| Alt 5 | (1.07,1.45,2.14) | (0.95,1.35,2.05) | (0.79,1.15,1.87) | (0.72,1.06,1.80) | (1,1,1) | (0.931.37,1.85) |
| Alt 6 | (0.71,1.03,1.79) | (0.65,0.90,1.42) | (0.58,0.80,1.19) | (0.56,0.76,1.14) | (0.54,0.73,1.08) | (1,1,1) |

*Table A-32: Pairwise comparison of alternatives with respect to social and political acceptance*

The synthetic extents were subsequently calculated and found to be as follow:

$S_1$= (0.07,0.14,0.25), $S_2$= (0.08,0.15,0.29), $S_3$= (0.09,0.18,0.34), $S_4$= (0.10,0.19,0.37),

$S_5$= (0.10,0.20,0.40), $S_6$= (0.08,0.14,0.29).

After calculating the degrees of possibilities, the priority weight vectors were found to be as follows:

W= (0.14,0.16,0.18,0.19,0.20,0.15).

| Local industrialization | Alt 1 | Alt 2 | Alt 3 | Alt 4 | Alt 5 | Alt 6 |
|---|---|---|---|---|---|---|
| Alt 1 | (1,1,1) | (1/2,1,3/2) | (1/2,1,3/2) | (2/5,1/2,2/3) | (1/3,2/5,1/2) | (1/2,2/3,1) |
| Alt 2 | (2/3,1,2) | (1,1,1) | (1/2,1,3/2) | (2/5,1/2,2/3) | (1/3,2/5,1/2) | (1/2,2/3,1) |
| Alt 3 | (2/3,1,2) | (2/3,1,2) | (1,1,1) | (2/5,1/2,2/3) | (1/3,2/5,1/2) | (1/2,2/3,1) |
| Alt 4 | (3/2,2,5/2) | (3/2,2,5/2) | (3/2,2,5/2) | (1,1,1) | (1/2,2/3,1) | (1,3/2,2) |
| Alt 5 | (2,5/2,3) | (2,5/2,3) | (2,5/2,3) | (1,3/2,2) | (1,1,1) | (3/2,2,5/2) |
| Alt 6 | (1,3/2,2) | (1,3/2,2) | (1,3/2,2) | (1/2,2/3,1) | (2/5,1/2,2/3) | (1,1,1) |

*Table A-33: Pairwise comparison of alternatives with respect to Local industrialization possibilities*

The synthetic extents were subsequently calculated and found to be as follow:

$S_1$= (0.06,0.11,0.2), $S_2$= (0.06,0.11,0.21), $S_3$= (0.07,0.11,0.23), $S_4$= (0.13,0.22,0.36),

$S_5$= (0.17,0.29,0.46), $S_6$= (0.09,0.16,0.27).

After calculating the degrees of possibilities, the priority weight vectors were found to be as follows:

W= (0.04,0.06,0.09,0.27,0.37,0.16).

| Logistical feasibility | Alt 1 | Alt 2 | Alt 3 | Alt 4 | Alt 5 | Alt 6 |
|---|---|---|---|---|---|---|
| Alt 1 | (1,1,1) | (3/2,2,5/2) | (3/2,2,5/2) | (1,3/2,2) | (1,3/2,2) | (1,3/2,2) |
| Alt 2 | (2/5,1/2,2/3) | (1,1,1) | (1/2,1,3/2) | (1/2,2/3,1) | (1/2,2/3,1) | (1/2,2/3,1) |
| Alt 3 | (2/5,1/2,2/3) | (2/3,1,2) | (1,1,1) | (1/2,2/3,1) | (1/2,2/3,1) | (1/2,2/3,1) |
| Alt 4 | (1/2,2/3,1) | (1,3/2,2) | (1,3/2,2) | (1,1,1) | (1/2,1,3/2) | (1/2,1,3/2) |
| Alt 5 | (1/2,2/3,1) | (1,3/2,2) | (1,3/2,2) | (2/3,1,2) | (1,1,1) | (1/2,1,3/2) |
| Alt 6 | (1/2,2/3,1) | (1,3/2,2) | (1,3/2,2) | (2/3,1,2) | (2/3,1,2) | (1,1,1) |

*Table A-34: Pairwise comparison of alternatives with respect to Logistical feasibility*

The synthetic extents were subsequently calculated and found to be as follow:

$S_1$= (0.13,0.25,0.43), $S_2$= (0.06,0.12,0.22), $S_3$= (0.07,0.12,0.24), $S_4$= (0.08,0.17,0.32),

$S_5$= (0.09,0.17,0.34), $S_6$= (0.09,0.17,0.36).

After calculating the degrees of possibilities, the priority weight vectors were found to be as follows:

W= (0.25,0.10,0.11,0.18,0.18,0.19).

# Appendix B: Multi-Criteria Evaluation (MCE) Calculations

This Appendix presents the calculations of the multi-criteria evaluation (MCE), which was utilized for results validation of the third phase. The MCE calculations depend on attaining the overall score for the evaluated alternative scenarios. In order to calculate the overall scores, it is required to find out the weight factors of each alternative and its performance. The overall scores were calculated as per Equations (B–1) to (B–3).

$$R_{oj} = \sum_{i=1}^{n} (W_{DCi} . r_{Alt\,j}) \qquad (B\ 1)$$

where $R_o$ is the overall score; W is the weight factor; r is performance; i is decision criteria; j is alternative; and n is the number of decision criteria. Accordingly, we obtain:

$$R_{oj} = (W_{Tech}.r_{Techj}) + (W_{Eco}.r_{Ecoj}) + (W_{Env}.r_{Envj}) + (W_{Soc}.r_{Socj})$$

The weight factors were calculated according to Equation (B–2). The weight factor is assigned a positive value if the preference is to obtain high values and assigned a negative value if the preference is to obtain low values. The performance of each decision criteria is calculated using Equation (B–3).

$$Wi = \pm |m_i| \, / \sum_i |m_i| \qquad (B\ 2)$$

$$r_{DCj} = \sum_i W_{DCi} . V_{ij} \qquad (B\ 3)$$

where $m_i$ is the median; W is the weight factor of sub-criteria; and V is the impact intensity. Accordingly, the performance of each decision criteria is obtained as follows:

$$r_{Techj} = \sum_i W_{Tech(i)} . V_{ij}, \qquad r_{Ecoj} = \sum_i W_{Eco(i)} . V_{ij},$$

$$r_{Envj} = \sum_i W_{Env(i)} . V_{ij}, \qquad r_{Socj} = \sum_i W_{Soc(i)} . V_{ij}$$

The medians were obtained through the inputs of the 44 participating stakeholders. Tables B–2 and B–3 illustrate the weight factors of the decision criteria and sub-criteria.

| Deceision criteria | Technical | Economic | Environmental | Social |
|---|---|---|---|---|
| Weight factor | 0.278 | 0.278 | 0.222 | 0.222 |

*Table B-1: Weight factors of decision criteria with respect to goal*

Accordingly, the overall score of an alternative is shown as follows:

$$R_{oj} = (0.278.r_{Techj}) + (0.278.r_{Ecoj}) + (0.222.r_{Envj}) + (0.222.r_{Socj})$$

| Sub-criteria abbreviation | T1 | T2 | T3 | T4 | T5 | T6 |
|---|---|---|---|---|---|---|
| Weight factor | 0.097 | 0.092 | 0.096 | 0.100 | –0.084 | 0.094 |
| Sub-criteria abbreviation | T7 | T8 | T9 | T10 | T11 | EC1 |
| Weight factor | 0.085 | 0.094 | 0.090 | 0.080 | 0.087 | –0.139 |
| Sub-criteria abbreviation | EC2 | EC3 | EC4 | EC5 | EC6 | EC7 |
| Weight factor | –0.135 | –0.139 | 0.122 | 0.129 | –0.101 | 0.112 |
| Sub-criteria abbreviation | EC8 | EN1 | EN2 | EN3 | EN4 | EN5 |
| Weight factor | 0.123 | –0.155 | 0.172 | –0.173 | –0.168 | –0.168 |
| Sub-criteria abbreviation | EN6 | S1 | S2 | S3 | S4 | N/A |
| Weight factor | 0.166 | 0.26 | 0.251 | 0.256 | 0.233 | N/A |

*Table B-2: Weight factors of sub-criteria based on MCE calculations*

Afterwards, the impact intensity was obtained for each alternative with respect to the decision criteria in order to calculate alternatives performances. The following is an example of calculating the performance of alternative 1 with respect to economic criterion. Quantitative and qualitative data revealed the impact intensities of the alternatives with respect to the sub-criteria.

$$R_{Eco\ (Alt\ 1)} = (-0.139*V_{Alt\ 1\ (EC1)}) + (-0.135*\ V_{Alt\ 1\ (EC2)}) + (-0.139*\ V_{Alt\ 1\ (EC3)}) + (0.122*\ V_{Alt\ 1\ (EC4)}) + (0.129*\ V_{Alt\ 1\ (EC5)}) + (-0.101*\ V_{Alt\ 1\ (EC6)}) + (0.112*\ V_{Alt\ 1\ (EC7)}) + (0.123*\ V_{Alt\ 1\ (EC8)})$$

Similarly, the performances were obtained for all criteria in order to find out the overall score of each alternatives as shown in Figure B–2.

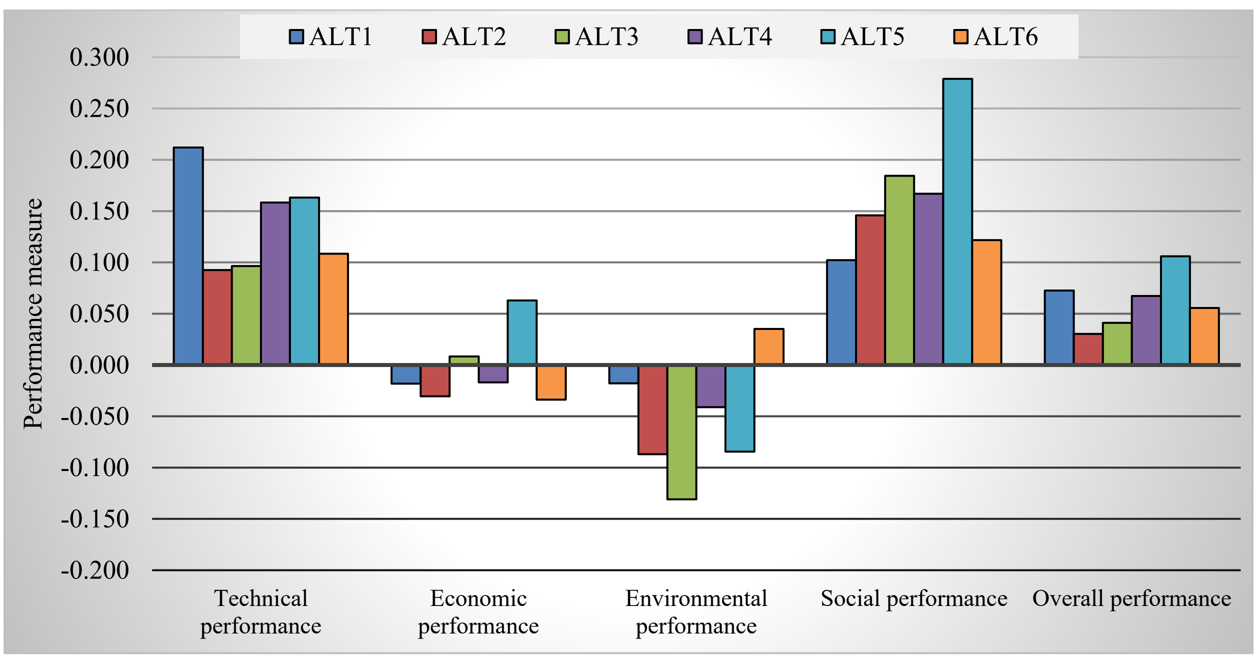


*Figure B-1: Alternatives performances with MCE*