MASTER'S OF

MANAGEMENT AND INDUSTRIAL STRATEGY

MASTER'S FINAL WORK

PROJECT

A DECISION SUPPORT MODEL TO PERFORM SUSTAINABLE CHOICES CONCERNING THE SELECTION OF MATERIAL SUPPLIERS IN THE SOLAR ENERGY INDUSTRY.

EDUARDA CANÇADO MANZINO ISRAEL

OCTOBER - 2024

MASTER'S OF

MANAGEMENT AND INDUSTRIAL STRATEGY

MASTER'S FINAL WORK

DISSERTATION

A DECISION SUPPORT MODEL TO PERFORM SUSTAINABLE CHOICES CONCERNING THE SELECTION OF MATERIAL SUPPLIERS IN THE SOLAR ENERGY INDUSTRY.

EDUARDA CANÇADO MANZINO ISRAEL

SUPERVISION:

PROF. DOUTOR JOSÉ MIGUEL ARAGÃO CELESTINO SOARES

PROF. DOUTOR RICARDO SIMÕES SANTOS

OCTOBER - 2024

ACKNOWLEDGMENTS

In this space, I would like to express my deep gratitude to all those who made this thesis possible. First and foremost, I am profoundly thankful to God, whose guidance and strength carried me through every step of this journey. I couldn't have done it without this divine support.

A huge thank you goes to my advisor, Professor Dr. Ricardo Simões Santos, for always being there with enthusiasm, encouragement, and brilliant ideas that helped me shape this work into something I'm truly proud of. I'm also immensely grateful to Professor Dr. José Miguel Soares, whose belief in this project, and thoughtful guidance helped bring everything together in the best way possible.

To my husband, Matthew, thank you for being my rock, my confidant, and my unwavering support. Your belief in me kept me going through the toughest moments, and I am endlessly grateful to have you by my side.

To my family— especially my mom Daniela and my wonderful grandparents—words can't fully express how much your unconditional love, endless support, and patience have meant to me. You created the perfect environment for me to focus and grow, and I wouldn't be who I am today without you. Thank you for being my foundation throughout this adventure.

I'm also grateful to my company and co-workers for sparking my interest in solar energy and for providing me with the chance to actively work on projects that make a tangible difference. To my incredible friends and colleagues, thank you for being part of this journey. A special thanks to Carolina and Mariana for your constant encouragement, friendship, and for always cheering me on. Your support has been invaluable.

Alone we can do so little; together we can do so much. (Helen Keller)

GLOSSARY

TBL	*Triple Bottom Line*
WCED	*World Commission on Environment and Development*
SMARTER	*Simple Multi-Attribute Rating Technique Exploiting Ranks*
AHP	*Analytic Hierarchy Process*
PROMETHEE	*Preference Ranking Organization Method for Enrichment Evaluation*
DC	*Direct Current*
AC	*Alternating Current*
EPC	*Engineering, Procurement, and Construction*
WTP	*Weighted Total Points*
TOPSIS	*Technique for Order Performance by Similarity to Ideal Solution*
MW	*Megawatt*

RESUMO

A rápida expansão da energia solar nos últimos anos tem exigido o desenvolvimento de modelos de tomada de decisão robustos e sustentáveis para diversos aspetos da implementação de projetos nesta indústria. A escolha de fornecedores para materiais, como inversores e painéis fotovoltaicos, para a construção de centrais solares, tornou-se cada vez mais complexa. Esta complexidade surge não apenas dos requisitos técnicos, mas também da necessidade de considerar os impactos económicos, sociais e ambientais, com o objetivo de cumprir os requisitos de sustentabilidade, cada vez mais adotados pelas empresas em geral. Como estes projetos contribuem para a obtenção de energia limpa, é essencial que a sua construção também reduza os impactos negativos no meio ambiente e na sociedade.

Esta dissertação visa abordar esta complexidade com o objetivo de auxiliar gestores no processo de decisão multicritério, que deve ser abrangente e sustentável. A pesquisa identifica e analisa critérios-chave historicamente importantes na seleção de fornecedores. Estes são examinados à luz da abordagem Triple Bottom Line, integrando as dimensões económica, social e ambiental no processo de tomada de decisão.

O estudo visa o desenvolvimento de um modelo de suporte à decisão, utilizando o Método de Análise Hierárquica (AHP), sendo este um método de decisão multicritério amplamente utilizado. O AHP é ideal para situações que requerem a priorização de critérios, estabelecendo uma hierarquia e atribuindo pesos com base na sua importância. Este método sistemático é fundamental para processos de tomada de decisão baseados em evidências, especialmente quando as empresas de construção expandem os seus projetos e portfólios.

Em suma, este estudo realiza uma seleção sustentável de fornecedores de materiais para projetos solares, contribuindo com uma ferramenta para a tomada de decisões sustentáveis em contexto empresarial, com maior enfoque em empresas de desenvolvimento e conceção de centrais de produção de energia.

PALAVRAS-CHAVE: Seleção de fornecedores, Suporte a tomada de decisão, Analise Multicritério, Método AHP, Sustentabilidade , Energia Solar;

ABSTRACT

The rapid expansion of solar energy in recent years has required the development of robust and sustainable decision-making models for various aspects of project implementation in this industry. The selection of suppliers for materials, such as inverters and photovoltaic panels, for the construction of solar power plants has become increasingly complex. This complexity arises not only from technical requirements but also from the need to consider economic, social, and environmental impacts, with the goal of meeting sustainability requirements, which are increasingly being adopted by companies in general. As these projects contribute to the generation of clean energy, it is essential that their construction also reduces negative impacts on the environment and society.

This dissertation aims to address this complexity with the goal of assisting managers in the multi-criteria decision-making process, which must be comprehensive and sustainable. The research identifies and analyzes key criteria that have historically been important in supplier selection. These criteria are examined in light of the Triple Bottom Line approach, integrating economic, social, and environmental dimensions into the decision-making process.

The study aims to develop a decision support model using the Analytic Hierarchy Process (AHP), which is a widely used multi-criteria decision-making method. AHP is ideal for situations requiring the prioritization of criteria, establishing a hierarchy, and assigning weights based on their importance. This systematic method is fundamental for evidence-based decision-making processes, especially as construction companies expand their projects and portfolios.

In summary, this study conducts a sustainable selection of material suppliers for solar projects, providing a tool for sustainable decision-making in a business context, with a greater focus on companies involved in the development and design of power generation plants.

KEYWORDS: Sustainability; Supplier Selection; Multi-Criteria Analysis; Solar Energy; Management; Triple Bottom Line; Procurement; Analytic Hierarchy Process.

INDEX

ACKNOWLEDGMENTS 1
GLOSSARY 2
RESUMO 3
ABSTRACT 4
INDEX 5
LIST OF TABLES 7
1. INTRODUCTION 8
2. LITERATURE REVIEW 10
2.1 SUSTENTAINABILITY 10
2.1.1 CONCEPT OF SUSTAINABLE DEVELOPMENT 10
2.1.2 THE ROLE OF SUSTAINABILITY IN THE SOLAR ENERGY INDUSTRY 11
2.1.3 THE TRIPLE BOTTOM LINE APPROACH 14
2.2 SUPPLIER SELECTION AND EVALUATION PROCESSES 15
2.2.1 THE IMPORTANCE OF SUPPLIER SELECTION AND EVALUATION IN THE CONSTRUCTION INDUSTRY 15
2.2.2 EXISTING APPROACHES 18
2.3 SELECTION CRITERIA 20
3. METHODOLOGY 27
3.1 INITIAL PROBLEM AND RESEARCH QUESTION 27
3.1.1 INITIAL PROBLEM 27
3.1.2 RESEARCH QUESTION 28
3.2 RESEARCH METHOD 30
3.3 DEVELOPMENT OF A MULTI-CRITERIA DECISION SUPPORT MODEL 32
3.3.1 MODEL ARCHITECTURE 32
3.3.2 COMPARISON WITH EXISTING METHOD 35
3.3.3 DEVELOPED METHOD 37
3.4 CASE STUDY: COMPANY IN THE ENERGY RENEWABLE INDUSTRY 38
3.4.1 BRIEF OVERVIEW OF THE COMPANY 38
3.4.2 CASE STUDY: SOLAR PROJECT SITE DEVELOPMENT IN FLORIDA 39
3.4.3 CHARACTERIZATION OF CURRENT SUPPLIERS 41

4. PRESENTATION AND RESULTS ANALYSIS ... 44
4.1 OBTAINING AND CALCULATING WEIGHTS USING THE AHP METHOD ... 44
4.1.1 PARTIAL AND GLOBAL RESULTS ... 48
4.2 PROCES OF AVALIATION OF ALTERNATIVES ... 51
4.3 ADVANTAGES AND LIMITATIONS ... 54
5. CONCLUSIONS AND RECOMENDATIONS OF FUTURE WORK ... 55
REFERENCES AND BIBLIOGRAPHY ... 58

LIST OF TABLES

Table I- Summary Economic Criteria 21

Table II- Summary Environmental Criteria 21

Table III- Summary Social Criteria...21

Table IV – Decision-maker 1…………………………………………………………………...48

Table V – Decision-maker 2……………………………………………………………………..49

Table VI – Decision-maker 3……………………………………………………………………49

Table VII – Global Results Ranking……………………………………………………………50

Table VIII – Pair-wise comparison matrix……………………………………………………...50

Table IX – Final Criteria Weights and Consistency Check Results……………………………...51

Table X – Supplier Performance Ranking………………………………………………………52

Table XI – Weighted Scores for Each Supplier…………………………………………………53

Table XII – Supplier Ranking…………………………………………………………………...53

LIST OF FIGURES

Figure 1- Model Architecture..32

1. INTRODUCTION

The world's solar energy industry is experiencing rapid growth, driven by significant advancements in technology and an increasing emphasis on sustainability. One of the countries where this growth is more noted is in the United States. In 2023 alone, the U.S. added 35.3 gigawatts of solar capacity, going up by 52% and bringing its cumulative solar electric capacity to over 150 GW—enough to power more than 27 million American homes (Solar Energy Industries Association, 2023; pv-magazine, 2023). This growth has expanded the scope of solar project development, making the process of selecting materials—such as inverters, solar panels, and other critical components for power plants—an increasingly complex and multifaceted task.

This complexity arises from the need to consider not only technical requirements but also economic, social, and environmental impacts, in line with the broader goals of sustainability. The continuous advancements in the solar energy industry, particularly in recent years, have increased the range of alternatives available to project developers, thus complicating the decision-making process (Khatib et al., 2012).

The primary objective of this work is to develop a robust and sustainable decision support model to assist in the selection of material suppliers—such as inverters, solar panels, and other essential components—for solar power projects, with a focus in the United States. This model is designed to integrate multiple criteria crucial for sustainable procurement, including economic, social, and environmental factors, following the Triple Bottom Line (TBL) approach (Elkington, 1999). By aligning the supplier selection process with both technical requirements and sustainability goals, the model aims to ensure that project developers make informed decisions that are cost-effective, environmentally responsible, and socially equitable.

To address the complexities involved in supplier selection, this dissertation employs a multi-criteria decision support model based on the Analytic Hierarchy Process (AHP). AHP is particularly suited for situations where decision-makers must prioritize multiple criteria, establishing a hierarchy and assigning weights based on their relative importance (Saaty, 1980). This method enables a systematic and evidence-based approach to decision-making, taking into account the three dimensions of sustainability: economic, environmental, and social.

This work is structured into five chapters. The first chapter provides an overview of the topic, outlining the research problem, objectives, scope, and the methodology applied. The second chapter presents a comprehensive literature review, discussing key concepts such as sustainability, sustainable development, and the various aspects of supplier selection and evaluation processes in the context of solar power projects. The third chapter details the methodology employed in the research, including the development and application of the AHP-based decision support model in a case study. The fourth chapter is presenting and analyzing the results obtained using the proposed model. The work concludes in the last chapter with recommendations for future research, emphasizing the importance of sustainable procurement practices in the solar energy industry and the potential for further refinement of the decision support model to adapt to evolving industry needs.

2. LITERATURE REVIEW

2.1 SUSTENTAINABILITY

2.1.1 CONCEPT OF SUSTAINABLE DEVELOPMENT

To understand the critical role of sustainable procurement in the solar energy sector, it is essential to first grasp the concept of sustainable development. This concept gained significant traction with the World Commission on Environment and Development (WCED) in 1987, famously known as the Brundtland Commission. Sustainable development was defined as the ability to meet the needs of the present without compromising the ability of future generations to meet their own needs (Brundtland, 1987). This definition has since become a cornerstone in global environmental policy and discourse.

The rapid industrialization and technological advancements over the past century have resulted in substantial economic growth and improved living standards. However, these developments have also led to significant environmental degradation. Industrial processes and increased energy consumption have substantially elevated greenhouse gas emissions, contributing to global warming and climate change (Gibson, 2006; Steffen et al., 2015). According to the Intergovernmental Panel on Climate Change (IPCC), global temperatures have already risen by approximately 1.1°C above pre-industrial levels, with dire consequences for ecosystems and human societies (IPCC, 2021).

In response to these environmental challenges, the Brundtland Commission introduced a holistic approach to development, integrating economic growth with environmental protection and social equity. This tri-dimensional framework, known as the Triple Bottom Line (TBL), emphasizes that true development must address economic, social, and environmental aspects in an interconnected manner (Elkington, 1997). The TBL framework has since been widely adopted by organizations aiming to achieve sustainable outcomes, as it provides a comprehensive approach to balancing diverse and often competing interests (Savitz & Weber, 2013).

In the context of the solar energy industry, sustainable procurement involves selecting suppliers and materials that meet not only economic and technical requirements but also environmental and social standards. Solar energy, being one of the cleanest and most abundant renewable sources, holds great promise for reducing dependency on fossil fuels and mitigating climate change. However, the production, installation, and disposal of solar panels must be managed sustainably to avoid shifting the environmental burden (Hernandez et al., 2014). Sustainable procurement within this industry addresses lifecycle environmental impacts of photovoltaic (PV) panels, social implications of raw material sourcing, and ethical treatment of workers in the supply chain (Tsoutsos *et al*., 2005; McDonald & Pearce, 2010).

By integrating sustainable development principles into procurement practices, the solar industry can contribute significantly to global sustainability efforts. This ensures that the expansion of solar energy infrastructure aligns with long-term environmental goals, promotes social equity, and maintains economic viability. In doing so, the solar energy sector can play a pivotal role in transitioning towards a more sustainable and equitable future (Prieto-Jiménez et al., 2021).

2.1.2 THE ROLE OF SUSTAINABILITY IN THE SOLAR ENERGY INDUSTRY

Solar energy has become a vital component of global energy strategies due to its potential to provide clean and renewable power. Solar power generation involves the conversion of sunlight into electricity, typically through photovoltaic (PV) panels, and has proven to be an effective alternative to fossil fuel-based energy sources. As the demand for renewable energy grows, the solar industry has gained increasing relevance in the global economy, offering a solution that not only reduces greenhouse gas emissions but also promotes sustainable development.

The solar industry enables companies and consumers to access clean energy without the need for significant upfront investments in fossil fuel infrastructure. Solar power systems can be installed at various scales, from residential rooftops to large utility-scale solar farms, allowing flexibility in energy generation while reducing environmental impacts (Maka & Alabid, 2022). This accessibility and scalability make solar energy an essential contributor to the broader goal of achieving global sustainability targets.

The solar energy industry already plays a central role in promoting sustainability. By providing one of the cleanest and most abundant renewable energy sources, the sector is significantly reducing reliance on fossil fuels and cutting down greenhouse gas emissions. Solar power has prevented millions of tons of CO_2 emissions annually, helping to mitigate climate change (Tabassum et al., 2021). Moreover, as technology advances and solar panels become more efficient, the environmental benefits of solar energy continue to grow.

Socially, the solar industry is fostering job creation and promoting economic development, particularly in rural areas. The construction, installation, and maintenance of solar projects provide employment opportunities while also supporting energy access in underserved communities. This contributes to social equity by expanding access to affordable, renewable energy (Carley & Konisky, 2020). The industry's efforts to maintain ethical standards, such as ensuring fair labor practices and avoiding conflict minerals in the supply chain, further enhance its social sustainability credentials.

Economically, solar energy is benefiting from financial incentives like tax credits and subsidies, which have made the technology more accessible and attractive to investors.

These incentives have helped lower the costs of solar projects, driving growth and innovation in the industry (Bolinger et al., 2019). The sector's ability to attract investment and foster economic growth solidifies its role as a key player in the global transition toward a sustainable energy future.

2.1.3 THE TRIPLE BOTTOM LINE APPROACH

In contemporary discourse on sustainability, the Triple Bottom Line (TBL) framework stands out as a pivotal concept introduced by Elkington and Rowlands (1999). This framework advocates for organizations to assess their performance based on three interconnected dimensions: economic, environmental, and social (Braccini & Margherita, 2019; Gimenez et al., 2012; Mok et al., 2022). The economic dimension of the TBL urges organizations to not only prioritize financial profitability but also to foster economic development that benefits all stakeholders involved. This includes generating employment opportunities, enhancing local economies, and investing in sustainable business practices that contribute to long-term economic stability.

On the environmental front, the TBL encourages organizations to adopt environmentally responsible practices aimed at minimizing ecological footprints and conserving natural resources. Strategies include reducing emissions, optimizing resource use, embracing renewable energy sources, and promoting sustainable supply chain practices. The social dimension of the TBL emphasizes the importance of corporate social responsibility (CSR) initiatives that benefit communities and stakeholders beyond financial gains. This involves promoting fair labor practices, supporting community development projects, ensuring workplace diversity and inclusion, and fostering positive relationships with local communities.

By integrating these three dimensions, the TBL framework challenges traditional business paradigms that focus solely on financial metrics. It advocates for a balanced approach where economic success is intertwined with environmental and social responsibility, then fostering sustainable development and enhancing organizational resilience in a dynamic global landscape. Despite its merits, the TBL framework faces challenges. Quantifying impacts across these dimensions can be complex and subjective (Verwaal et al., 2022). Also, tensions may arise among the dimensions; actions that enhance economic sustainability may sometimes conflict with social or environmental goals (Braccini & Margherita, 2019).

The TBL remains a powerful tool for organizations seeking to balance profit-making with environmental responsibility and social equity. By integrating these dimensions into strategic decision-making, organizations can enhance their resilience, reputation, and long-term sustainability in a rapidly evolving global landscape.

2.2 SUPPLIER SELECTION AND EVALUATION PROCESSES

2.2.1 THE IMPORTANCE OF SUPPLIER SELECTION AND EVALUATION IN THE CONSTRUCTION INDUSTRY

Selecting the appropriate suppliers is a crucial process for the best result of the selection of materials and services on its quality, sustainability, and cost. In the construction industry, the performance of suppliers plays a critical role in determining the success of a project. Supplier underperformance can lead to significant negative consequences, including delays, increased costs, and compromised quality. This underscores the importance of a robust supplier selection and evaluation process (Patil & Kumthekar, 2016). Given the heavy reliance on suppliers for a wide range of materials and services, construction companies must carefully assess their partners to ensure they meet the necessary standards.

Supply Chain Management (SCM), which, according to Taherdoost & Brard (2019), aims to improve the flow of information, goods, and services from the point of origin to the point of consumption, has become a cornerstone in modern management practices, particularly in capitalizing on the benefits brought about by globalization. In the construction industry, SCM has been pivotal in ensuring that projects are completed on time, within budget, and to the required quality standards by streamlining the supply chain process.

In today's globalized market, advances in technology and connectivity have expanded the range of available suppliers, offering construction companies access to a broader spectrum of options in terms of quality, pricing, availability, and service offerings. However, this increased choice also brings complexity, as the selection process now requires a more sophisticated approach to manage the diverse criteria and varying standards of suppliers.

Supplier selection is not just about finding partners who can deliver materials on time and at a competitive price; it also involves evaluating suppliers based on environmental and social criteria, as sustainability has become a decisive factor in the industry. For instance, in the solar power sector, components like racking systems are critical for ensuring the efficiency and stability of installations. Suppliers must therefore not only provide high-quality materials but also align with sustainable practices as defined by the Triple Bottom Line concept, which emphasizes the importance of balancing economic, environmental, and social considerations (Govindan et al., 2013; Elkington & Rowlands, 1999).

Despite the inherent challenges of evaluating multiple criteria and managing the complexity of specialized materials, the supplier selection and evaluation process remains indispensable for any construction company aiming to achieve long-term success when building solar power plants. By optimizing this process, companies can mitigate the risks associated with supplier underperformance, gain a competitive edge, and ensure that their projects are not only economically viable but also environmentally and socially responsible. This focus on comprehensive supplier evaluation ultimately positions construction firms to capitalize on the full range of benefits that effective Supply Chain Management offers, driving sustained growth and success in an increasingly competitive industry.

2.2.2 EXISTING APPROACHES

Given the complexity of modern supply chains, especially in renewable energy projects, multi-criteria decision-making (MCDM) methods are essential for evaluating suppliers against a broad set of criteria, including cost, quality, delivery reliability, and sustainability.

The Analytic Hierarchy Process (AHP) is a widely used method that structures complex decisions into a hierarchy and assigns relative weights to each criterion. For example, Zhang et al. (2020) applied AHP in the evaluation of wind turbine suppliers, prioritizing sustainability alongside cost and technological capabilities. In the solar energy sector, Wang et al. (2022) demonstrated how AHP can optimize supplier selection by integrating both financial and environmental performance metrics.

TOPSIS (Technique for Order Performance by Similarity to Ideal Solution) is another popular MCDM method, which ranks alternatives based on their proximity to an ideal solution. Liu et al. (2021) used TOPSIS to evaluate solar panel suppliers, showing how this method balances competing criteria like cost and environmental impact in renewable energy projects.

Fuzzy Logic is a computational approach that handles uncertainty in decision-making by converting qualitative assessments into quantitative values. Saputro et al. (2022) applied Fuzzy Logic in solar panel supplier selection to evaluate criteria that are difficult to quantify, such as supplier reputation. PROMETHEE II (Preference Ranking Organization Method for Enrichment Evaluation) is a robust method for comparing alternatives based on several criteria. Nguyen and Bui (2019) utilized PROMETHEE II to assess renewable energy equipment suppliers, emphasizing the need to consider not just cost but also sustainability and supplier reliability.

SMARTER (Simple Multi-Attribute Rating Technique Exploiting Ranks) simplifies the decision-making process by assigning weights to criteria based on their rank order, offering a quicker and more straightforward approach compared to methods like AHP, while still providing robust decision support. Martins et al. (2020) applied SMARTER in selecting suppliers for renewable energy projects, highlighting its ability to streamline decision-making without sacrificing robustness.

Despite the proven effectiveness of these methods in academic research, many companies find them too complex, time-consuming, or difficult to integrate into existing procurement workflows. As a result, procurement decisions remain heavily cost-driven, often at the expense of other critical factors such as long-term sustainability and ethical sourcing. This research aims to fill this gap by developing a decision-making model that balances practical ease of use with a structured, multi-criteria evaluation framework, making sustainable procurement more accessible to companies

2.3 SELECTION CRITERIA

Based on a comprehensive literature review and the analysis of criteria considered in previous research, as well as data gathered through structured interviews with industry experts, it was possible to identify the most crucial factors for supplier selection in the solar energy sector for companies building solar power plants. These final criteria represent a balanced approach across economic, environmental, and social dimensions, each of which plays a key role in ensuring the success and sustainability of EPC (Engineering, Procurement, and Construction) projects.

Economic criteria are often regarded as the most critical factors in the selection of material suppliers, and in many cases, they are the primary or even sole considerations in the decision-making process. Cost efficiency is frequently the focal point of these evaluations, with companies heavily relying on competitive pricing to align with project budgets. However, industry experts caution against the pitfalls of basing decisions solely on cost. While a lower price may seem advantageous, it can lead to significant risks if the supplier lacks financial stability. For instance, if a supplier goes out of business midway through the project, the entire endeavor can be jeopardized, leading to delays, increased costs, and potentially catastrophic consequences for the business.

Cost Efficiency remains a fundamental economic criterion, involving the evaluation of suppliers based on competitive pricing and their overall financial structure. Suppliers must offer pricing that not only fits within the project budget but also ensures the long-term financial health of their operations. Research by Fu et al. (2018) and Liu et al. (2000) highlights the importance of not only focusing on the initial cost but also considering the supplier's ability to maintain stable operations throughout the project's duration.

Another vital economic factor is **Capital Expenditure (CapEx)**, which encompasses the upfront costs associated with the construction of solar projects. While some suppliers may offer lower initial costs, it is crucial to evaluate the long-term benefits of investing in higher-quality materials. These materials may have higher upfront costs but can result in lower maintenance and replacement expenses over the project's lifecycle (Maka & Alabid, 2022; Bolinger et al., 2019). This comprehensive view of CapEx is essential for making informed decisions that balance immediate financial outlays with long-term cost savings.

Operational Efficiency is another key economic criterion, focusing on the supplier's ability to minimize supply chain disruptions and ensure timely delivery of materials. Suppliers who demonstrate strong operational efficiency help maintain the project timeline and reduce the risk of costly delays. Research by Patil & Kumthekar (2016) and ZION Market Research (2023) underscores the importance of selecting suppliers who can scale production effectively to match project demands, thereby ensuring that the project proceeds smoothly without interruptions.

Financial Stability and Incentives are also critical considerations within the economic domain. This criterion involves assessing the supplier’s financial health and their capacity to handle large orders without compromising their operations. Moreover, the ability to leverage financial incentives or subsidies can significantly reduce overall procurement costs (Bolinger et al., 2019; Fu et al., 2018). This factor is especially relevant in large-scale solar projects, where the financial stability of suppliers is crucial for ensuring continuous progress and mitigating the risks associated with supplier insolvency.

Contractual Flexibility is an important economic factor that influences the supplier selection process. This includes the ability of suppliers to offer flexible contractual terms, such as varied payment schedules, warranties, and service agreements. Flexibility in these areas can significantly enhance the project's financial and operational risk management (Govindan et al., 2013; Rezaei et al., 2018). The ability to negotiate favorable terms is essential for managing financial risks associated with potential delays or defects in the supplied materials.

While economic criteria often dominate the decision-making process, social criteria are increasingly recognized as essential for ensuring that supplier selection aligns with broader societal goals. These criteria include regulatory compliance, community impact, and ethical labor practices, all of which contribute to the long-term success and reputation of the project.

Permitting and Regulatory Compliance is a critical social criterion, requiring that suppliers adhere to all relevant regulatory standards and obtain the necessary permits, including compliance with domestic content requirements (Sherwood, 2011; Carley & Miller, 2012). This compliance is essential to ensure that the project meets all legal and regulatory obligations, thereby avoiding potential legal issues and delays.

Technical Specifications are another important criterion, focusing on the supplier's ability to meet the specific technical requirements of the project site, including interconnection agreements and site-specific engineering constraints. Suppliers must demonstrate that their materials are suitable for the unique demands of the project, as noted by Manohar (2015) and Patil & Kumthekar (2016). This ensures that the materials provided not only meet the technical specifications but also contribute to the overall success of the project.

Local Content Requirements prioritize suppliers that source materials domestically, which not only supports local industries but also ensures compliance with regulations that may be critical for obtaining certain subsidies or meeting policy requirements (Sherwood, 2011; Gawusu et al., 2022). Additionally, selecting local suppliers can positively impact the community around the project site, potentially reducing opposition from local residents who may view large construction projects as disruptive. By supporting local businesses and contributing to the local economy, EPC companies can foster better community relations and reduce resistance to the project, which is often a concern when construction disrupts local farms or other community assets.

Community Impact and Relations evaluate the supplier's contribution to local employment, community development, and their efforts to build positive relationships with local communities. Suppliers with strong community engagement are preferred, as they contribute to the social sustainability of the project (Carley & Konisky, 2020; Sherwood, 2011). This criterion is particularly relevant in large-scale projects that can significantly impact local communities, making it essential to select suppliers who prioritize social responsibility.

Health, Safety, and Labor Practices are critical social criteria that ensure suppliers comply with health and safety standards, treat workers ethically, and adhere to fair labor practices. These practices are essential for maintaining a safe and ethical supply chain, as highlighted by Govindan et al. (2013) and Patil & Kumthekar (2016). Ensuring that suppliers maintain high standards in these areas is crucial for minimizing risks associated with workplace accidents and unethical labor practices.

Environmental considerations have become increasingly important in the sustainable development of solar energy projects. These criteria focus on minimizing the environmental impact of materials throughout their lifecycle, ensuring that the project aligns with the broader sustainability goals of the industry.

Environmental Impact and Certifications involve assessing the lifecycle environmental impacts of the materials, including their carbon footprint and compliance with environmental certifications such as ISO 14001 (Hernandez et al., 2014; Fthenakis & Kim, 2011). Suppliers with strong environmental practices are preferred, as they contribute positively to the project's sustainability goals.

Engineering Constraints are site-specific environmental criteria that require suppliers to provide materials suitable for specific environmental conditions, such as wetlands, wildlife habitats, or other sensitive areas. This ensures that the materials are not only effective in supporting solar panels but also environmentally responsible in their deployment (Turney & Fthenakis, 2011; Carley & Konisky, 2020). This criterion is particularly important in projects located in ecologically sensitive areas, where minimizing environmental disruption is a priority.

Resource Efficiency and Renewable Energy Use refer to the supplier's practices in optimizing resource use, minimizing waste, and utilizing renewable energy sources in manufacturing processes. These practices help reduce the overall environmental footprint of the materials, aligning with the sustainability objectives of the project (Govindan et al., 2013; Fthenakis & Kim, 2011). Suppliers who adopt these practices demonstrate a commitment to sustainability, which is increasingly valued in the selection process.

Circular Economy Practices are another crucial environmental criterion, involving the adoption of principles such as recycling, reuse, and refurbishment of materials.

Suppliers who implement circular economy practices reduce the environmental impact of their products and contribute to a more sustainable supply chain (Gawusu et al., 2022; Vijayan et al., 2023). This approach not only supports the project's environmental goals but also promotes a more sustainable approach to resource management within the industry.

Considering social and environmental criteria, in addition to economic ones, can offer EPC companies significant long-term benefits. These include tax benefits, enhanced relationships with local communities, and a competitive advantage when working with developers who prioritize sustainability. By taking a holistic approach to supplier selection, companies can not only reduce risks and ensure project success but also position themselves favorably within the industry, achieving benefits that extend beyond immediate financial gains.

The various criteria historically considered relevant for the selection of materials have been compiled in Table I, Table II, and Table III, categorized by economic, social, and environmental dimensions. These tables also include the corresponding bibliographic references, providing a comprehensive overview of these factors as supported by the literature.

Table I -Summary Table Economic Criteria

Economic Criteria	**References**
Cost Efficiency	(Fu et al., 2018; Liu et al., 2000; Gawusu et al., 2022)
Capital Expenditure (CapEx)	(Maka & Alabid, 2022; Bolinger et al., 2019)
Operational Efficiency	(Patil & Kumthekar, 2016; Liu et al., 2000)
Financial Stability and Incentives	(Bolinger et al., 2019; Fu et al., 2018)
Contractual Flexibility	(Govindan et al., 2013; Rezaei et al., 2018)

Economic Criteria	References
Delivery Schedule	(Patil & Kumthekar, 2016; Gawusu et al., 2022)
Innovation and Technological Advancements	(Prieto-Jiménez et al., 2021; Govindan et al., 2013)

Source: Own elaboration (2024).

Table II -Summary Table Social Criteria

Social Criteria	References
Permitting and Regulatory Compliance	(Sherwood, 2011; Carley & Miller, 2012)
Technical Specifications	(Manohar, 2015; Patil & Kumthekar, 2016)
Local Content Requirements	(Sherwood, 2011; Gawusu et al., 2022)
Community Impact and Relations	(Carley & Konisky, 2020; Sherwood, 2011)
Health, Safety, and Labor Practices	(Govindan et al., 2013; Patil & Kumthekar, 2016)

Source: Own elaboration (2024).

Table III -Summary Table Environmental Criteria

Environmental Criteria	References
Environmental Impact and Certifications	(Hernandez et al., 2014; Fthenakis & Kim, 2011)
Engineering Constraints	(Turney & Fthenakis, 2011; Carley & Konisky, 2020)
Resource Efficiency and Renewable Energy Use	(Hsu et al., 2013; Kuşkaya et al., 2023) (Govindan et al., 2013; Fthenakis & Kim, 2011)
Circular Economy Practices	(Gawusu et al., 2022; Vijayan et al., 2023)

Source: Own elaboration (2024).

3. METHODOLOGY

3.1 INITIAL PROBLEM AND RESEARCH QUESTION

3.1.1 INITIAL PROBLEM

Based on the literature review, this research aims to assist decision-makers in the solar energy industry by developing an adaptable model that meets the specific needs of companies involved in solar projects to enable managers to select and evaluate material suppliers for solar project sites in a sustainable and informed manner.

As the solar energy industry continues to grow, the need for sustainable and informed decision-making in selecting material suppliers becomes increasingly critical. Traditionally, many companies have relied primarily on economic criteria, such as cost, when choosing suppliers. However, this narrow focus has led to suboptimal decisions that fail to consider the broader impact on social and environmental spheres. Such an approach has proven inadequate in the long term, as it neglects the interconnected nature of sustainability considerations, potentially leading to negative outcomes for businesses and stakeholders alike.

The challenge, therefore, is to develop a model that integrates a broader set of criteria to ensure that material supplier selection is not only economically sound but also socially and environmentally responsible, but that is also straightforward and of practical appliance. This research seeks to address this issue by employing the Analytic Hierarchy Process (AHP), a robust multi-criteria decision-making (MCDM) method, to develop a framework that allows decision-makers to evaluate and prioritize economic, social, and environmental criteria in a structured, quantifiable manner. The goal is to assist managers in making more balanced and sustainable decisions that align with their company's strategic objectives and sustainability goals.

3.1.2 RESEARCH QUESTION

Considering the identified problem, this research seeks to answer the investigatory question "How can decision-makers within solar energy companies systematically evaluate and prioritize economic, social, and environmental criteria when selecting material suppliers to ensure sustainable procurement that aligns with strategic and sustainability goals?"

This study is both exploratory and descriptive. Exploratory research, as defined by Saunders et al. (2019), is used when the objective is to explore a phenomenon or issue in depth, often when there is limited prior knowledge available. In the context of this study, the goal is to uncover and understand the specific criteria that decision-makers prioritize in the selection of material suppliers for solar projects. This aligns with the exploratory nature of the research, which seeks to generate insights and inform future studies on the subject. According to Stebbins (2001), exploratory studies are particularly useful for gaining familiarity with phenomena that are not well understood or for generating hypotheses for further investigation.

At the same time, the study is descriptive, which involves providing an accurate and systematic account of events or phenomena (Sandelowski, 2000). Descriptive research helps to clarify the 'what,' 'how,' and 'why' questions related to a particular situation. In this study, structured interviews with three industry experts and decision-makers provide detailed insights into how economic, social, and environmental criteria are applied in real-world decision-making for supplier selection. Descriptive research allows for the articulation of these criteria and the way they are evaluated within a structured framework.

Following Yin's (2014) perspective, descriptive research is key to gaining detailed, real-world insights, especially when focusing on specific cases or scenarios, as is the case in this research. By combining both exploratory and descriptive approaches, this study provides both a deep understanding of the decision-making criteria and a comprehensive description of how these criteria are prioritized in practice.

3.2 RESEARCH METHOD

To answer the research question, this study adopts a mixed-methods approach, utilizing both qualitative and quantitative research techniques to address the research question. The primary research method employed is the Analytic Hierarchy Process (AHP), a robust multi-criteria decision-making (MCDM) method, paired with a case study approach to demonstrate its practical application in the solar energy industry.

The AHP method, as developed by Saaty (1980), is particularly suited for this research because it systematically structures complex decision-making processes. AHP breaks down the problem into a hierarchy of criteria and sub-criteria, allowing for pairwise comparisons and the calculation of weighted scores. This makes it an effective tool for integrating both subjective judgments and quantitative data, especially in the context of supplier selection for solar projects.

Data collection involved two primary methods. First, structured interviews were conducted with three professionals directly involved in the decision-making process for procuring materials for solar project sites across the United States. The participants included a Senior Project Manager, an Assistant Manager, and a Project Manager, each with over five years of experience in the construction industry. These interviews were designed to gather qualitative data, focusing on the decision-makers' perspectives regarding the importance of economic, social, and environmental criteria in supplier selection. During the interviews, the main categories and their associated sub-criteria were presented. For instance, the economic category included considerations such as capital expenditure (CAPEX) and cost efficiency, while the social category incorporated aspects like fair labor practices. The decision-makers were asked to rank the importance of the three categories—economic, social, and environmental—on a scale from 1 to 5, where 1 indicated equal importance and 5 signified strong importance. This ranking process formed the basis for the pairwise comparisons required in the AHP model.

In addition to the interviews, document analysis was employed to provide further context and validation for the decision-making framework. This method involved reviewing internal company reports and procurement policies related to supplier selection in the solar energy industry, allowing for a deeper understanding of the criteria and considerations at play in the real-world decision-making process.

Data analysis was carried out using the AHP model. The rankings provided by the decision-makers during the interviews were used to create pairwise comparison matrices, enabling the quantification of their preferences. This process resulted in weighted scores for each criterion, which were then used to prioritize the economic, social, and environmental factors influencing supplier selection. To further validate the AHP model, a case study was conducted. The case study applied the developed model to real-world supplier evaluations, incorporating the rankings and preferences of the decision-makers to ensure the model's practical utility. This case study helped demonstrate the effectiveness of the AHP model in guiding decision-makers toward more balanced and sustainable supplier selection decisions, which align with their companies' strategic objectives.

By adopting this comprehensive research strategy, the study ensures that the developed AHP model is grounded in both theoretical insights and real-world practices, enabling decision-makers in the solar energy industry to make informed, sustainable procurement decisions.

3.3 DEVELOPMENT OF A MULTI-CRITERIA DECISION SUPPORT MODEL

3.3.1 MODEL ARCHITECTURE

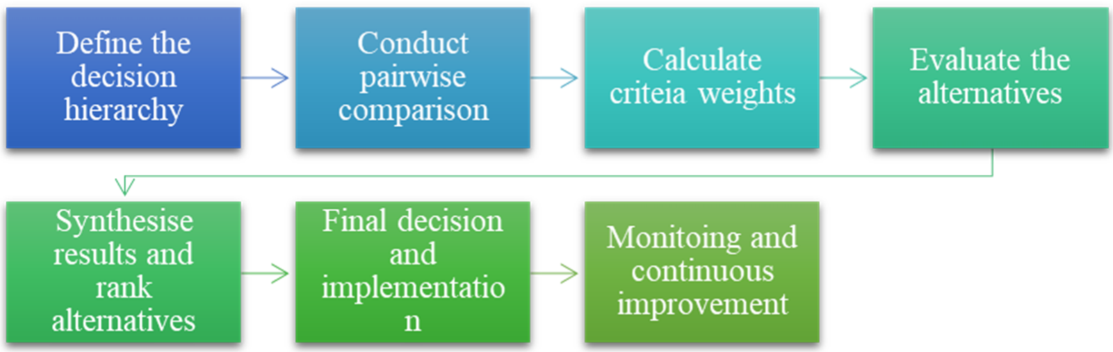

Figure 1- Model Architecture

Source: Own elaboration

Figure 1 outlines the architecture of the decision-making model developed using the Analytic Hierarchy Process (AHP). This seven-step guide provides a comprehensive framework for selecting suppliers based on economic, social, and environmental criteria. Each step in the model supports a structured, systematic approach to making balanced and sustainable decisions, while maintaining it straightforward and of facilitated use.

Step 1: Define the Decision Hierarchy

The first step in using the AHP model is to define the decision hierarchy. This involves breaking down the decision into its main components: the goal (e.g., selecting the best supplier), the key criteria (economic, social, and environmental), and the sub-criteria that fall under each category. For example, the economic category might include sub-criteria such as capital expenditure (CAPEX) and cost efficiency, while the environmental category could include criteria like sustainability practices and resource use. Defining this hierarchy is crucial because it provides the structure for the decision-making process and ensures that all relevant factors are considered.

Step 2: Conducting Pairwise Comparisons

The second step involves conducting pairwise comparisons between the main categories—economic, social, and environmental—based on their relative importance in the decision-making process. Decision-makers should rank the categories using a scale from 1 to 5, where 1 represents equal importance, and 5 represents a strong preference for one category over another. This process helps in establishing how significant each criterion is in relation to the others. The pairwise comparison matrix is then formed, which provides the foundation for calculating the relative weights of each criterion.

Step 3: Calculating Weightage of Criteria

Once the pairwise comparisons are completed, the next step is to calculate the weight of each criterion (economic, social, and environmental). These weights reflect the relative importance of each criterion in achieving the decision-making goal. To ensure the validity of these weights, the AHP method normalizes the comparison matrix, and it is essential to check the consistency ratio. A consistency ratio of 0.2 or less is considered acceptable; if the ratio exceeds this value, the pairwise comparisons should be re-evaluated to improve consistency. This step ensures that the decision-making process remains accurate and reliable.

Step 4: Evaluating Alternatives

After the criteria weights are established, the next phase involves evaluating supplier alternatives. Each supplier is assessed based on how well they meet the economic, social, and environmental criteria. To perform this evaluation, decision-makers should rate each supplier on how they fulfill the specific requirements. For example, under the environmental category, suppliers are evaluated on their sustainability efforts and measures. The scores from these evaluations are then weighted according to the criteria established in Step 3, providing a detailed assessment of each supplier's performance.

Step 5: Synthesizing Results and Ranking Alternatives

Once the suppliers have been evaluated, their weighted scores should be synthesized to determine their overall ranking. The supplier with the highest total score is considered the most suitable for the project. It is important to review these results carefully and ensure transparency by sharing the rankings with stakeholders. This step allows decision-makers to confirm that the selected supplier aligns with the project's economic, social, and environmental objectives. Additionally, the results should be reviewed to ensure consistency and alignment with the sustainability goals.

Step 6: Final Decision and Execution

In this step, the final decision is made based on the rankings generated from the model. However, the decision often involves additional stakeholder input, leading to a consensus that reflects both the model's outputs and practical considerations. Once the final supplier is selected, the procurement process begins, including contract negotiations, signing, and the planning of delivery and monitoring. It is important to document the decision-making process, including the reasons for selecting a particular supplier and how this choice advances the project's sustainability agenda. The model also allows for decision-makers to account for the case when most suitable supplier can't meet their needs, by presenting them the rank with the best next options in this case.

Step 7: Monitoring and Continuous Improvement

After the supplier is selected and procurement is underway, regular performance evaluations should be conducted to ensure the supplier meets the project's quality standards, delivery schedules, and sustainability requirements. This step involves ongoing monitoring and feedback, allowing for continuous improvement. If issues arise, they should be addressed promptly to ensure alignment with the project's goals. Monitoring also helps to provide the supplier with feedback, ensuring that they continue to meet the expectations set forth in the decision-making process. Continuous assessment contributes to the overall value of the procurement system and ensures that sustainability remains a core focus.

3.3.2 COMPARISON WITH EXISTING METHOD

Currently, the most prevalent existing method, as demonstrated by the company in the case study presented in the next section, is to employ a traditional supplier selection method, focusing primarily on economic considerations, such as selecting the vendor with the lowest quote. This approach, while straightforward, overlooks the broader dimensions of sustainability—namely social and environmental factors—that are increasingly vital in today's business landscape.

In the existing method, companies follow a standardized operating procedure that includes a supplier facility visits. The company coordinates visits to supplier fabrication facilities and corporate offices. During these visits, teams assess the supplier's operations, engage with the supplier's executive team, and may request product demonstrations. These visits result in a Supplier Facility Visit Report, which includes an assessment checklist and photo documentation. The report is then reviewed internally in a debriefing session with key stakeholders from various departments, such as operations and field teams.

If the company is interested in pursuing a relationship with the supplier, they send a

Master Purchasing Agreement (MPA) template to the supplier for review. The negotiation process involves several rounds of revisions and meetings, including legal reviews, until a mutual agreement is reached. If an agreement cannot be reached, the company discontinues further discussions with that supplier.

While this method includes thorough procedural steps for assessing and negotiating with suppliers, it is primarily focused on economic efficiency and operational compatibility, with limited consideration for social and environmental dimensions. The emphasis remains on securing the lowest price, supplemented by in-person assessments to ensure basic operational standards.

3.3.3 DEVELOPED METHOD

In contrast, the proposed approach utilizing the Analytic Hierarchy Process (AHP) introduces a more holistic evaluation method. The AHP model allows decision-makers to systematically consider a broader range of criteria beyond just economic factors. By incorporating social and environmental dimensions, the AHP approach provides a more balanced assessment framework that aligns with sustainable development goals.

Through structured interviews with industry experts and decision-makers, the AHP method enables the quantification of the relative importance of economic, social, and environmental criteria. This data-driven approach allows for a comprehensive comparison of suppliers based on a weighted scoring system, offering a more nuanced evaluation that goes beyond cost considerations alone.

The current method's strength lies in its straightforwardness and operational rigor, focusing on economic efficiency and basic quality assurance through site visits and direct assessments. However, this approach may miss opportunities for broader sustainability impacts and long-term value creation by neglecting social and environmental factors.

The AHP-based method addresses these gaps by providing a structured framework to evaluate suppliers against multiple criteria, ensuring that the selected suppliers not only offer competitive pricing but also contribute positively to social and environmental goals. This integrated approach supports the company’s strategic objectives of sustainable growth and resilience in an increasingly complex market landscape.

By combining the rigorous assessment steps of the existing method with the comprehensive, criteria-based analysis of AHP, the company can enhance its supplier selection process to better align with evolving industry standards and stakeholder expectations.

3.4 CASE STUDY: COMPANY IN THE ENERGY RENEWABLE INDUSTRY

3.4.1 BRIEF OVERVIEW OF THE COMPANY

Company X, LLC, headquartered in Fort Lauderdale, Florida, is a leading company in the construction industry, specializing in large-scale commercial and utility-scale solar projects. Established in 2004, Company X began its venture into solar energy in 2008, rapidly becoming a significant force in renewable energy construction. The average size of Company X's solar projects typically ranges from 100 MW to over 200 MW, showcasing the company's capacity to handle substantial and complex installations.

Company X operates on two primary fronts: self-performance efforts and construction management (CM) services. In its self-perform capacity, Company X directly oversees and executes the construction work, leveraging its in-house teams for tasks like installation, wiring, and panel setup. This approach allows for greater control over quality, schedule, and safety. On the construction management side, Company X coordinates and manages subcontractors, ensuring that projects are completed to the highest standards while maintaining a strong focus on safety and efficiency.

Company X is deeply committed to social responsibility, particularly in promoting safety and providing second-chance employment opportunities. As a "safety first" company, Company X has implemented rigorous safety training programs for all employees, emphasizing the importance of workplace safety in every project. The company's core value of "improving lives and building the future" reflects its dedication to not only constructing high-quality projects but also contributing positively to the communities in which it operates. This commitment extends to supporting the future of clean energy through its extensive portfolio of solar projects.

Company X has a long-standing history of collaboration with one of the largest utility companies in the United States, Company Y. Through this partnership, Company X has played a crucial role in the development and expansion of Company Y's solar energy capacity, contributing to the growth of clean energy in the U.S. This collaboration highlights Company X's expertise and reliability in delivering large-scale solar projects that align with the broader goal of transitioning to renewable energy sources.

3.4.2 CASE STUDY: SOLAR PROJECT SITE DEVELOPMENT IN FLORIDA

This case study examines a solar project undertaken by an EPC company specializing in the construction of large-scale solar project sites in Florida, Company X. The project in focus is a 100 MW solar power plant to be developed in Broward County over a two-year period, with a total budget of $50 million.

The project's objective is to enhance utility company Y's renewable energy portfolio and contribute to Florida's clean energy goals. The 100 MW solar plant will occupy a strategically located site in Broward County, chosen for its favorable solar irradiance and accessibility. The construction phase is planned to span over two years, during which the EPC company will manage all aspects of the project, including design, procurement, construction, and commissioning.

One of the critical components required for this solar project is the inverter, a key piece of equipment that converts the direct current (DC) electricity generated by solar panels into alternating current (AC) electricity, which can be fed into the utility grid.

Given the scale and importance of the project, selecting the right inverter supplier is crucial. The company aims to acquire inverters that not only meet technical specifications and cost constraints but also align with broader sustainability objectives, such as minimizing environmental impact and supporting socially responsible practices.

The EPC company traditionally follows a standard operating procedure for supplier selection, heavily focused on economic considerations like cost. The process typically involves:

Supplier Assessments: Potential suppliers are initially vetted through a Non-Disclosure Agreement (NDA) and a detailed Supplier Assessment Questionnaire. The company reviews the supplier's responses and assesses their technical capabilities and compliance with project requirements.

Facility Visits: The company conducts visits to the supplier's manufacturing facilities and corporate offices to evaluate their production processes, quality control measures, and operational standards. These visits provide an opportunity to directly engage with the supplier's executive team and observe their operations first-hand.

Contract Negotiation: If a supplier passes the initial assessment and facility visit stages, the company engages in contract negotiations, using a Master Purchasing Agreement (MPA) template. This stage involves multiple rounds of revisions and negotiations to ensure both parties reach a mutual agreement.

While this process is thorough, it primarily emphasizes cost-efficiency and basic operational checks, with limited consideration for the broader social and environmental impacts of the supplier's practices.

Recognizing the need for a more comprehensive approach, it was adopted the Analytic Hierarchy Process (AHP) method for this project to enhance its supplier selection process for inverters. AHP will allow the company to evaluate potential suppliers not only based on cost but also considering additional criteria such as environmental sustainability and social responsibility.

To implement the AHP model, it was conducted structured interviews with key decision-makers involved in material procurement, including a project manager, assistant manager and a senior project manager. These interviews helped to determine the relative importance of economic, social, and environmental criteria when selecting inverter suppliers. By quantifying these criteria, the AHP model facilitates a more balanced decision-making process, aligning with both the project's technical requirements and the company's strategic sustainability goals.

The objective of this case study is to demonstrate the effectiveness of the AHP model in enhancing the supplier selection process. By applying this method, the company aims to select an inverter supplier that not only offers competitive pricing and meets technical specifications but also contributes positively to the company's sustainability initiatives and long-term strategic objectives. This approach provides a real-world example of how a more holistic evaluation model can improve decision-making in the solar energy industry, ensuring better alignment with evolving market demands and stakeholder expectations.

3.4.3 CHARACTERIZATION OF CURRENT SUPPLIERS

Company X collaborates with a select group of inverter suppliers known for their reliability, innovation, and sustainability. The suppliers provide critical inverter systems required for the solar project, and each plays a unique role in supporting Company X’s large-scale projects. These suppliers include:

Supplier A: Known for their robust and versatile inverter systems, Supplier A offers solutions compatible with a wide range of solar panel models. Their systems are designed to withstand extreme weather conditions, ensuring the durability and longevity of solar installations.

Supplier B: A leader in inverter innovation, Supplier B provides customizable solutions that optimize energy conversion efficiency. Their products are designed to reduce installation time and labor costs, making them a preferred choice for large-scale projects.

Supplier C: Focused on sustainability, Supplier C produces inverter systems made from recycled materials. Their eco-friendly approach aligns with Company X's commitment to reducing environmental impact. Supplier C's inverters are also known for their ease of maintenance and adaptability to different terrains.

Supplier D: Specializing in high-efficiency inverters, Supplier D provides systems with superior energy conversion rates. Their advanced manufacturing techniques help to minimize defects and increase the lifespan of inverters, making them ideal for long-term projects requiring reliable performance.

Supplier E: Supplier E manufactures inverter systems that allow for quick and efficient installation, especially in difficult terrains. Their systems are designed to reduce the number of components needed for assembly, leading to lower overall project costs and faster setup times.

Supplier F: A global leader in solar inverters, Supplier F provides both centralized and decentralized inverter solutions. Their products are equipped with real-time monitoring features to optimize performance under varying weather conditions.

Supplier G: Known for their specialization in integrated inverter and energy storage systems, Supplier G combines inverters with battery storage to provide seamless energy conversion and distribution. Their products are ideal for projects where energy storage is crucial for balancing supply and demand.

Supplier H: Supplier H provides custom-designed inverter systems that adapt to a variety of site conditions, including high-wind and coastal areas. Their designs are optimized for structural integrity and long-term performance, making them a reliable choice for projects in challenging environments.

4. PRESENTATION AND RESULTS ANALYSIS

4.1 OBTAINING AND CALCULATING WEIGHTS USING THE AHP METHOD

The following section outlines the steps involved in calculating the weights for the economic, social, and environmental criteria using the Analytic Hierarchy Process (AHP) method. After conducting structured interviews with key decision-makers, their preferences were captured through pairwise comparisons, which were then used to derive the relative weights of each criterion. This process ensures a balanced evaluation of the criteria based on the judgments provided by experts.

Step 1: Constructing the Pairwise Comparison Matrix

Using the data gathered from interviews, a pairwise comparison matrix is created for the three main criteria: economic, social, and environmental. Each decision-maker provided pairwise comparisons, scoring each criterion relative to one another on a scale of 1 to 5, where:

1 indicates equal importance between the two criteria,

3 indicates moderate importance of one criterion over the other,

5 indicates strong importance of one criterion over the other.

The pairwise comparisons are captured in a matrix format, where each element represents the comparison between two criteria. For example, if the economic criterion is deemed to be strongly more important than the environmental criterion, a score of 5 would be placed in the corresponding cell. For each pair of criteria, when a decision-maker assigns a value to represent the importance of one criterion over another, the reciprocal value is automatically assigned to the inverse comparison. For example, if the decision-maker assigns a value of 3 to indicate that the economic criterion is moderately more important than the social criterion, the reciprocal value of 0.33 is assigned to the comparison of the social criterion relative to the economic criterion. This ensures consistency in the pairwise comparison matrix and allows the matrix to remain symmetrical, as required by the AHP method.

Step 2: Normalizing the Pairwise Comparison Matrix

Once the pairwise comparison matrix is established, the next step is to normalize the matrix. Normalization ensures that the matrix can be used to calculate the relative weights of each criterion accurately. The normalization process involves the following steps:

Sum all the values in each column of the pairwise comparison matrix.

Divide each element in the matrix by the sum of its respective column, which normalizes the values so that each column adds up to 1.

The resulting normalized matrix provides a basis for calculating the relative importance of each criterion in relation to the others, accounting for the reciprocal values added for inverse comparisons.

Step 3: Calculating the Criteria Weights

After normalizing the matrix, the next step is to calculate the weight for each criterion. The weight of each criterion is determined by averaging the values in each row of the normalized matrix. The formula for calculating the weight of each criterion is:

$$\text{Weight of Criterion} = \frac{\sum \text{Normalized Values of the Row}}{\text{Number of Criteria}} \quad (1)$$

This process is repeated for each criterion (economic, social, and environmental) to determine their respective weights.

Step 4: Checking Consistency of the Matrix

The AHP method requires checking the consistency of the pairwise comparisons to ensure that the judgments made by decision-makers are reliable. The consistency ratio (CR) is calculated to assess the level of consistency in the matrix. The consistency ratio is calculated by first determining the consistency index (CI) using the formula:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (2)$$

Where:

λmax is the largest eigenvalue of the comparison matrix,

n is the number of criteria (in this case, 3).

Once the CI is calculated, the consistency ratio (CR) is obtained by dividing the CI by the random index (RI), which depends on the number of criteria. For three criteria, the RI used was 0.58. The formula for the consistency ratio is:

$$CR = \frac{CI}{RI} \tag{3}$$

Based on recent studies, a consistency ratio of 0.2 or less is considered acceptable for decision-making processes, allowing for a reasonable level of inconsistency in complex scenarios where multiple criteria are involved (Saaty, 2006; Ishizaka & Labib, 2011). If the CR exceeds 0.2, it indicates that the pairwise comparisons are inconsistent, and the decision-makers should review and adjust their judgments to improve reliability.

Step 5: Applying Weights to Evaluate Alternatives
Once the weights for each criterion are calculated and confirmed to be consistent, they are applied to evaluate the alternative suppliers. Each supplier is rated based on their performance across the economic, social, and environmental criteria, using the same pairwise comparison method. The scores for each supplier are weighted according to the criteria weights calculated in the previous steps, resulting in a final score for each supplier.

Step 6: Final Decision and Ranking
The final weighted scores for each supplier are synthesized to generate a ranking. The supplier with the highest total score is considered the most suitable based on the balance of economic, social, and environmental criteria. This ranking forms the basis for the final procurement decision.

4.1.1 PARTIAL AND GLOBAL RESULTS

The results gathered from interviews with three key decision-makers—Senior Project Manager, Assistant Manager, and Project Manager—are presented below. Their assessments were collected through structured interviews, where they provided pairwise comparisons of the criteria, allowing for a systematic calculation of weights.

Tables IV, V, and VI display the individual results for each decision-maker, showing how they rated the importance of each criterion. These tables provide insight into the decision-makers' perspectives, highlighting their focus on different aspects of the supplier selection process, such as cost-efficiency, sustainability, or operational impact.

Table IV: Decision-maker 1

Decision Maker 1	**Economic**	**Social**	**Environmental**
Economic	1.00	4.00	5.00
Social	0.25	1.00	3.00
Environmental	0.20	0.33	1.00
Sum	1.45	5.33	9.00

Table V: Decision-maker 2

Decision Maker 2	Economic	Social	Environmental
Economic	1.00	5.00	5.00
Social	0.20	1.00	2.00
Environmental	0.20	0.50	1.00
Sum	1.40	6.50	8.00

Table VI: Decision-maker 3

Decision Maker 3	Economic	Social	Environmental
Economic	1.00	3.00	4.50
Social	0.33	1.00	3.50
Environmental	0.22	0.29	1.00
Sum	1.56	4.29	9.00

Following the individual results, the global average of the three evaluations is presented in a summarized table. This global average is calculated by taking the mean of the weights assigned to each criterion by the decision-makers, offering a balanced representation of their collective input.

Table VII: Global Results Ranking

Global Results	**Economic**	**Social**	**Environmental**
Economic	1.00	4.00	4.83
Social	0.26	1.00	2.83
Environmental	0.21	0.37	1.00
Sum	1.47	5.37	8.67

After applying the necessary calculations to the data obtained from the decision-makers, the results of the pairwise comparisons are presented. These results have been normalized to reflect the relative importance of each criterion (economic, social, and environmental) as evaluated by the decision-makers. The table below shows the final pairwise comparison results after the appropriate calculations were applied, including the normalized values for each criterion.

Table VIII: Pair-wise comparison matrix

Pair-wise Comparison	**Economic**	**Social**	**Environmental**	**Criteria Weights**
Economic	0.68	0.74	0.56	0.66
Social	0.18	0.19	0.33	0.23
Environmental	0.14	0.07	0.12	0.11

The normalized pairwise comparison results provide the basis for calculating the final weights for each criterion. These weights reflect the relative importance of each criterion in the decision-making process and are used to evaluate the suppliers.

The next table summarizes the final criteria weights for the economic, social, and environmental categories, including the calculated values of λmax , consistency index (CI), and consistency ratio (CR). The consistency ratio was evaluated to ensure the reliability of the decision-makers' judgments, with a threshold of 0.2 or less considered acceptable based on recent studies.

Table IX: Final Criteria Weights and Consistency Check Results

Criteria Weights	0.66	0.23	0.11	
	Economic	**Social**	**Environmental**	**Weighted Sum Value**
Economic	0.66	0.92	0.531666667	2.111666667
Social	0.172333333	0.23	0.311666667	0.714
Environmental	0.1368888889	0.08579	0.11	0.33268254
Lambda Max	3.118702989			
Consistency Index (C.I)	0.059351494			
Consistency Ratio (C.R)	0.102330163	<0.20		

The consistency ratio (CR) for the pairwise comparisons was calculated based on the consistency index (CI) and the random index (RI). Since all CR values are below 0.2, the comparisons are considered consistent and reliable for use in the supplier evaluation process.

4.2 PROCES OF AVALIATION OF ALTERNATIVES

With the final criteria weights established, the following tables illustrate how each supplier (A through H) performs across the economic, social, and environmental criteria. Scores are assigned on a scale of 1 to 5, and then the criteria weights are applied to determine the total weighted score for each supplier. The highest-ranked supplier will be considered the most suitable for the project. Scores were assigned based on the decision-makers' evaluations of each supplier's performance across the criteria, drawing from their professional experience and the documented reports provided by suppliers during the contract phase. It is also important to note that the decision-makers were presented with clear definitions of each criterion and agreed that they were the most relevant and suitable for their company's objectives, ensuring that the evaluation process aligned with industry goals.

Table X: Supplier Performance Ranking

Supplier	Economic (1-5)	Social (1-5)	Environmental (1-5)
Supplier A	4	3	5
Supplier B	5	4	4
Supplier C	3	5	4
Supplier D	2	2	3
Supplier E	4	3	3
Supplier F	5	4	5
Supplier G	3	3	4
Supplier H	4	5	5

Criteria weights applied to each score: Economic = 0.66, Social = 0.23, Environmental = 0.11

Table XI: Weighted Scores for Each Supplier

Supplier	Economic (0.66)	Social (0.23)	Environmental (0.11)	Total Weighted Score
Supplier A	4 * 0.66 = 2.64	3 * 0.23 = 0.69	5 * 0.11 = 0.55	**3.88**
Supplier B	5 * 0.66 = 3.30	4 * 0.23 = 0.92	4 * 0.11 = 0.44	**4.66**
Supplier C	3 * 0.66 = 1.98	5 * 0.23 = 1.15	4 * 0.11 = 0.44	**3.57**
Supplier D	2 * 0.66 = 1.32	2 * 0.23 = 0.46	3 * 0.11 = 0.33	**2.11**
Supplier E	4 * 0.66 = 2.64	3 * 0.23 = 0.69	3 * 0.11 = 0.33	**3.66**
Supplier F	5 * 0.66 = 3.30	4 * 0.23 = 0.92	5 * 0.11 = 0.55	**4.77**
Supplier G	3 * 0.66 = 1.98	3 * 0.23 = 0.69	4 * 0.11 = 0.44	**3.11**
Supplier H	4 * 0.66 = 2.64	5 * 0.23 = 1.15	5 * 0.11 = 0.55	**4.34**

Table XII: Supplier Ranking

Rank	Supplier	Total Weighted Score
1	Supplier F	4.77
2	Supplier B	4.66
3	Supplier H	4.34
4	Supplier A	3.88
5	Supplier E	3.66
6	Supplier C	3.57
7	Supplier G	3.11
8	Supplier D	2.11

Supplier F ranks as the top supplier with a total weighted score of 4.77, excelling across all criteria, particularly in economic performance, making it the most likely candidate to supply the required materials. If, for any reason, Supplier F is not available, the advantage of this ranking model is that it clearly identifies the next best option. In this case, Supplier B follows closely with a score of 4.66, showing strong performance in both economic and social categories. This allows the company to seamlessly transition to an alternative supplier without significant compromise in key areas. Supplier H ranks third, offering a solid balance between social and environmental considerations, while Supplier D ranks lowest, reflecting weaker performance across all three criteria. This structured approach provides a clear, step-by-step selection process, ensuring that the company is always equipped with the best available options.

4.3 ADVANTAGES AND LIMITATIONS

The application of the Analytic Hierarchy Process (AHP) in this case study presents several key advantages. One of the most significant strengths of AHP is its ability to systematically integrate multiple criteria—economic, social, and environmental—into the decision-making process. This ensures that decision-makers do not rely solely on cost-based evaluations, but also account for sustainability and social responsibility. AHP allows for flexibility in adapting the model to different project needs by adjusting the weight of criteria based on organizational priorities. Furthermore, the pairwise comparison method provides transparency in how criteria are evaluated, enabling stakeholders to understand how each factor contributes to the final decision.

However, AHP is not without its limitations. One challenge lies in the subjectivity of the pairwise comparison process, where decision-makers' judgments may introduce biases. Despite the use of consistency ratio checks, human judgment remains vulnerable to inconsistencies, particularly when handling complex or closely related criteria.

It is also important to consider the potential variation in the acceptable consistency ratio, which can range from 0.1 to 0.2 depending on the context of the study. While this introduces some flexibility, it can also lead to differences in how the method is applied. However, despite this variability, AHP remains a reliable method for decision-making, as long as the established steps are carefully followed. Its strength lies in its adaptability—decision-makers can adjust the criteria weights and comparisons based on specific project needs or organizational objectives, making it a flexible tool for various industries and procurement scenarios. By adhering to the structured framework of the model, AHP ensures that decisions are consistent and systematically evaluated, even when the context varies.

In summary, AHP offers a structured and transparent approach to supplier selection, especially when balancing diverse criteria such as cost, sustainability, and social impact. However, its reliance on subjective judgment and the complexity of managing many comparisons are important factors to consider in its application.

5. CONCLUSIONS AND RECOMMENDATIONS OF FUTURE WORK

This study applied the Analytic Hierarchy Process (AHP) to the supplier selection process in a solar energy project, demonstrating how a multi-criteria decision-making approach can enhance the traditional cost-driven procurement strategies by incorporating economic, social, and environmental factors. The AHP model provided a systematic and transparent method for evaluating suppliers based on weighted criteria, allowing decision-makers to select suppliers that align with both financial objectives and broader sustainability goals. The use of the AHP method resulted in a comprehensive ranking of suppliers, clearly identifying which supplier best met the company's strategic objectives.

Importantly, this research successfully answered the investigatory question: "How can decision-makers within solar energy companies systematically evaluate and prioritize economic, social, and environmental criteria when selecting material suppliers to ensure sustainable procurement that aligns with strategic and sustainability goals?" By developing and applying the AHP model, the study demonstrated that it is possible to create a structured, methodical approach that provides a balanced evaluation of these critical criteria, ensuring that decision-makers can make informed choices that align with both sustainability and business objectives.

The key conclusions of this study are:

- AHP significantly improves decision-making by offering a balanced evaluation of both qualitative and quantitative factors.
- The inclusion of social and environmental criteria ensures that the supplier selection process is aligned with sustainability objectives, rather than being solely cost-driven.
- The use of pairwise comparisons and consistency checks enhances transparency and accountability in the decision-making process.

For future work, these is a potential to expand the model by incorporating more detailed sub-criteria within the economic, social, and environmental categories, which would allow for a deeper level of analysis. An important direction for future work could be assigning specific weights to each of these sub-criteria or the attributes associated with them, to establish their relative importance. This would enhance the model's ability to capture the nuanced priorities of decision-makers, leading to more informed and precise outcomes.

Additionally, in industries less specific or specialized than the one used in this case study, the model could be expanded to evaluate a larger pool of suppliers. This flexibility would make it possible to apply the model across different sectors with varying procurement needs.

Overall, AHP has proven to be a valuable tool for supplier selection, but further research and development are needed to fully harness its potential in larger, more dynamic procurement environments.

REFERENCES AND BIBLIOGRAPHY

Bolinger, M., Seel, J., & Robson, D. (2019). Utility-Scale Solar, 2018 Edition: Empirical Trends in Project Technology, Cost, Performance, and PPA Pricing in the United States. Lawrence Berkeley National Laboratory. https://emp.lbl.gov/publications/utility-scale-solar-2018-edition

Braccini, A. M., & Margherita, E. G. (2019). Exploring organizational sustainability: The three-dimensional triple bottom line. Sustainability, 11(1), 118. https://doi.org/10.3390/su11010118

Brundtland, G. H. (1987). Our Common Future: Report of the World Commission on Environment and Development. Oxford: Oxford University Press. https://digitallibrary.un.org/record/139811

Carley, S., & Konisky, D. M. (2020). The justice and equity implications of the clean energy transition. Nature Energy, 5, 569–577. https://doi.org/10.1038/s41560-020-0641-6

Elkington, J., & Rowlands, I. H. (1999). Cannibals with forks: The triple bottom line of 21st century business. Alternatives Journal, 25(4), 42.

Fu, R., Feldman, D. J., & Margolis, R. M. (2018). U.S. Solar Photovoltaic System Cost Benchmark: Q1 2018. National Renewable Energy Laboratory (NREL). https://doi.org/10.2172/1462912

Fthenakis, V. M., & Kim, H. C. (2011). Photovoltaics: Life-cycle analyses. Solar Energy, 85(8), 1609–1628. https://doi.org/10.1016/j.solener.2009.12.002

Gawusu, S., Addae, E., & Duodu, S. (2022). Analyzing the role of local content requirements in renewable energy policies. Journal of Sustainable Energy Development, 20(3), 45–57.

Govindan, K., Khodaverdi, R., & Jafarian, A. (2013). A fuzzy multi-criteria approach for measuring sustainability performance of a supplier based on triple bottom line approach.

Journal of Cleaner Production, 47, 345–354. https://doi.org/10.1016/j.jclepro.2012.04.014

Hernandez, R. R., Easter, S. B., Murphy-Mariscal, M. L., Maestre, F. T., Tavassoli, M., Allen, E. B., ... & Allen, M. F. (2014). Environmental impacts of utility-scale solar energy. Renewable and Sustainable Energy Reviews, 29, 766–779. https://doi.org/10.1016/j.rser.2013.08.041

IPCC. (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar6/wg1/

Ishizaka, A., & Labib, A. (2011). Review of the main developments in the Analytic Hierarchy Process. *Expert Systems with Applications, 38(11),* 14336–14345.

Khatib, T., Mohamed, A., & Sopian, K. (2012). A review of solar energy modeling techniques. Renewable and Sustainable Energy Reviews, 16, 2864–2869. https://doi.org/10.1016/j.rser.2012.01.064

Liu, J., Al-Enezi, F., & Wardlaw, M. (2000). Evaluation of solar energy technologies for public buildings. Journal of Solar Energy Engineering, 122(3), 151–157. https://doi.org/10.1115/1.1287333

Maka, A. A., & Alabid, J. (2022). The role of solar energy in achieving sustainability goals: An analysis of renewable energy policies. Energy Policy Research, 10(2), 120–135.

Manohar, K. (2015). Technical specifications and supplier selection: A study in the renewable energy sector. Journal of Engineering and Technology Management, 32(5), 134–148.

Martins, A. G., Pereira, J., & Neves, J. C. (2020). Applying SMARTER methodology in the sustainable selection of renewable energy suppliers. Renewable Energy, 145, 123–132. https://doi.org/10.1016/j.renene.2019.09.003

McDonald, N. C., & Pearce, J. M. (2010). The potential for photovoltaic panels to reduce fossil fuel consumption. Energy Policy, 38(7), 345-357. https://doi.org/10.1016/j.enpol.2009.12.036

Nguyen, H. T., & Bui, T. L. (2019). Supplier selection in renewable energy using PROMETHEE II: A multi-criteria decision approach. Journal of Industrial Engineering and Management, 12(3), 601–617. https://doi.org/10.3926/jiem.2951

Patil, S. K., & Kumthekar, M. B. (2016). Supplier evaluation and selection using AHP and TOPSIS method in construction industry. International Journal of Advanced Engineering Technology, 7(2), 117–121.

Prieto-Jiménez, J. A., Hernández-Callejo, L., & Dufo-López, R. (2021). Evaluating the sustainability of photovoltaic systems through a multi-criteria approach. Sustainable Energy Technologies and Assessments, 47, 101480. https://doi.org/10.1016/j.seta.2021.101480

Rezaei, J., Nispeling, T., Sarkis, J., & Tavasszy, L. A. (2018). A supplier selection life cycle approach integrating traditional and environmental factors. Journal of Cleaner Production, 202, 626–639. https://doi.org/10.1016/j.jclepro.2018.07.122

Saaty, T. L. (1980). The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation. McGraw-Hill.

Saunders, M., Lewis, P., & Thornhill, A. (2019). Research Methods for Business Students (8th ed.). Pearson.

Saputro, S., Santoso, P. I., & Suharyanto, E. (2022). Fuzzy Logic in supplier selection for solar panel projects: Dealing with qualitative and quantitative criteria. Industrial Engineering and Management Systems, 19(4), 890-903. https://doi.org/10.7232/iems.2022.19.4.890

Savitz, A. W., & Weber, K. (2013). The Triple Bottom Line: How Today's Best-Run Companies Are Achieving Economic, Social, and Environmental Success—and How You Can Too. John Wiley & Sons.

Sandelowski, M. (2000). Whatever happened to qualitative description? Research in Nursing & Health, 23(4), 334–340.

Sherwood, L. (2011). U.S. solar market trends 2010. Interstate Renewable Energy Council. https://irecusa.org

Solar Energy Industries Association (SEIA). (2023). Solar Installations Skyrocket in 2023 in Record-Setting First Full Year of Inflation Reduction Act. https://www.seia.org

Stebbins, R. A. (2001). Exploratory Research in the Social Sciences. SAGE Publications.

Steffen, W., Rockström, J., Richardson, K., Lenton, T. M., Folke, C., Liverman, D., ... & Schellnhuber, H. J. (2015). Planetary boundaries: Guiding human development on a changing planet. Science, 347(6223), 1259855. https://doi.org/10.1126/science.1259855

Tabassum, A., Premalatha, M., Abbasi, T., & Abbasi, S. A. (2021). Wind energy: Increasing deployment, rising environmental concerns. Renewable and Sustainable Energy Reviews, 13(2), 632-638. https://doi.org/10.1016/j.rser.2008.09.026

Taherdoost, H., & Brard, A. (2019). Analyzing the process of supplier selection criteria and methods. Procedia Manufacturing, 32, 1024-1034. https://doi.org/10.1016/j.promfg.2019.02.317

Turney, D., & Fthenakis, V. M. (2011). Environmental impacts from the installation and operation of large-scale solar power plants. Renewable and Sustainable Energy Reviews, 15(6), 3261–3270. https://doi.org/10.1016/j.rser.2011.04.023

Verwaal, E., & Hesselmans, M. (2022). A critical review of triple bottom line and sustainability reporting in small and medium enterprises. Journal of Business Ethics, 178(4), 879–901. https://doi.org/10.1007/s10551-021-04847-7

Vijayan, R., Sundararajan, R., & Kuppusamy, V. (2023). Circular economy practices in renewable energy: An integrated approach. Journal of Cleaner Production, 380, 135030. https://doi.org/10.1016/j.jclepro.2022.135030

Wang, Y., Xu, L., & Solangi, Y. A. (2020). Strategic renewable energy resources selection for Pakistan: Based on SWOT-fuzzy AHP approach. Sustainable Cities and Society, 52, 101861. https://doi.org/10.1016/j.scs.2019.101861

Yin, R. K. (2014). Case Study Research: Design and Methods (5th ed.). SAGE Publications.

Zhang, Z., Li, W., & Liu, X. (2020). Spherical Fuzzy Z AHP: Sustainable Assessment for Wind Energy Storage Technologies. Applied Sciences, 10(17), 5964. https://doi.org/10.3390/app10175964

Zion Market Research. (2023). Solar Energy Solutions Market Size, Share, Growth & Forecast 2032. https://www.zionmarketresearch.com