A MULTI-PERSPECTIVE TECHNOLOGY ASSESSMENT FOR THE OIL AND GAS INDUSTRY

by

Özgül Ayyıldız

B.S. in Environmental Engineering, Middle East Technical University, 2011

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APPROVED BY:

Prof. Dr. Ayşen Erdinçler . . . . . .
Dissertation Advisor

Prof. Dr. Tuğrul Ünsal Daim . . . . . .
Dissertation Co-Advisor

Prof. Dr. Mehmet Özgür Kayalıca . . . . . .

Prof. Dr. Melek Türker Saçan . . . . . .

Prof. Dr. Ferhan Çebi . . . . . .

Assist. Prof. Dr. Cem İskender Aydın . . . . . .

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ABSTRACT

A MULTI-PERSPECTIVE TECHNOLOGY ASSESSMENT FOR THE OIL AND GAS INDUSTRY

This research addresses the pressing challenge of decarbonizing of oil and gas industry to undergo a radical transformation to align with global emission reduction commitments. Recognizing the complexity and energy-intensive nature of the industry, I propose a comprehensive framework utilizing Hierarchical Decision Modelling (HDM) to systematically evaluate low-carbon energy technology alternatives. This research emphasizes the importance of integrating methodological pathways into the decision-making processes of the oil and gas sector to facilitate the selection of technology alternatives that not only meet strategic and environmental goals but also consider technical, social, political, and behavioural factors.

The developed model provides a multi-perspective assessment that categorizes and quantifies relevant factors, thereby offering a detailed analysis of both criteria and sub-criteria essential for technology adoption within the industry. This research contributes to the existing literature by filling identified gaps and demonstrating the utility of multicriteria analysis for evaluating low-carbon energy technologies. This model serves as a structured guide for organizations in directing their technological R&D towards sustainability, presenting a clear understanding of evaluation metrics for clean energy technologies, and facilitating informed decision-making in the oil and gas sector to achieve a sustainable future.

ÖZET

PETROL VE GAZ ENDÜSTRİSİ İÇİN ÇOKLU BAKIŞ AÇILI TEKNOLOJİ DEĞERLENDİRMESİ

Bu araştırma, petrol ve gaz endüstrisinin karbon salımını azaltma taahhütleriyle uyumlu bir şekilde radikal bir dönüşüme geçmesi için karşılaştığı sorunu ele almaktadır. Bu araştırma, endüstrinin karmaşıklığını ve enerji yoğunluğunu göz önüne alarak, düşük karbonlu enerji teknolojilerini sistemli bir şekilde değerlendirmek için Hiyerarşik Karar Modelleme (HKM) kullanımını önermektedir. Bu çalışmanın çıktıları, petrol ve gaz sektörünün karar verme süreçlerine metodolojik yol haritalarını entegre etmenin önemini vurgulayarak, stratejik ve çevresel hedefleri karşılayan teknoloji alternatiflerinin seçimini kolaylaştırmayı amaçlamaktadır. Ayrıca, teknik, sosyal, politik ve davranışsal faktörleri de dikkate alan bir yaklaşım sunmaktadır.

Araştırma kapsamında geliştirilen model, endüstri içinde teknoloji benimseme için esaslı olan kriterleri ve alt kriterleri detaylı bir şekilde analiz ederek çoklu perspektifli bir değerlendirme sağlamaktadır. Bu çalışma, tanımlanan boşlukları doldurarak mevcut literatüre katkıda bulunmakta ve düşük karbonlu enerji teknolojilerini değerlendirmek için çoklu kriter analizinin faydalılığını göstermektedir. Geliştirilen model, organizasyonlara teknolojik Ar-Ge'lerini sürdürülebilirliğe yönlendirmeleri için yapılandırılmış bir rehber olarak hizmet etmekte, temiz enerji teknolojileri için değerlendirme metriklerinin net bir anlayışını sunmakta ve sürdürülebilir üretim için petrol ve gaz sektöründe bilinçli karar almayı kolaylaştırmaktadır.

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LIST OF SYMBOLS/ABBREVIATIONS

Symbol	Explanation
CaO	Calcium Oxide
CH_4	Methane
CO_2	Carbon dioxide
H_0	Null Hypothesis
H_1	Alternative Hypothesis
H_2	Hydrogen
H_2S	Hydrogen sulfide
Ir	Iridium
KOH	Potassium Hydroxide
Ni	Nickel
NiO	Nickel Oxide
NOx	Nitrogen Oxides
O_3	Ozone
OH^-	Hydroxide Ions
PM_{10}	Particulate Matter
SOx	Sulphur oxides

Abbreviation	Explanation
AEM	Anion exchange membrane
AEM-WE	Anion exchange membrane electrolyzer
AHP	Analytic Hierarchy Process
ANP	Analytical Network Process
APCTs	Air pollution control technologies
AWE	Alkaline water electrolyzer
BOP	Balance of plant
CAPEX	Capital expenditure
CBM	Condition-based maintenance

CCMTs	Climate change mitigation technologies
CCS	Carbon capture and storage
CCUS	Carbon capture utilization and storage
CDU	Crude distillation unit
CNPC	China National Petroleum Cooperation
CPC	Cooperative patent classification
CRM	Critical raw materials
CSCM	Combined sorbent-catalyst materials
DBD	Dielectric barrier discharge
DEMATEL	Decision-making trial and evaluation laboratory
DSS	Decision support system
E-PRTR	European pollutant release and transfer register
E-SMR	Electrified steam methane reforming
EC	European Commission
EoL	End-of-Life
EPA	Environmental Protection Agency
ESCs	Electrolyte-supported cells
ETS	Emission trading system
EU	European Union
FCC	Fluid catalytic cracking
FITs	Feed-In-Tariffs
GHG	Greenhouse gas
HAC	Hierarchical Agglomerative Clustering
HDM	Hierarchical Decision Modeling
HSCs	Hydrogen electrode-supported cells
HSE	Health and safety
ICAO	International Civil Aviation Organization
IEA	International Energy Agency
IMO	International Maritime Organization
IP	Intellectual property
IPCC	Intergovernmental Panel on Climate Change
IPR	Intellectual property rights

LCA	Life Cycle Assessment
LCC	Life cycle costing
LCE	Low-carbon energy
LCOE	Levelized cost of energy
LCOH	Levelized cost of hydrogen
LPG	Liquefied petroleum gases
MACC	Marginal abatement cost curve
MBIs	Market-based policy instruments
MCDM	Multi-Criteria Decision Making
MEAs	Membrane electrode assemblies
MNCs	Multinational companies
MULTIMOORA	Multi-objective optimization on the basis of ratio analysis
NDCs	Nationally determined contributions
NIMBY	Not in my backyard
NMVOCs	Non-methane VOCs
NOCs	National oil companies
OECD	Organization for Economic Co-operation and Development
OPEX	Operational expenditure
ORC	Organic rankine cycle
P-MR	Plasma methane reforming
PCM	Pair-wise comparison method
PEM	Proton exchange membrane
PEM-WE	Proton exchange membrane electrolyzer
PGM	Platinum group metals
PI	Process Intensification
R&D	Research and development
ROI	Return on investment
RSV	Root sum of the variance
SA	Sensitivity analysis
SAF	Sustainable aviation fuels
SE-SMR	Sorption enhanced steam methane reforming
SIP	Synthesized Iso-Paraffinic

SMEs	Subject matter expert
SMR	Steam methane reformers
SOE	Solid oxide water electrolyzer
SSZ	Scandia-stabilized zirconia
STEEP	Social, Technical, Environmental, Economic, and Political
STEM	Science, Technology, Engineering and Mathematics
TCI	Total capital investment
TE	Technology Evaluation
TEA	Techno-Economic Analysis
TEC	Technology Executive Committee
TFNs	Triangular Fuzzy Numbers
TGCs	Tradable Green Certificates
TIC	Techno-Institutional Complex
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
TRL	Technology Readiness Level
UN	United Nations
VOCs	Volatile organic compounds
YSZ	Yttria-stabilized zirconia

1. INTRODUCTION

The Intergovernmental Panel on Climate Change's (IPCC) reports unambiguously stated the impact of human activities on global warming, with the global surface temperature having risen by 1.1°C above the 1850–1900 baseline in the decade 2011–2020. Unsustainable energy use, industrial processes, and unavoidable land-use changes cause this warming (IPCC, 2023). As it was stated in the Paris Agreement, Article 2, global temperature rise should be limited to 1.5°C above pre-industrial levels. However, the implementation of Article 2 (Article 4) represents reaching global peaking of greenhouse gas (GHG) emissions as soon as possible and pursues rapid reductions with the best available technologies to achieve a balance between anthropogenic emissions by sources and removals by sinks of GHGs in the second half of the century, achieving this global commitment is becoming difficult substantially from day to day since the world is reaching the warming limit which causes irrevocable results (UNFCCC, 2015). Due to financial and technological constraints, the transition to low-emission technologies remains slow, especially in developing countries. Achieving the emission reduction targets necessitates reaching net zero CO_2 emissions since current projections indicate that emissions from existing fossil fuel infrastructures, without further mitigation, would surpass the carbon budget required to limit warming to 1.5°C. Rapid and extensive decarbonization across all sectors, including energy, industry, and transport, is mandatory to achieve deep emissions reductions. The energy sector, needs to undergo significant transformations, including reducing fossil fuel use by integrating CO_2-neutral energy carriers like hydrogen and synthetic fuels, transitioning to net-zero CO_2 electricity systems, and adopting energy efficiency measures (Fleiter et al., 2023; IPCC, 2023).

Net-zero emission policies of governments have created pressure on oil and gas companies which are the most energy-intensive sector to cut emissions in the short term and prepare a long-term action plan. When the oil and gas companies' emission reduction commitments have been reviewed, it can be seen that they aim to reduce emissions from production plants to distribution lines (DNV GL, 2021). According to the S&P Global Market Intelligence report, among the top 30 oil and gas companies, 11 companies have existing net-zero targets, and only five of them; BP, Equinor, Neste, Repsol, and Occidental Petroleum, have announced their targets which also cover Scope 3 emissions. However, the US biggest oil companies like Exxon Mobil and Chevron have no specific net-zero emission targets. Moreover, when it is considered that Scope 3 emissions can account for approximately 85 % of some oil and gas companies' total emissions, the commitments remain far beyond the Paris Climate Goals (2020). Besides the private oil and gas companies,

national oil and gas companies have also fallen into the decarbonization dilemma, according to Carbon Tracker Organization, some countries which economic activities rely on petroleum production and refining such as Azerbaijan, Bahrain, and Oman are the most vulnerable countries since it is expected that 40 % of revenue shortfall due to transition to low carbon economy (Carbon Tracker, 2021). Under these circumstances and the existing climate crisis, the oil and gas industry keep pace with the low-carbon energy transition.

The oil and gas industry, sitting at the nexus of the global energy supply chain and carbon emissions, faces a pivotal role in this transition (Hertbertson, 2020). Decarbonizing this sector is crucial for achieving significant carbon reductions and fulfilling the commitments of the Paris Agreement. According to the International Energy Agency (IEA), the global oil demand will reach a saturation level in the next two decades and other new clean energy technology alternatives will penetrate the world energy system (IEA, 2023a). Therefore, the selection of clean energy technology alternatives will become an indispensable assignment for oil and gas companies. The energy transition of oil and gas industry is also essential for staying relevant and competitive in a rapidly evolving energy market.

Investments in the oil and gas sector are actualized with substantial capital and time commitments, it's imperative for organizations to accurately assess technologies and choose the appropriate research and development (R&D) strategy to ensure efficient resource allocation. While many companies predominantly utilize economic evaluation tools (DNV GL, 2021), it's crucial to recognize the influence of technological, social, political, environmental, and behavioural factors in the transition to low-carbon energy (Herbertson, 2020; Seto et al, 2016), since economic evaluation tools alone are insufficient for evaluating the complex and multifaceted nature of clean energy technologies. This highlights a significant gap in the oil and gas industry’s approach to technology selection, where environmental, social, and technological aspects are often underrepresented.

The complexity of selecting the most appropriate low-carbon technology alternatives requires a more comprehensive and adaptive solution. The challenge of developing a holistic solution, lies in incorporating various criteria beyond financial metrics and it is ensured that a balanced and comprehensive evaluation of potential technologies are performed. Without such type of multi-dimensional evaluation framework, oil and gas industry faces difficulty to progress towards achieving sustainability goals and fails to capitalize on innovative energy opportunities. In summary, the oil and gas industry need to enhance capabilities for selecting clean energy

technologies, moving beyond traditional financial assessments to a more inclusive and strategic approach.

Multi-Criteria Decision Making (MCDM) techniques offer a robust assessment tool, ensuring a balanced and systematic evaluation for decision-makers. This study seeks to introduce a comprehensive framework tailored for evaluating low-carbon energy alternatives in the oil and gas industry, aiming to meet emission reduction targets. It emphasizes the importance of understanding the impact of each criterion in technology roadmapping activities. To this end, Hierarchical Decision Modelling (HDM) is employed as the chosen MCDM technique. The ultimate goal is to develop a decision-making tool that facilitates a multi-perspective technology assessment tailored for the oil and gas industry.

The main objective of this research is to develop an assessment model based on HDM which is one of the sophisticated decision-making methodologies in order to select the best low-carbon technology alternatives. HDM methodology provides the analysis of complex and unstructured problems by dividing them into smaller and categorized sections and allowing them to evaluate these factors at the same time (Abotah and Daim, 2017). The model results provide a clear understanding of the evaluation metrics of clean energy technologies.

This thesis is structured to systematically explore and address the challenges and opportunities in selecting low-carbon technology alternatives in the oil and gas industry. Chapter 2 provides a comprehensive literature review, outlining the current state of the oil and gas industry, the low-carbon energy technologies alternatives and assessment criteria for the selection of low carbon energy technology alternatives. It gives detailed information about various assessment criteria of these technologies from social, economic, technical, environmental, and political perspectives. Chapter 3 introduces the research framework and methodology, detailing the objectives, research gap analysis, and the design of the research. It further explains the HDM methodology and its components, used as the primary tool for technology assessment. In Chapter 4, the results and data analysis are presented. This includes the initial model, expert panel formation, model validation, and quantification results across different criteria. Chapter 5 applies the research model to actual technology alternatives, providing technology evaluation scores and suggesting improvements. Scenario analysis is also conducted in this chapter. Chapter 6 discusses the research findings in depth, investigating the implications from various perspectives and assessing the generalizability of the research model. Finally, Chapter 7 concludes the thesis, summarizing key findings, discussing limitations, and future research activities.

In summary, this research identifies and analyzes several key factors influencing the adoption of low-carbon technologies in the oil and gas sector. The findings reveal that while economic considerations remain a primary driver, non-economic factors such as technological maturity, environmental impact, and political policies play a crucial role in technology selection. The developed model provides a nuanced understanding of these factors, offering a comprehensive framework to assist decision-makers in the oil and gas industry. The application of this model demonstrates its effectiveness in guiding towards more sustainable and environmentally responsible technology choices, aligning with global emission reduction targets.

2. LITERATURE REVIEW

The pressing challenge of global warming and the pivotal role of the oil and gas industry in the energy transition paradigm necessitate a nuanced understanding of low-carbon technologies and their multifaceted implications (Carbon Tracker, 2021; IEA, 2023a). This literature review begins with the overview of oil and gas industry and continue with the low-carbon energy technologies, the Social, Technical, Environmental, Economic, and Political (STEEP) factors influencing their adoption, and the application of HDM in evaluating these technologies. The synthesis of these themes will illuminate research gaps and contribute to the development of a comprehensive framework for technology assessment in the oil and gas industry.

2.1. Overview of Oil and Gas Industry

The oil and gas industry are broadly categorized into three distinct segments: upstream, midstream, and downstream. The upstream segment covers the exploration and extraction of oil and natural gas, where state-owned national oil companies (NOCs) play a significant role. These NOCs are critical players in the global arena, controlling approximately 90% of the world's oil and gas reserves. The midstream segment focuses on the transportation and storage of these extracted resources, serving as a crucial link between the extraction sites and processing facilities. Lastly, the downstream segment involves the refining of crude oil and the distribution and marketing of the final products. This last segment is predominantly managed by publicly owned companies, which are responsible for bringing refined products to the market and end-users (Lima-de-Oliveira and Sturgeon, 2017).

The oil and gas industry primarily relies on two fossil fuel feedstocks: crude oil and natural gas. Crude oil, extracted from diverse geological formations around the globe, varies significantly in its physical and chemical properties (Fahim et al., 2010). Each type of crude oil, as well as the derived petroleum products, possesses unique characteristics. Fundamentally, crude oil is a complex mixture of hydrocarbon compounds. These hydrocarbons, which primarily consist of carbon and hydrogen atoms in varying configurations, form the backbone of crude oil. Additionally, crude oil contains a minor but crucial fraction of organic compounds with elements such as sulphur, oxygen, and nitrogen. Trace amounts of metals like vanadium, nickel, iron, and copper are also present, further contributing to the complexity of crude oil’s composition (Fahim et al., 2010).

Oil refineries represent the first stage in the transformation of crude oil into valuable products. These complex industrial facilities are instrumental in producing a wide array of petroleum products, including from liquefied petroleum gases (LPG) to asphalt (bitumen), and numerous other derivatives (EPA, 2010). Globally, refineries vary significantly in their design and capabilities. Fundamentally, every refinery is equipped with a distillation column, which is the initial step in separating crude oil into various components based on their boiling points. Subsequent to distillation, a refinery includes a diverse combination of secondary processing units. The selection of these units is strategically tailored to suit the specific type of crude oil being processed and the desired end products, reflecting the refinery's operational focus and market demands.

The refineries are categorized into four types: topping, hydroskimming, upgrading (conversion, complex), and coking refineries. The simplest refineries have a crude distillation unit (CDU) and generally, they are referred to as topping refineries. Topping refineries produce naphtha and other intermediate products. However, they cannot manufacture end products like gasoline or diesel. Hydroskimming refineries include mild conversion units such as hydrotreating units and reforming units in addition to CDU. They can produce finished products such as gasoline, but they are not capable of upgrading heavier components of crude oil, which is the bottom of the CDU. In some refineries, these heavier components of crude oil are sent to asphalt production units. The third type of refinery is upgrading/conversion. Upgrading refineries that are classified as complex refineries, have catalytic cracking and hydrocracking units. They convert long-chain, high molecular-weight hydrocarbons into smaller hydrocarbons. They produce middle-distillate (diesel) and light-distillate (gasoline) products and other high-value products for petrochemical stocks. The last type is coking refineries. This type of refinery has both hydrocracking, catalytic cracking units, and delayed coking unit. Delayed coking unit converts fuel oil to more valuable products such as middle and light distillates and coke. Due to the high conversion capacity of delayed coking units, much more energy is needed for this process (US EPA, 2010; Johansson et al. 2012; Kaiser, 2017).

In addition to the core processing units, refineries integrate several supplementary processes that are essential for ensuring the quality and safety of the final products. These auxiliary processes are designed to treat and remove impurities, also enhanced the refinery's overall efficiency and adherence to environmental standards. Among these, desalters play a crucial role in removing salt from crude oil, while sulphur removal units are tasked with extracting harmful sulphur compounds, significantly reducing emissions, and improving the quality of fuels. Hydrogen production units within refineries are particularly vital. Hydrogen, which is produced on-site, is a key input for many refining processes, including hydrotreating, isomerization, fluid catalytic cracking (FCC), and

hydrocracking. These processes rely on hydrogen to change the chemical composition of various fractions, enhancing fuel quality and meeting specific product requirements (Branco et al., 2010). Refineries also include power and steam generation facilities, fundamental for powering a wide range of equipment within the refinery. Wastewater treatment plants are also integral, ensuring the responsible management and treatment of water used throughout the refining process, in compliance with environmental regulations. A simplified diagram, provided in Figure 2.1 illustrates these major streams and processes within a typical refinery (Elgowainy et al., 2014). This visual diagram demonstrates how the various units, including those for hydrogen production and utilization, interlink and contribute to the functionality of a modern refinery, highlighting the complexity and integrated nature of these industrial operations.

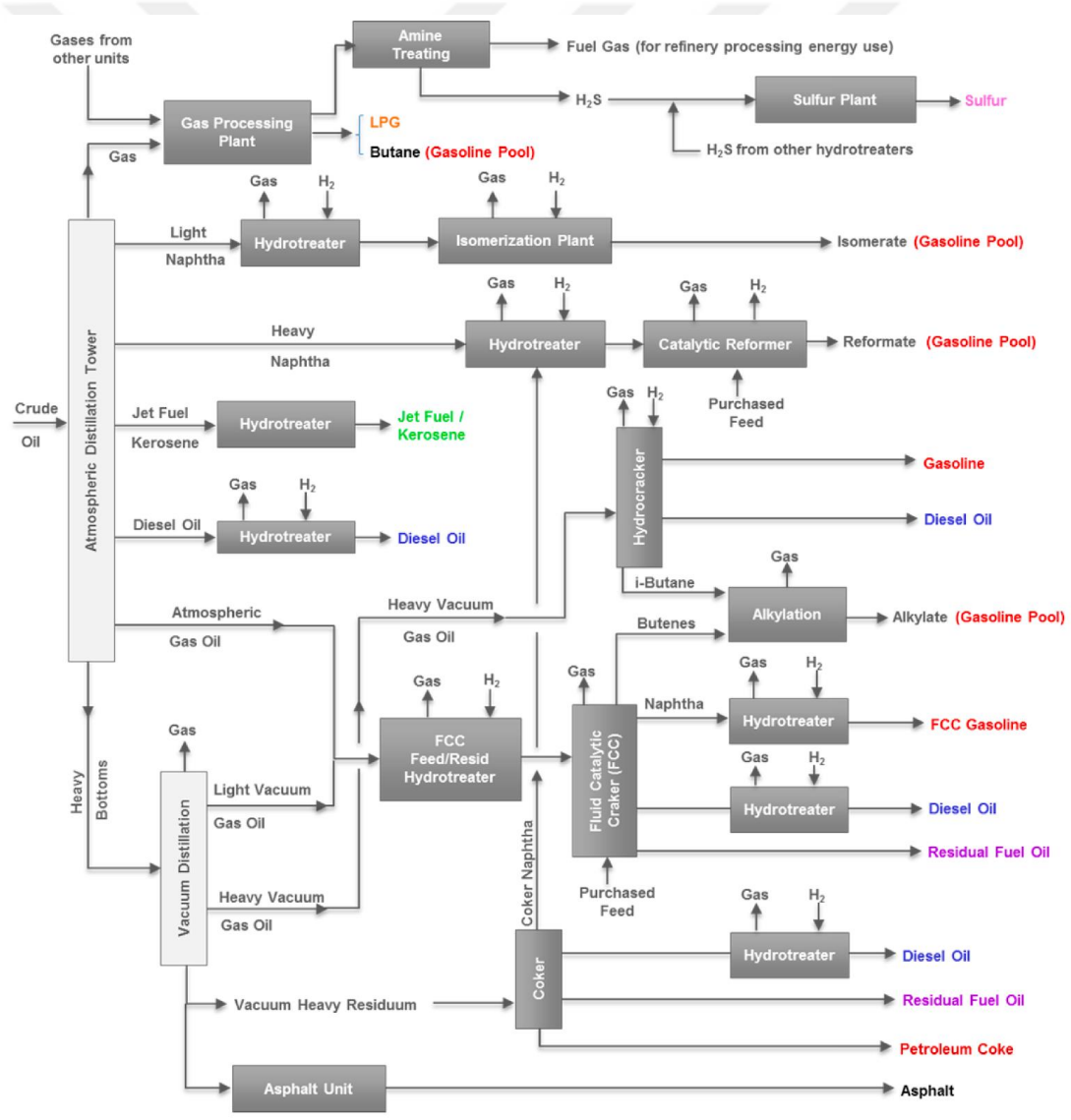

Figure 2.1. Major streams of a refinery.

2.2. Low-carbon Energy Technology Alternatives

As reported by IEA, hydrogen production in the refining and chemicals industry is a significant contributor to global CO_2 emissions, accounting for up to 3% (IEA, 2023b). The majority of this hydrogen is currently derived from natural gas, using steam methane reformers (SMR), which emit considerable amounts of CO_2. A substantial part of these emissions, nearly 41%, originates from the combustion process for heat supply in SMR. The transformation of SMR system that significantly reduces CO_2 emissions is crucial for a net zero emissions future. The diversification of low-emission hydrogen sources is vital given the urgency of scaling up capacity in line with net zero targets and varying energy resources among countries. Moreover, as highlighted by Fleiter et al., deep decarbonization of the EU industry, without de-industrialization, necessitates a comprehensive system perspective and the strategic use of CO_2-neutral secondary energy carriers like electricity, hydrogen, and synthetic fuels (2023). This approach is integral for the deep decarbonization pathway of oil and gas industry, where sector coupling plays a key role as fossil fuels are replaced by these alternative energy carriers (Bossmann et al., 2018). This further underlines the importance of the selected technology alternatives in this research, as they represent essential tools in the broader context of transforming energy systems and achieving net zero emissions.

The technology alternatives, that are chosen for the case study application, include various forms of hydrogen production, namely sorption enhanced steam methane reforming (SE-SMR), electrified steam methane reforming (E-SMR), plasma methane reforming (P-MR) and different types of water electrolysers such as alkaline water electrolyser (AWE), anion exchange membrane electrolyser (AEM-WE), proton exchange membrane electrolyser (PEM-WE), and solid oxide water electrolyser (SOE). The chosen technology alternatives align with the need to explore renewable options for replacing portions of the fossil-based energy and hydrogen demand in oil and gas industry (IEA, 2023b). These technologies are part of a broader set of mitigation options which includes energy efficiency measures, CO_2 capture and storage, bio-oil co-processing, and the use of green electricity, all aimed at reducing GHG emissions in the oil and gas sector. Specifically, the use of green electricity is identified as a key mitigation alternative in refineries, replacing fossil-based electricity and thereby reducing carbon intensity (Yanez et al., 2022). Furthermore, Squadrito et al. emphasize the growing importance of green hydrogen in the global energy transition. Their critical analysis underlines how various green hydrogen production technologies, particularly through water electrolysis, are emerging as key solutions for decarbonizing the energy sector (Squadrito et al., 2023). This aligns with the focus of this research on SE-SMR, E-SMR, P-MR, and

different electrolysers, recognizing their potential in efficiently transitioning from fossil fuels to renewable energy sources.

SE-SMR process is a variant of the traditional SMR process. This method is gaining importance as it can both eliminate CO_2, a major pollutant and increase the purity and yield of hydrogen. It is a cutting-edge technique that has attracted significant attention in recent years for its potential to produce high-purity hydrogen. This method stands out due to its capability to simultaneously reform hydrocarbons and capture carbon dioxide in situ, thereby enhancing the overall hydrogen yield and purity (Udemu and Font-Palma, 2023). The process leverages specialized catalysts and sorbents, with notable mentions being Ni-based catalysts and CaO-based adsorbents (Soltani et al., 2021). The SE-SMR approach offers a sustainable solution to the increasing global demand for clean energy, particularly hydrogen, while also addressing the pressing issue of carbon emissions. The continuous research and advancements in this field underscore the potential of SE-SMR as a pivotal method for future hydrogen production (Dang et al., 2022).

E-SMR is developed as a transformative approach for hydrogen production, leveraging electric energy as an alternative heat source for the reforming process. This innovative method offers a cleaner and more sustainable pathway for hydrogen generation, eliminating a significant portion of CO_2 emissions traditionally associated with steam methane reforming (Do et al., 2023). By utilizing electric heating instead of conventional methane co-firing, E-SMR benefits from the excess or renewable energy, transforming it into valuable feedstocks like syngas rich in hydrogen. The process is further enhanced by the use of structured catalysts, which are directly electrified to achieve high power densities. These reactors are capable of producing syngas and hydrogen and reducing CO_2 emissions by approximately 40%. This approach not only intensifies the heat transfer rates but also addresses the challenges posed by traditional reforming methods, paving the way for a more efficient and environmentally friendly hydrogen production process (Ambrosetti et al., 2021).

P-MR is an advanced technique that employs electrically induced plasmas to facilitate the reforming of methane. This method stands out due to its ability to operate at lower temperatures compared to traditional steam methane reforming, offering potential energy savings. The process leverages the unique properties of plasmas, which provide highly reactive species that can enhance the methane conversion rates and hydrogen yield. Recent studies have explored the integration of various heat recovery systems with electrified heating mechanisms, aiming to optimize the overall

heat recovery and assess the potential capital involved (Kim et al., 2020; King et al., 2021; Abiev et al., 2020).

AWE is a well-established method for the electrochemical splitting of water into hydrogen and oxygen. This process utilizes an aqueous solution of electrolytes, typically potassium hydroxide (KOH), as the conducting medium. The core advantage of alkaline water electrolysers lies in their operational simplicity, robustness, and the use of non-precious metal catalysts, making them cost-effective. Recent advancements in this field have focused on enhancing the efficiency and durability of the electrolyser, with particular emphasis on electrode materials and design. The integration of renewable energy sources, such as solar and wind, with alkaline water electrolysis offers a sustainable pathway for green hydrogen production, positioning it as a key technology in the global energy transition (Serov et al., 2021; Ehlers et al., 2023).

AEM Electrolysis is a promising technology for the efficient production of hydrogen through the electrochemical splitting of water. Unlike the traditional PEM electrolysis and alkaline electrolysis, AEM electrolysis utilizes anion-conducting membranes that allow the transport of hydroxide ions (OH^-) from the cathode to the anode. This unique ion transport mechanism offers several advantages, including the potential for reduced membrane degradation, the ability to operate under alkaline conditions, and the use of non-precious metal catalysts. Recent advancements in AEM materials and cell designs have further enhanced the efficiency and durability of AEM electrolysers, positioning them as a competitive alternative for sustainable hydrogen production. Consequently, AEM electrolysis provides a cost-efficient and stable method for hydrogen generation. Despite its potential, it's noteworthy that research on AEM electrolysis is still in its emerging stages compared to its PEM and alkaline counterparts (Vincent et al., 2017; Vincent et al., 2021; Motealleh et al., 2021; Santoro et al., 2022).

PEM electrolysers represent a cutting-edge technology in the domain of hydrogen production through the electrochemical splitting of water. These electrolysers are composed of a solid polymer electrolyte, or proton exchange membrane, which allows the transport of protons from the anode to the cathode. This technology stands out due to its high operational efficiency, ability to achieve high current densities, and rapid response to variable power inputs, making it particularly suitable for integration with renewable energy sources. The use of noble metal catalysts, such as Platinum and Iridium, ensures high electrochemical activity. However, the use of noble metal catalysts, such as Platinum and Iridium, can make PEM electrolysers more expensive than other types of electrolysers. Furthermore, PEM electrolysers operate under acidic conditions, which, are combined

with the absence of liquid electrolytes, minimize the risk of electrolyte leakage, and enhance system safety. As research and development in this field continue, PEM electrolysers play a pivotal role in the sustainable production of hydrogen (Koponen et al., 2017; Price, 2017; Ouimet et al., 2022; Clapp et al., 2023; Riedmayer et al., 2023).

SOE electrolysers have emerged as a pivotal technology in the realm of electrochemical energy conversion and storage, bridging the gap between electricity generation and hydrogen production. These devices operate at high temperatures, typically ranging from 600°C to 800°C, and employ a ceramic, or solid oxide, electrolyte. This high-temperature operation does not only accelerate the electrochemical reactions but also, reveals the need for precious metal catalysts. A distinct advantage of SOE electrolysers is their ability to operate in both fuel cell and electrolysis modes, enabling electricity generation and hydrogen production, respectively. Their high-temperature operation enhances reaction kinetics, reducing the need for expensive catalysts. Moreover, they can utilize a variety of fuels, including hydrogen, methane, and carbon monoxide, offering flexibility in applications. From a technological viewpoint, the solid-state nature of SOE electrolysers offers inherent advantages such as reduced risk of electrolyte leakage and enhanced mechanical robustness. However, the high operational temperatures, while beneficial for reaction kinetics, can lead to material degradation, particularly of the electrolyte and electrodes. Ongoing research in the field focuses on material innovation, system design optimization, and integration with renewable energy sources (Golkhatmi et al., 2022; Nami et al., 2022; Glenk et al., 2023).

A comprehensive overview of the properties and capabilities of each technology alternatives is given in Table 2.1. As seen in Table 2.1, some of the technology alternatives are in the phase of scaling up. Squadrito et al. also discuss the challenges and opportunities in scaling up these technologies, highlighting the need for strategic development and implementation to achieve effective decarbonization. Their insights on the geopolitical and water resource implications of large-scale green hydrogen adoption provide a broader context for the technology alternatives of this research, underscoring the multifaceted impact of these alternatives in driving sustainable energy transitions (2023).

Table 2.1. Characterization of Technology Alternatives.

Technology Alternatives	SE-SMR	E-SMR	P-MR	AWE	AEM WE	PEM WE	SOE
Market Adoption Level	Early Prototype	Large Prototype	Concept phase	Market Uptake	Large Prototype	Market Uptake	Pre-commercial Prototype
Capital Cost	Unknown	560 EUR/kW	Unknown	450-1320 EUR/kW	572-1279 USD/kW	500-1000 USD/kW	2220-5600 EUR/kW
Operational Cost	5% of Capital	4% of Capital	Unknown	7% of Capital	Unknown	1-2% of Capital	5-6.7% of Capital
Feedstock Cost	Methane	Methane	Methane	Water, Renewable Electricity	Water, Renewable Electricity	Water, Renewable Electricity	Water, Renewable Electricity
Cost Competitiveness	0.06 - 0.09 EUR/kWh	0.047 EUR/kWh	Unknown	0.01 - 0.06 EUR/kWh	0.084 EUR/kWh	0.01 - 0.06 EUR/kWh	Unknown
Energy Efficiency	69-77%	70-80%	66-79%	63-70%	52-67%	56-60%	74-81%
Technology Readiness Level (TRL)	TRL 4	TRL 5	TRL 3	TRL 9	TRL 6	TRL 9	TRL 7
Operational Stability	200 hours	Unknown	8 hours	90 000 hours	10 000 hours	50 000 hours	93 000 hours
Environmental Impact	Low water pollution	Reduces GHG emissions 77%	Requires renewable energy integration	Requires water purification	Requires water purification	Deionized water needed	High Critical Mineral Use
References	Bossmann et al., 2018	Mion et al., 2022; Bukkholm, 2021; Do et al., 2023	Kim et al., 2020; King et al., 2021	Nami et al., 2022; Ajanovic et al., 2022	Ionomr, 2020; Gul et al., 2023; Santoro et al., 2022; Motealleh et al., 2021	IRENA, 2020; Price, 2017; Yang et al., 2023	Nami et al., 2022; Golkhatmi et al., 2022

2.3. Assessment Criteria of Low-Carbon Energy Technologies

There are various elements linked to the uptake of low-carbon energy technologies within the oil and gas sector. In this section, these elements are investigated in a systematic way by classifying as perspectives, criteria and sub-criteria that affect the low carbon energy technology adoption in oil and gas industry. Extensive literature research in the area of technical specifications, market dynamics, regulatory frameworks and social trends is performed for the development of the model with HDM methodology.

The systematic review of literature has revealed a total of twenty-five primary criteria and thirty-five sub-criteria related to technology evaluation in the oil and gas industry. These criteria and sub-criteria are critical in facilitating the penetration of low-carbon energy technologies within

the oil and gas sector. This comprehensive research was conducted by considering the entire technology development cycle. These twenty-five criteria have been methodically classified into five distinct categories, encompassing social, economic, technical, environmental, and political dimensions (Iskin et al., 2012; Giadedi and Daim, 2021; Khanam and Daim, 2021).

2.3.1. Social Perspectives

Transitioning to a cleaner energy system requires concurrent transformations across various interconnected systems. The shift towards biofuels can be given as a characteristic example, which necessitates a fundamental change from relying on fossil fuels to utilizing agricultural products as an energy source. This transition also gives rise to a social shift in perception, as agricultural products are increasingly viewed as energy sources rather than food source. As German and Schoneveld (2012) highlighted in their study that the European Union (EU) has implemented voluntary monitoring mechanisms to assess the social sustainability of such shifts. However, they note that social factors often receive less emphasis compared to environmental or economic factors. Despite this, social perspectives maintain an intrinsic link with other dimensions, particularly political and economic perspectives. This interconnection emphasizes the necessity for a comprehensive examination of the social impacts stemming from clean energy adoption in the oil and gas industry. Furthermore, Scott and Powells's (2020) study underscores that energy transition needs a broader assessment in terms of social, cultural, and economic dimensions. They emphasize the importance of public perception, economic reflections of infrastructure change for new energy source, and cultural practices.

Furthermore, the social perspectives cover both barriers and criteria influencing the adoption of low-carbon energy technologies. These criteria were identified with the consideration of all stakeholders, including society and the workforce. The criteria under this perspective are public acceptance, employment opportunities, working conditions, public health and safety, and stakeholder pressure. Such an inclusive approach ensures a holistic understanding of the societal implications of transitioning to low-carbon energy solutions.

2.3.1.1. Public acceptance. This criterion evaluates public attitudes towards low carbon technologies, ranging from opposition to acceptance. The EU's Scientific Foresight Unit conducted a crucial study, identifying key factors influencing societal responses to these technologies (Mander and Minas, 2019). The research showed that 'Not in My Backyard' (NIMBYism) was a significant local social barrier, with public opposition often driven by aesthetic or visual concerns for

renewable energy technologies. However, other determinants, such as political and environmental beliefs, as well as emotional and moral considerations, were found to play a role in shaping public acceptance (Mander and Minas, 2019). Furthermore, spatial proximity to technology implementations emerged as a crucial factor. This is exemplified in Tan and co-workers' investigation of public perceptions of shale gas development in Weiyuan, China. Their research, involving interviews with local residents, revealed that two-thirds of the residents in close proximity (approximately 0.5 km) to a shale gas operation plant opposed its existence, citing fears of soil and groundwater contamination (Tan et al., 2020). Also, Merk et al. (2022) demonstrated the effect of exporting or importing CO_2 on public attitudes towards carbon capture and storage (CCS) projects. Their study, performed in Germany and Norway, revealed significant differences in perceptions of the CO_2 source and storage site with respect to nationality. While Norwegian respondents showed a more negative attitude towards projects where foreign-sourced CO_2 is stored domestically, German respondents were unaffected by the variation in CO_2 source nationality. This difference in acceptance could be attributed to psychological distancing from CCS, influenced by varying levels of familiarity and political support for CCS in these countries. The study's findings highlight the complexities in public acceptance and the potential challenges in establishing a transnational carbon storage market, emphasizing the need for context-specific communication strategies to enhance public support for CCS initiatives.

Additionally, educational acquisition has been observed to influence public acceptance. A study conducted in the Netherlands revealed that individuals with higher education levels often perceive advanced technologies, such as hydrogen-powered vehicles, as bearing greater risks, leading to a reluctance to adopt such innovations (Achterberg, 2014).

Lack of knowledge. Educating the public is a significant step in encouraging acceptance for low carbon technologies. Hess and Sovacool (2020) stated that there is a gap between scientific risk assessments, which are often acknowledged as incomplete by scientists themselves, and the public's understanding of these uncertainties. This gap is seen in public perceptions of risks associated with technologies like hydraulic fracturing. Furthermore, the research underscores how lack of knowledge, influenced by political and industrial strategies that limit information disclosure, hampers the public's ability to effectively evaluate risks and uncertainties associated with new technologies. Such a deficit in public knowledge can lead to resistance against these technologies, demonstrating the critical need for comprehensive and transparent public education efforts.

Public awareness. Public awareness has a pivotal role in the acceptance of emerging low-carbon energy technologies. The effectiveness of information campaigns and the role of media in highlighting these technologies significantly shape public awareness. Technologies that are not prominently featured in media or environmental debates often remain unrecognized by the public, as indicated by Pianta et al. (2021). This trend was also seen in a study by Bögel et al. (2018), which showed a notably low awareness of hydrogen fuel cell technology in the EU, despite its potential in the automotive sector. The study found that 13% of participants were familiar with this technology, but their attitudes became more positive upon receiving information about it, underscoring the transformative power of information in altering public perceptions.

Similarly, a study in China on public awareness of carbon capture utilization and storage (CCUS) revealed limited initial knowledge about the technology. Only a small fraction (3.6%) of respondents were familiar with CCUS. However, once informed, a significant majority (80.4%) acknowledged its potential in climate change mitigation. Yet, concerns about the infrastructure, such as carbon transportation pipelines and storage facilities, remained a challenge (Li et al., 2017).

Public concern. Public concern is closely related to environmental beliefs and the perception of risks. Arning et al. (2019) highlighted that innovative technologies like CCUS are generally less known to the public during their development stages, and this issue cause a scepticism. However, public perception become more positive as awareness increases. In Germany, for instance, CCUS is perceived more favourably than CCS, reflecting its perceived positive impact on climate change mitigation goals. This difference in perception underlines the importance of understanding public concerns and effectively communicating the benefits, barriers, and risks of these technologies to garner support (Arning et al., 2019). Public reaction towards low-carbon energy technologies can significantly impact policy and industry, and it influences the development and rollout of new technologies. Perceptions of risks associated with different stages of the CCS and CCUS process chains play a critical role in acceptance. Storage and transport risks negatively influence CCS acceptance, while disposal and product risks affect CCUS acceptance (Arning et al., 2019).

The oil and gas industry must navigate these public concerns by investing in transparent communication strategies and stakeholder engagement. By considering public concerns in the development and communication of low-carbon energy technologies, the industry should perform a more informed and positive strategy for the adoption of low-carbon energy technologies.

2.3.1.2. Employment.In the 21st century, the concept of employment, particularly in the energy sector, has evolved beyond just the creation of new job areas. It emphasizes the importance of both the quality of these roles and their accessibility to a diverse range of individuals (IRENA, 2020). This broader perspective on employment is reflected in three key sub-criteria: the generation of new job opportunities, the essential training and education of the workforce, and the commitment to gender equity. These elements together ensure that employment is not only about job availability but also about developing a skilled, knowledgeable, and diverse workforce.

New job opportunities. The commercialization of new low-carbon energy technologies requires more human resources and new job opportunities emerge in the manufacturing, marketing, and deployment phases of these innovative technologies (Narimisa, 2013; IRENA, 2020). According to another study from IRENA, a transition in the energy sector's employment from fossil fuels to renewable sources by 2050 is forecasted. This shift also involves the rise of job opportunities due to the adoption of low-carbon energy technologies (IRENA, 2020).

Training and education of employee. Transition towards low carbon energy technologies, in the oil and gas sector, needs comprehensive training and education programs. The research studies of Beasy et al. (2023) and Skiba (2020) emphasized that there is a growing demand for a skilled workforce capable of operating within the low-carbon energy sector, especially in green hydrogen. This includes a range of job roles such as engineers, technicians, gas fitters, and energy system installers. In addition to that, both research studies emphasize significant gaps in the current training and education available for these technologies. According to Beasy et al., (2023) about 90% of industry participants study perceived the need for substantial training in hydrogen technologies, while Skiba highlights the necessity for competency standards in hydrogen's safe handling and storage.

Gender equity. In the oil and gas industry, achieving gender equity is complex issue, especially with the shift to low carbon energy technologies. Williams (2019) study shows that women in science, technology, engineering, and mathematics (STEM) roles, like oil and gas industry, often leave their jobs more than men. This is due to reasons like work-life balance challenges, unfriendly work environments, and fear of job loss. To make the industry fairer, it's important to change these biases and make sure job practices are equal for everyone, no matter their gender or family situation.

2.3.1.3. Working conditions. In the oil and gas industry, workers are continually exposed to a range of occupational hazards. The industry is known for its high-risk environment, with hazards including exposure to chemical materials, confined spaces. Workers face hazards such as chemical, physical, biological, ergonomic, and psychosocial dangers. Specifically, psychosocial hazards arise from factors like excessive workloads, long hours, shift work, and site isolation (Benson et al., 2021).

Working time. This subfactor examines various components of working condition such as the working hours, rest periods, and shift schedules of workers. It delves into the balance required in managing these elements to ensure workforce well-being and efficiency. Particularly, offshore oil exploration workers, faced difficulties due to extended working hours and the demanding nature of travel to operation sites, as highlighted by Parkes (2012). This aspect underscores the critical need for strategic scheduling that prioritizes both operational demands and worker health.

Health and safety of workers. Sovacool and co-workers (2016) performed research about the comparison of low-carbon energy technologies in terms of accident risks. They assessed biofuels, biomass, geothermal, hydroelectricity, hydrogen, nuclear, solar, and wind energy. According to the research results, biofuels carry the most similar risks with conventional oil refining technologies because of product type. The safest low-carbon energy technology has been accepted as solar energy. Half of the accidents which were used as accident data belonged to wind energy but in contrast to frequency, the fatality rate was very low (Sovacool et al, 2016; Kim et al., 2021).

Remuneration. Although this sub-criterion is directly related to the maintenance cost of the plant, it is also related to the working conditions of workers. Remuneration can be explained as the financial compensation for work or services, and the salary of workers (Kamali et al., 2018).

2.3.1.4. Public health and safety. The criterion of public health and safety fundamentally encompasses the overall well-being of society. As it is a well-known fact that not only the operation of oil and gas plants but also using fossil fuels adversely affects human health. According to the research that was performed by Lelieveld et al. (2019), fossil fuel-related emissions are responsible for 65 % of excess mortality. Despite the long-term effects of air pollution, the oil and gas industry has carried fire and explosion risks. Sovacool and others (2021) stated that if fossil fuel is substituted with low-carbon energy technologies (excluding nuclear and hydroelectric) 38 million lives could be saved between 2000 - 2020 and 41.2 million lives can be saved from 2021 to 2040.

These model results show that the transition to low carbon energy technologies has a positive impact on public health.

2.3.1.5. Stakeholder pressure. This criterion evaluates how oil and gas companies respond to the urgent call for climate change mitigation. Many of these firms have developed various impact management strategies. According to research, these oil companies respond with symbolic actions, and then the stakeholder pressure increases, they respond substantively (Halderen et al., 2014; de Abreu et al., 2016; Glanz and Schönauer, 2021).

2.3.2. Economic Perspectives

The oil and gas industry are the central point for the chemical manufacturing, petrochemical, power, and transportation industries. The current energy system of the world is heavily dependent on this industry, for this reason, the economic implications of the decarbonization of the oil and gas industry should be assessed in detail. This perspective includes the economic factors that affect the development of low-carbon energy technologies and deployment in the oil and gas industry. The criteria under this perspective are market adoption, R&D investments, cost of plants, land usage, and location, and product type.

2.3.2.1. Market adoption. The concept of market adoption is intricately tied to the acceptance by consumers and investors. In the context of low carbon energy technologies, three primary groups emerge as critical players: major oil corporations, providers of low carbon energy solutions, and stakeholders in the financial sector. For market adoption to be deemed successful, it is crucial to establish a synergy between political frameworks, community requirements, and prevailing market dynamics, as emphasized by Mander and Minas (2019). Notably, providers of low-carbon energy technologies, often smaller in scale compared to giant oil companies, face the challenge of effectively disseminating their innovations to captivate the interest of these larger entities, as explored by Luthra et al. (2015).

2.3.2.2. R&D investments. R&D expenditure is a good indicator for the development path of new technologies, and it contributes to the reduction of cost (Fragkiadakis et al., 2020). R&D budget allocation of private companies shows the penetration of low carbon energy technologies. According to IEA, companies in the energy technology sector increased their R&D expenditure by 40 % as compared to the last decade. However, the oil and gas sector decreased its R&D expenditure by 10 % due to oil price collapse in 2015 - 2018 and it will take more than two years to

recover the R&D budget allocation. When comparing the oil and gas industry with other industries, such as automotive, renewables, and combustion equipment, it can be stated that the R&D expenditure of oil and gas companies is very low with respect to their revenues (2020). These results show that the oil and gas industry will be technology-dependent on other energy sectors in the coming years. In addition to that, Hötte and others conducted research on the scientific development path of low carbon technologies, according to their research results, they stated that the patents of solar PV and biofuels were mostly dependent on scientific papers, and they are more science intensive. Therefore, these low carbon energy technology alternatives need more R&D investment (2021). In addition to that Organic Rankine Cycle (ORC) turbines are also applied in the oil and gas industry for achieving emission reduction, but researchers suggested that to decrease the capital cost of this technology R&D investment should be required (Gudde et al., 2019).

Private R&D investments. Measurement of R&D investments in the private sector is very difficult because of insufficient data. Pasimeni and his friends proposed that patent analysis could be useful for the investigation of private R&D investments. Their study covered the EU and, in the study, the Cooperative Patent Classification (CPC) groups of Climate Change Mitigation Technologies (CCMTs) were used. The patent applications in CCMTs from 2003 to 2014 were examined and according to the results, the private companies have invested 250 billion EUR in the R&D activities in total. Most applications (approximately over 60 %) were done in energy and transportation areas (others: CCS, smart systems, waste, adaptation, buildings, and goods) (EC, 2017). The companies located in Germany have the highest total R&D expenditure. Also, researchers examined that Multinational Companies (MNCs) in the EU make substantial contributions with their R&D expenditures (Pasimeni et al., 2019). Wene proposed that private R&D and public R&D mechanisms use different financial supports and have different goals. Public R&D mechanisms create a financial flow with a tax-paying system; however, private R&D mechanisms use business resources and aim to create commercialized products that have a higher market value (2008). Fragkiadakis et al. (2020) investigated the effect of different R&D mechanisms. According to their results, private R&D investments contribute to the know-how of the firm positively, and due to the effect on commercialization, it reduces the price gap in the market.

Governmental R&D investments. Public R&D mechanisms play a very critical role in the diffusion of low-carbon energy technologies. This sub-criterion is directly related to government energy policies and strategic technology plans. Linares and Perez (2009) claim that there are three fundamental steps for the successful deployment of the technology. The first one is to identify the technical process, economic and environmental input, and outputs of the low-carbon energy

technologies. The second one is to design appropriate regulatory policies according to the readiness level of the low-carbon energy technologies. The technology push and market pull model is beneficial for different technology and market readiness levels. At this step, regulatory policies should be designed according to strategic technology plans (Garnone and Grilli, 2010). The third one is the preparation of technology-oriented agreements to reach climate targets and technology transfer. There are several governmental R&D investment methods such as direct R&D grants via R&D programs, Feed-In-Tariffs (FITs), and Tradable Green Certificates (TGCs) (Linares and Perez, 2009).

Technology push instruments such as direct R&D grants are very advantageous for the support of low Technology Readiness Level (TRL) level technologies which are entitled as basic research since these technologies are disruptive and have new solutions, carry high-risk for the commercialization and private firms are not generally willing to invest (Wene, 2008). Governmental R&D investment is also important for market creation, R&D grants for demonstration projects allow the new technologies for deployment, and governments partially give financial support to the industry (Hartley and Medlock, 2017).

The most common “market pull” instrument is the FIT. FIT is generally suggested for the massive deployment of solar or wind technologies. Therefore, only identified renewable technologies can benefit from this system, this is also accepted as a disadvantage for the deployment of innovative but expensive clean technologies (Hartley and Medlock, 2017).

2.3.2.3. Cost of plant. The cost of the plant is one of the main economic criteria. This criterion includes all aspects related to the cost: capital cost, operational cost, cost of the feedstock, transportation cost, and cost competitiveness between the technologies.

Capital cost. Capital expenditure (CAPEX) is generally defined as all direct costs incurred from the construction or retrofitting of a fixed asset. It includes the payment of goods and equipment, and services that are taken during the construction and recorded as financial costs. Deployment of new technologies into the oil and gas industry requires high capital cost for that reason, the initial capital cost is one of the most important parameters for decision-makers. Therefore, process design engineers sometimes consider the usage of existing plants. For instance, according to Concawe Low Carbon Pathway study, an assessment of e-fuel production technologies has been carried out in order to decrease the emissions in an oil refinery and also produce low-carbon fuel. CAPEX is one of the assessment criteria in order to evaluate this technology. Since the equipment cost of e-fuel

technologies is very high, high CAPEX is considered as a major disadvantage, and usage of existing hydrocracker units is suggested to decrease the capital cost (Soler, 2020). The maturity of technologies or new technological developments also provides positive feedback in terms of the decline of CAPEX (Fasihi et al., 2019).

Operational cost. Operational expenditure (OPEX), which is also called maintenance cost, covers whole expenses of the specified unit during the operation such as consumed heat, steam, electricity cost, fuel cost, waste management cost, the salary of the operators, cost of consumables such as chemicals, water, pressurized air. Operational cost is mainly assessed with CAPEX. Fernandez-Dacosta et al. (2019) performed an analysis in order to compare low-carbon energy technology alternatives; CO_2-to-methanol, CO_2-to-DME, hydrogen production via electrolysis, and conventional hydrogen production (SMR). The highest OPEX value belongs to the CO_2-to-methanol technology alternative with 72 EUR/Gj and the lowest one belongs to SMR technology. Electricity costs have the highest portion in the breakdown of the OPEX (Soler, 2020).

Cost of feedstock. The operation of the oil and gas industry depends on crude oil and natural gas prices. The decarbonization of the oil industry gives rise to the processing of other types of feedstocks rather than fossil fuels. Although wind and solar as renewable energy have no fuel cost for energy production, biomass is always the first alternative for liquid fuel production instead of crude oil, however, the cost of feedstock affects the penetration of bioenergy, especially, since low oil prices cause a tendency to fossil fuels. Also, low oil prices affect the petrochemical industry, because approximately 90 % of chemicals are fossil-based (Nesbitt, 2020). According to Krishnan and McCalley (2016), although biomass resources are at higher costs, biofuel production is important for decreasing the importation of crude oil and reaching the emission reduction goals in the production of transportation fuels. The price of biomass feedstock differs according to its type. The price of primary agricultural feedstock is in the range of 40 to 80 $/per metric tonnes, for forest resources this value ranges from 10 to 200 $/per metric tonnes, and for the secondary resources such as urban wood wastes, municipal solid wastes, animal fats, and waste oils range from 10 to 60 $/metric tonnes. Yeh and friends also argued that the low carbon fuel production market is not dynamic, only two significant factors; higher production costs and feedstock prices affect the cost-effectiveness of biofuel production. Moreover, although high crude oil prices and subsidies favour biofuel production, high crude prices also affect fertilizer prices, and this price increase reflects feedstock prices (2009).

Transportation cost. Transportation costs mainly originate from waste-to-energy facilities and renewable natural gas production because of the transportation of wastes, and pipeline infrastructure for renewable natural gas (Parker et al., 2017). Moreover, the transportation of CO_2 creates a cost category for CCS technologies. There are three most common methods for CO_2 transportation, these are onshore pipeline, offshore pipeline, and ship transportation. Transportation cost differs with respect to distance in offshore and onshore pipeline transportation. For instance, cost estimates of a 180 km offshore pipeline for a CCS demonstration project are 9.3 EUR/tonne CO_2, this value increases to 20.4 EUR/tonne CO_2 for a 500 km pipeline and 51.7 EUR/tonne CO_2 for a 1500 km pipeline. However, according to the European Technology Platform for Zero Emission, pipeline costs are mostly composed of CAPEX (approximately 90 %), while shipping costs are less CAPEX intensive. In the shipment transport, liquefaction cost is needed, generally assumed as 5.3 EUR/tonne CO_2 independent from distance. The shipment cost for 180 km distance is 8.2 EUR/tonne CO_2, for 500 km, this cost increases to 9.5 EUR/tonne CO_2, and for 1500 km distance, the cost of transportation is 14.5 EUR/tonne CO_2. The shipment of CO_2 is more cost-effective for long-distance transport (Nilsson et al., 2010; IEA, 2020). In addition to that, Smith et al. proposed that the transportation cost of CO_2 also depends on the scale in terms of transportation capacity, and geologic variety of storage sites (Smith et al., 2021).

Cost competitiveness. Cost-competitiveness shows the relative value of application cost for selected technologies. For instance, when the CCS technologies will be compared in terms of cost: carbon capture technology from biomass combustion is more cost-competitive with respect to direct air capture (Gudde et al., 2019).

2.3.2.4. Land use and location. Land use and location can be accepted as indirect economic factors for the decarbonization of the energy sector since the reliability of resources in terms of sourcing and origin, feedstock delivery, land requirement, and location of the plant have an impact on feasibility studies at the stage of deployment of low carbon energy technologies (Konadu et al.,2015; Luthra et al., 2015). Renewable energy (solar and wind), and bioenergy give rise to intermittency because of availability; to construct a reliable and economical energy system, a sustainable supply chain should be established (Lap et al., 2020; Lo et al., 2021).

For some low-carbon energy technologies, land is required in order to plant feedstocks such as first-generation biofuels which are derived from biomass. Even if advanced biofuels are considered, huge areas will be needed for the cultivation of algae (Naik et al., 2010). The other land that

requires low-carbon technology is CCS technologies. Geological storage sites cover an enormous area in the ground (Johansson et al., 2012).

Reliability of resources. Continuity of feedstocks is the most important factor in biomass conversion technologies (Torjai et al., 2015) since the cost efficiency of the operation, storage, and transport scheduling depends on biomass availability and reliability. Yield fluctuation due to weather conditions (floods, droughts), seasonal efficiencies, wildfires, and disruptions affect the biomass stocks (Huang et al., 2014; Liu et al., 2017; Lap et al., 2020). Ren and Sovacool (2015) investigated the effects of low-carbon energy sources on China's energy security, and they found that biomass is the third most reliable option after hydro and wind energy.

Feedstock deliverable. Feedstock delivery is another significant driver for low-carbon energy technologies such as biomass conversion technologies, waste-to-energy technologies, and CCU. Forestry residues, agricultural byproducts or dedicated energy crops, and municipal solid wastes require collection, storage, and distribution systems. To design cost-efficient operations for a biomass conversion plant, the location of the plant, quantity of feedstock, storage, and shipment cycles should be optimized (Liu et al., 2017).

Storage and delivery are also important for gaseous feedstocks. For instance, CCS technologies require geological storage sites and CO_2 pipeline infrastructure for the injection of CO_2 and newly designed ships for the transport of CO_2. This causes high infrastructural and operational costs (Anderson et al., 2009).

Land requirement for resources. The energy versus food dilemma creates conflict in land use, for that reason biomass conversion technologies are not preferred in some countries. For instance, according to Troldborg's study, biomass and energy from waste technologies were the least preferred technologies in Scotland because of the land competition for agricultural, recreational, and conservational usage. On the other hand, contaminated lands also are an option for harvesting energy crops and phytoremediation (Troldborg et al., 2014).

There is a huge difference between land use of energy systems. Land-use change is generally measured by a unit of square meters (m^2) per energy produced in megawatt-hours. In non-renewable energy systems such as nuclear energy and natural gas production, land-use footprints range from 0.1 to 1 m^2/MWh. However, in coal and fossil fuel energy systems, this value increases to 0.6 m^2/MWh. This increment stems from the spacing of gas and oil wells, the depth of coal

seams. However, biomass energy systems have large land footprints because of the cultivation of feedstock. The land footprint rate differs from 100 to 1000 m^2/MWh, the largest land-use intensity belongs to biomass from crops and cellulose, short rotation coppice (Fritsche et al., 2017).

2.3.2.5. Final Product type. The commercial value of the final product, and the market cap are the most important criteria for the assessment of low-carbon energy technology alternatives. For instance, methanol is a widely used fuel type in China, and the demand for methanol is high, however, dimethyl ether is only used in restricted vehicle types such as buses and heavy-duty vehicles. When any investment should be considered in China, e-methanol (synthetic production) is a preferable option for deployment (Soler, 2020).

2.3.3. Technical Perspectives

The technical perspectives section includes the factors that affect the technical development of low-carbon energy technologies. Technological maturity, the efficiency of the system, operational stability, process safety, process intensification, and integration capability issues are investigated in the scope of this perspective.

2.3.3.1. System efficiency. Efficient design is the most critical and primary element for oil and gas systems. System efficiency can be defined in different ways depending on the process but mainly, it is described as the division of energy outputs to the energy of all inputs (IPIECA, 2022). The efficient use of energy in terms of heat and power is the first thing that comes to mind when system efficiency is in the oil and gas industry.

Energy efficiency. Energy efficiency technologies stand at the forefront of innovation in the oil and gas sector, characterized by their minimal technical risk and substantial contributions to both emission reduction and cost optimization. These technologies represent sustainable practices in this industry, aligning with global environmental objectives. As highlighted in the study of DNV GL (2015), the integration of energy-efficient solutions is not just a strategic action for accomplishing environmental targets but also provides economic efficiency for the sector. Furthermore, recent study of Jahanger et al. (2023), emphasizes that energy efficiency is a cornerstone in the technological fight against greenhouse gas emissions. The significance of energy efficiency extends beyond immediate industry benefits, playing a pivotal role in global efforts to mitigate GHG emissions, as per the latest directives of the IPCC.

Utility consumption. Efficient use of steam and electricity is crucial for the energy performance of oil and gas plants (Concawe, 2012). As stated by Zhang et al. (2023), adopting energy-efficient technologies and trading energy use rights can significantly enhance utility system efficiency, and it promotes a market-driven approach to energy savings in the oil and gas industry.

2.3.3.2. Technology readiness level. The TRL is the most widely used assessment scale for measuring technology maturity and it was developed by NASA in the 1970s (Krahn et al., 2008). TRL is composed with respect to the demonstration type or implementation environment for a given technology in time. This methodology has been deployed in governmental agencies and industries such as aerospace, oil and gas, and electronics since 1990 (Persons and Mackin, 2020). Generally, TRL is composed of 9 levels (TRL 1-9) and since it belongs to broad definitions, the scale metrics are inclusionary for different energy technologies. Some associations like Organization for Economic Co-operation and Development (OECD) use 4 levels for the assessment of the technologies; level 1 is for basic research (TRL 1-3), level 2 is for development (TRL 3-5), level 3 is for demonstration (TRL 6-7) and level 4 is for early deployment (EU, 2017).

2.3.3.3. Process safety. Effective and safe design is a priority in process safety to prevent serious incidents that could harm people, workers, and the environment, and potentially damage a company's reputation and financial stability. This necessitates careful consideration in selecting equipment materials, ensuring operational stability, and implementing regular, straightforward maintenance protocols (IOGP, 2018).

Operational stability. The long-term operational stability is highly critical for the integration of new technologies in the oil and gas industry. For instance, in developing new catalysts or processes, it is essential to conduct extensive testing, often exceeding 1000 hours, to affirm system stability and facilitate commercialization (Yang et al., 2020).

Equipment material. Choosing the right material during process design is vital for process safety. For instance, corrosion is a prevalent issue in the oil and gas sector due to the nature of crude oil and natural gas. Additionally, to mitigate the risks of explosiveness and flammability in plants, it is essential to use explosion-proof materials and make appropriate material selections (Popoola et al., 2013; Fayomi et al., 2019).

Easy maintenance. Proactive maintenance activities enhance the useful life of equipment, for that reason, applying Condition-Based Maintenance (CBM) is crucial for predicting failures in the

system. Also, real-time data monitoring and decision-making activities can be used in order to determine the maintenance intervals (Telford et al., 2011).

The longevity of equipment is significantly enhanced by proactive maintenance activities. Employing Condition-Based Maintenance (CBM) in oil and gas facilities is crucial for predicting system failures. Furthermore, leveraging real-time data monitoring and decision-making processes is instrumental in establishing maintenance schedules (Telford et al., 2011).

2.3.3.4. Process intensification Process Intensification (PI) is defined as any chemical engineering development that provides smaller, cleaner, safer, and more energy-efficient technologies. The most distinctive feature of PI technologies is size and/or volume reduction in the process plant, this ensures resource efficiency during the plant construction. There are four principles to develop process intensification technologies successfully. The first one is to improve the reaction kinetics by changing the frequency of collision or orientation of molecules. The second one is to provide a uniform processing experience to all input molecules. The third principle is to optimize the driving forces at every scale and to maximize the specific surface area. The last one is to add multifunctionality to the system in order to combine several processing features (Reay et al., 2013; Abdulrahman et al., 2021).

2.3.3.5. Integration capability. Integration of emerging low-carbon energy technologies into the oil and gas industry requires strict rules to meet reliability and affordability metrics. Production variability and reliability issues are the most important barriers to overcome. To solve these problems, hybrid systems are proposed, however, they increase the complexity and cost. On the other hand, renewable energy alternatives such as solar-generated heat applications, offshore wind platforms reduce fuel use and they are environmentally friendly options for upstream or downstream activities (Ericson et al., 2019).

2.3.4. Environmental Perspectives

The oil and gas industry are one of the most carbon-intensive industries. Environmental reflections of emerging low-carbon technologies are highly important for oil and gas companies that target to reach net-zero carbon by 2050. The criteria under this perspective are air emissions, pollution, aesthetics, co-benefitting, and usage of resources.

2.3.4.1. Air emissions. Oil and gas plants are huge industrial complexes. At every stage of oil products, from well to wheel, petroleum products generate emissions to the atmosphere. According to the European Pollutant Release and Transfer Register (E-PRTR), 38 different air pollutants were identified in the oil and gas sector (Concawe, 2020).

Greenhouse gas emissions. This sub-criterion covers the reduction of GHG emissions from upstream and downstream operations and reduction of GHG emissions from oil and companies' products. In this sense, exploitation of low carbon transportation fuels, decarbonization of natural gas through blue and green hydrogen value chains, and electrification of oil and gas platforms are becoming significant for oil companies (Gudde et al., 2019; Concawe, 2020).

Odor. Although odour is accepted as a subjective and aesthetic problem, it mainly originated from compounds that contain sulphur, nitrogen, and Volatile Organic Compounds (VOCs). Odor problems can occur at any place in an oil refinery and oil production platforms that are uncovered. Storage, loading operations, venting, and flaring of gas causes emissions of odorous compounds (Concawe, 2020).

Other air emissions. Other air pollutants that are emitted from an oil and gas plant are SO_x, NO_x, particulate matter (PM10), benzene, and non-methane VOCs (NMVOCs) (Concawe, 2020).

2.3.4.2. Pollution. This criterion refers to all pollution types except air emissions. Water pollution, solid waste generation, hazardous waste generation, and soil and groundwater pollution topics due to oil and gas exploration and refining activities are assessed under this criterion.

Water pollution. Extraction of oil and gas and the processing of them requires huge amounts of water and generates wastewater. In the upstream, fresh water is used for hydraulic fracturing and drilling activities. Since crude oil includes high levels of sulphur, salts, and metals, before the conversion of crude oil to valuable fuels downstream, these impurities are eliminated in desalter units. Desalter units remove a major amount of these impurities, but it generates a major part of wastewater flow. After the desalting process, the distillation process generates wastewater which includes sulphides, ammonia, phenols, oil chlorides, and petroleum hydrocarbons. Both produced water and refining wastewater contains hazardous compounds to aquatic environments and advanced treatment technologies should be applied before the discharge to receiving water bodies (Radelyuk et al., 2021; Pichtel, 2016).

Solid waste generation. Solid wastes generated in the oil and gas industry can be classified into three categories: domestic, industrial, and hazardous wastes. According to researchers, most of them are industrial wastes that are coming from oil and gas exploration and processing activities. Examples can be given as pipes, drilling cuttings, non-hazardous chemicals, metals, grits, and fibres. Industrial waste sources in oil processing plants can be defined as crude oil desalting, distillation, hydrocracking, isomerization, alkylation, polymerization, residual upgrading, lube oil processing, sulphur complex, and residual oil tank storage processes. Domestic waste sources can be described as accommodation services, and offices (Elshorbagy and Alkamali, 2005).

Hazardous waste generation. Hazardous wastes are defined as waste streams that are harmful to human health and safety and/or environment. They can be classified as flammable, toxic, reactive, radioactive, explosive, infectious and ecotoxic. Hazardous wastes in a petroleum refinery, are tank bottom sludge, crude oil tank sludge, spent catalysts and spent caustic. All these wastes should be stored and disposed carefully (Elshorbagy and Alkamali, 2005).

Soil and groundwater pollution. Soil and groundwater pollution generally occurs via accidental releases and natural events such as damaged pipes, overflowed wells, and shifted oil tanks. Soil remediation techniques and in-situ bioremediation can be applied for soil and groundwater contamination (Pichtel, 2016).

2.3.4.3. Aesthetics. Noise and visual disturbance are accepted as aesthetic problems, and they are assessed under the environmental impact assessment (TANECO, 2009).

Visual amenity. Visual impact analysis is conducted for most of the oil and gas projects. Visibility of industrial plants from sensitive viewpoints, mapping analysis for all visible lands within a five-mile radius is applied to assess the visual influence of the plant (Gillespie and Clark, 1979; Carlsson, 2018).

Noise. Noise can be defined as pollution and suitable precautions should be taken in an industrial plant. Noise causes acoustic discomfort in workplaces and is harmful to human health and safety. Noise problems can be seen during the construction and operation period of oil and gas facilities. Pumps, compressors, air cooling units, ventilation systems, gas and steam turbines, disposal furnaces can cause noise pollution. To reduce the noise level, high noise level units should be placed as far as possible in fully automated blocks. Auxiliary equipment for noise suppression, silencers, noise absorbers should be used in oil and gas facilities (TANECO, 2009).

2.3.4.4. Co-benefitting. Co-benefitting is explained as a contribution to the circular economy. In the circular economy principle, the resource flow of a specified process unit can be closed by the 4R approach (reuse, recycling, remanufacturing, or recovering), or it can be slowed via retrofitting the plant and use long-life materials, or it can be reduced by applying resource efficiency techniques (Sellier and Spataru, 2020).

2.3.4.5. Usage of resources. This criterion examines natural resource management in terms of freshwater usage, critical minerals, and feedstock types. Alternative energy resources are remarkable options for emission reduction; however, it should also be investigated with respect to sustainable resource management.

Fresh Water Usage. Freshwater is used at every stage of the oil and gas industry. In the oil production process, the water is used for hydraulic fracturing. In the oil refining process, energy production requires an enormous amount of water for steam generation, treatment of crude oil. The refineries mainly use "fresh" surface water (lakes and rivers) and "fresh" groundwater (aquifers). In addition, some of them can use saline water (seawater and brackish water) (Sun et al., 2018).

Critical Minerals. The movement to clean energy technologies causes one drawback in terms of resource management. Renewable energy technologies, electric systems require more minerals than fossil fuel-based energy systems. For instance, huge amounts of copper and aluminium are required for electricity networks. Wind energy systems need nine times more mineral resources than gas-fired power plants (IEA, 2021).

Feedstock Usage. There are various routes for alternative energy production instead of fossil fuel-based energy production. However, feedstock type affects sustainable resource management, especially biomass energy. Food crops such as sugar cane, sugar beet, canola, and soya can be used as biomass feedstock, but usage of these types of food crops creates an imbalance between food water and energy nexus (Stafford et al., 2019; Brennan and Owende, 2010).

2.3.5. Political Perspectives

Political criteria dominate both market and environmental restrictions. This perspective covers all related criteria from governmental policies to standardization issues. The criteria under this

perspective are legal and regulatory instruments, market-based policy instruments, energy security, Intellectual Property Rights (IPR), and standardization.

2.3.5.1. Legal and regulatory instruments. This criterion refers to command and control mechanisms that control the pollution emissions with the laws or regulations. The oil and gas industry are the most affected sector among the energy-intensive industries from climate-related regulations and international agreements (Guo et al., 2021).

Governmental regulations. The biggest challenge in the world is climate change and governments have tried to combat this challenge with international climate negotiations. The Kyoto Protocol and then, Paris Agreement have guided world countries to set stringent control regulations. The oil and gas industry must comply with the regulations related to emissions stemming from the production process and their products (Panoutsou et al., 2021).

International regulations. Especially the marine and civil aviation sector regulated by international organizations. International Civil Aviation Organization (ICAO) has arranged policy mechanisms for reducing aviation-derived carbon emissions, ICAO generally regulates the fuel blending issues and usage of alternative fuels in the aviation sector. The International Maritime Organization (IMO) regulates the policies in the marine sector and develops policy mechanisms for sulphur and carbon emission reductions (Panoutsou et al., 2021).

2.3.5.2. Market-based policy instruments. Market-based policy Instruments (MBIs) are relatively more flexible policy mechanisms than regulatory instruments since MBIs offer many more alternatives to firms to internalize their pollution costs. They include taxes, trading mechanisms, subsidies (Guo et al., 2021).

Emission trading system. Emission Trading System (ETS) consists of many variables and units. For this reason, it is accepted as a complex price instrument. However, since its target is directly related to the reduction of carbon emissions, it is accepted as the most effective climate policy instrument. ETS has changed the multinational oil companies' strategies related to climate change. Emissions from oil exploration, production, and refining are covered by ETS (Tang et al., 2020, Skjaerseth, 2013).

Taxation. Another way to put a price on carbon is the carbon tax. Unlike ETS, in the carbon taxation system, the government determines a price for emissions. However, researchers suggest

that a differentiated carbon tax model could be more beneficial to reduce emissions. For instance, the carbon tax rates for road transport and aviation and water transport should be different and thus, this issue creates price differences in fuels (Boyce, 2018; Hafstead et al., 2016; Zhou et al., 2018).

Subsidies. Subsidies can be in various forms such as direct funding, tax reductions, loans, or guarantees, providing resources like fresh water at a low cost. Governments' renewable subsidies can accelerate low carbon technology adoption, but subsidies to fossil fuels affect the adoption of low carbon technologies adversely (Erickson and Achakulwisut, 2021; Gillingham and Sweeney, 2012; Metcalf, 2009; Chen et al, 2017).

2.3.5.3. Energy security. Energy security can be defined as the ability of an energy system to tolerate shocks and any other imbalances inside the system and provide sustainable and reasonably priced energy services. Low carbon energy technologies have positive and negative effects on energy security. First of all, low carbon energy technologies can increase the fuel mix and provide more resilience to the system, on the other hand, it may decrease the demand diversity (Gracceva and Zeniewski, 2014).

2.3.5.4. Intellectual property rights (IPR). Patent application is one of the best ways to examine technology diffusion. Organizations' Intellectual Property (IP) strategies affect the technology transfer and intersectoral diffusion of the low carbon technologies. For that reason, patent pools, open innovation platforms, and knowledge sharing platforms increase the adoption of low carbon energy technologies (Yin et al., 2020; Eppinger et al., 2021; Duch-Brown and Costa-Campi, 2015).

2.3.5.5. Standardization. Standardization is the most critical part of the commercialization of a product. Among the alternative fuels, only some Sustainable Aviation Fuels (SAF) has been approved by ASTM D7566; for instance, synthetic paraffinic kerosene with aromatics via Fischer Tropsch can be used with conventional jet fuels up to 50 % blends, and renewable synthesized iso-paraffinic fuels can be blended up to 10 % (Panoutsou et al., 2021).

2.4. Previous Studies on Technology Assessment in Oil and Gas Industry

In examining the literature pertaining to technology assessment within the oil and gas industry, it is noticed that a multifaceted array of investigative methodologies and insights have been employed, each distinctly enriching the collective comprehension of technological evolutions and their respective outcomes in this area.

Research on technology assessment in the oil and gas industry, though limited, reveals diverse approaches, technologies, and criteria. A notable contribution in this field is the study by Pandejpong (2016), which introduced an interactive decision support model for technology selection in the industry. This study stands out for aligning technology choices with an organization's overarching objectives, employing the Analytic Hierarchy Process (AHP) to evaluate the influence of various technological options on a company's mission, goals, and operational factors. The research focused on a specific case in 1993, examining a Thai company engaged in olefins and aromatics production. Facing national policy and market demand pressures, this company contemplated diversifying into a broader spectrum of petrochemical products. Pandejpong's decision-making framework was studiously structured: the top hierarchy encompassed the company's mission and corporate goals, followed by a two-tier section comprising systems and decision factors, culminating in a focus on technology alternatives. The systems were categorized to reflect the company's operational aspects, including strategic, technical, internal, competitive, and external systems. While the study was comprehensive, the study notably lacked depth in its social and environmental assessment. Although environmental factors were acknowledged within the external system, the absence of detailed sub-factors resulted in a less thorough environmental analysis (Pandejpong and Kocaoglu, 2001).

In another significant study within this field by Alidi (1996) which is embarked on an assessment of technologies in the petrochemical industry, using a Saudi Arabian petrochemical company as a case study. This research adopted the AHP and structured it into a comprehensive five-level hierarchy. The primary focus, situated at Level 1, was the 'ranking of petrochemical manufacturing technologies.' Subsequent to this, Level 2 delineated groups identified for technology selection. Criteria and sub-criteria were methodically laid out in Levels 3 and 4, culminating in Level 5, where specific technology alternatives were enumerated. Key criteria such as system operability, product type, and catalyst features emerged as pivotal in the technology selection process. However, it is noteworthy that the study's framework predominantly centred on internal system considerations, largely overlooking external systems. As a result, the technology assessment was primarily conducted from the company's internal perspective, focusing significantly on its profitability, potentially limiting a broader, and lack of more holistic understanding of the technologies' impact.

A research study conducted by China National Petroleum Co. (CNPC) focused on identifying key oil refining technologies in the context of China's evolving petroleum refining industry. CNPC

undertook this study to pinpoint emerging technologies crucial for enhancing the core competence of its petroleum refining operations. Utilizing the Delphi method, the study involved expert interviews. This process resulted in the identification of five technological fields: catalytic cracking, catalytic hydroprocessing and hydrotreating, residue upgrading/processing, lube oil production, and high-octane number component production. 19 technology topics were subsequently selected for in-depth investigation. The study concluded in a priority ranking of these technologies, accordance with their perceived importance and feasibility. Key technologies identified as critical for CNPC's petroleum refining business included integrated FCC technology, hydroprocessing technology, residue hydrocracking technology, and high-grade lubricant production technology. Notably, the study's focus was primarily on productivity and feasibility from the company's internal perspective (Liu et al., 2007).

In a comprehensive study by Wang et al. (2019), the focus was on optimizing phytoremediation strategies for petroleum-contaminated soils, specifically in the Changning shale gas field and the Liaohe oil field. The study employed a novel evaluation system, integrating the AHP and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), enhanced with Triangular Fuzzy Numbers (TFNs). This approach facilitated the assessment of 23 plants based on three key criteria and nine indexes, with an emphasis on moisture as a critical factor. This study contributes valuable insights for decision-makers in managing petroleum-contaminated sites, highlighting the significance of innovative approaches in environmental remediation within the oil and gas industry.

The study by Giadedi and Daim (2021) addresses into the complexities of offshore oil projects, characterized as mega projects with substantial inherent risks and high failure potential. It highlights that while financial analysis is commonly used to evaluate these projects, a more comprehensive approach considering various internal and external factors is essential. The paper employs a multi-criteria decision model to evaluate and weigh the impact of critical factors influencing investment decisions in offshore oil projects. A detailed literature review identified four key perspectives – economic, technical, political, and environmental and safety – as essential for the success of these projects. Utilizing a HDM methodology, the study provides a structured approach to evaluate offshore oil projects, aiming to enhance investment decisions and minimize failure risk. This methodology ensured a robust and reliable framework for assessing these complex projects.

In an innovative study by Tayebi et al. (2022), a hybrid decision support system (DSS) was developed for assessing the sustainability of air pollution control technologies (APCTs) in the oil, gas industry. This comprehensive system integrated analytical network process (ANP), decision-

making trial and evaluation laboratory (DEMATEL), and multi-objective optimization on the basis of ratio analysis (MULTIMOORA) methods within a fuzzy set theory framework. The study was applied to three specific cases in Iran: a petrochemical plant, a gas refinery, and an oil refinery, focusing on evaluating four common APCTs — electrostatic precipitators, fabric filters, wet scrubbers, and cyclones. The sustainability of each technology was ranked, aiding stakeholders and decision-makers in aligning their practices with energy and carbon management policies. This approach proved effective for group decision-making, leveraging expert opinions, and managing uncertain data, and is significant for guiding the oil and gas sector towards sustainable, green growth, and a low-carbon future.

In conclusion, the review of literature on technology assessment in the oil and gas industry shows that a dynamic and complex landscape exists with diverse methodologies and a range of critical factors. Studies such as those by Pandejpong (2016), Alidi (1996), and CNPC demonstrate the industry's evolving approach to technology selection. These studies also emphasize the alignment of technological choices with organizational objectives and the importance of comprehensive evaluation frameworks. These studies collectively underscore the necessity of considering not only economic and technical factors but also environmental, political, and social aspects in technology assessment. Innovative approaches like those in the studies by Wang et al. (2019), Giadedi and Daim (2021), and Tayebi et al. (2022) highlight the need for advanced decision support systems and multi-criteria models to navigate the complexities inherent in the industry, ranging from environmental remediation to investment decisions in high-risk projects. This body of work reflects a growing recognition of the multifaceted nature of technology assessment in the oil and gas sector, encouraging a move towards more integrated, sustainable, and stakeholder-inclusive strategies for future technological developments.

2.5. Hierarchical Decision Modelling (HDM)

Technology planning is a pivotal task for organizations, particularly when faced with the crucial decision of investing in existing technologies versus developing new ones. This challenge, central to executive management, necessitates a systematic approach to technology planning. In the face of the inherent uncertainties in technology development, MCDM techniques emerge as key tools for evaluating various technological alternatives (Intepe et al., 2013). MCDM provides a structured framework for aligning an organization's preferences with the decision-making process, especially when multiple, often conflicting, objectives are involved. These techniques enable the assessment of alternatives against multiple criteria, ensuring a comprehensive evaluation (Kalbar et

al., 2012). As a collective term, MCDM encompasses various decision-making methods that facilitate the ranking or prioritization of options. A crucial aspect of this process is the weighting of criteria, which acknowledges the differing values that various criteria hold for stakeholders (Murrant and Radcliffe, 2018). There are numerous MCDM methods that are applied in the energy sector and energy-intensive industries (Poladitis et al., 2006; Daim et al., 2018; Daim et al., 2014; Giadedi and Daim, 2021).

The HDM approach, which is one of the MCDM techniques, was developed by Kocaoglu and it was first applied by the US Department of Agriculture in the Combined Forest Pest Program. According to Kocaoglu's claim, if the subjective judgments of experts can be quantified systematically, their opinions can enlighten the complex problems (1983). Many organizations develop strategic plans to accomplish their goals and arrange human and financial resources for the realization of strategic targets. However, even annual budget plans, progress reports, and technical reports give information to the decision-makers, if it is not evaluated systematically, they do not give any effectual information to measure the impacts of these decisions on the company goals. However, executives and team leaders should know the impacts of each strategic decision and its consequences on their projects or programs. For that reason, they need a decision-making tool for systematic thinking.

HDM divides a complex decision problem into smaller sub-problems and provides a systematic approach to evaluate multiple decision alternatives. It is one of the most beneficial systematic thinking tools for organizations (Lavoie and Daim, 2020). In the HDM process, the decision problem is structured into levels consisting of objectives, sub-criteria, and alternatives. The decision maker's preferences are elicited through pairwise comparisons among all variables at every hierarchical level of the decision model. The input from the decision-maker is then processed, and the priorities of the objectives are calculated. The consistency of the decision-makers' responses is checked to ensure logical and not random comparison of the criteria (Gerdsi and Kocaoglu, 2007; Daim et al., 2011; Hogaboam and Daim, 2018).

In HDM, the pairwise comparison method is a crucial step that helps in determining the relative importance of the criteria and alternatives. This method involves comparing each pair of criteria or alternatives in terms of their significance to the overall goal or to the criterion they are under. Experts are asked to make these comparisons based on their knowledge and experience. Each pair is compared in terms of which of the two elements is more important, and to what extent (Fenwick and Daim, 2011). The results of these comparisons are then used to calculate weights for

each criterion and alternative. These weights represent the relative importance of each element in the hierarchy. HDM shares several similarities with the AHP except for their computational approaches and scaling systems (Morgan, 2014; Hogaboam et al., 2014; Gibson et al., 2019; Estep et al., 2021; Lavoie and Daim, 2020). While AHP uses a scale from 1–9 and eigenvectors to calculate results, HDM employs a 100-ratio scale and constant-sum calculations, which are considered more comfortable for experts in terms of relative and absolute preference (Giadedi and Daim, 2021; Khalifa and Daim, 2021) This difference in scaling systems makes HDM easier to interpret and reduces subjectivity in decision-making, thereby enhancing the reliability of the outcomes (Khalifa and Daim, 2021). In addition, the essential feature of HDM methodology is the capability to convert qualitative assessments into numerical values, aiding decision-makers. Thus, HDM employs a tiered framework that enables managers to assess and select among various options under consideration (Lavoie and Daim, 2020).

The desirability curve approach is integrated into the HDM methodology. The desirability curves offer a valuable tool, especially when aiming for a reusable model or when evaluating numerous alternatives. It was developed by Phan to measure the innovativeness of a company (Phan, 2013). Metrics for each criterion are identified for the design of desirability curves. These metrics, tied to individual criteria, serve as pivotal values aiding decision-makers. Experts, using this approach, assess relevant metrics for each criterion, assigning them a scaled quantitative value, and ensuring a standardized evaluation across all criteria (Estep et al., 2021; Shaygan and Daim, 2023).

The robustness and reliability of the resulting model, which are critical attributes for ensuring accurate and dependable outcomes, are provided by inconsistency, disagreement, and sensitivity analysis. Specifically, HDM incorporates provisions for addressing disagreement among experts, detecting inconsistencies in data or judgments, and conducting sensitivity analysis. This sensitivity analysis evaluates how different inputs or variations can impact the model's results. By integrating these provisions, HDM ensures that the model not only produces consistent results but also remains resilient against potential biases or subjective influences, thereby enhancing its overall trustworthiness (Giadedi and Daim, 2021).

3. RESEARCH FRAMEWORK AND METHODOLOGY

3.1. Research Objectives

The phenomenon of "carbon lock-in," as conceptualized by Unruh (2000), is crucial in understanding the persistent reliance on fossil fuel-based energy systems despite the availability of cleaner alternatives. Unruh's analysis reveals the presence of infrastructural, technological, institutional, and behavioural dimensions contributing to this lock-in, underpinned by a Techno-Institutional Complex (TIC). TIC is the creation of systematic interactions between technological developments and institutions. The lock-out of TIC, in other words, displacement with other alternative technologies, is difficult because it is believed that displacement with other alternative technologies creates market and policy failures. For that reason, the diffusion of carbon-saving technologies is very slow, even though they can reduce the adverse effects of climate change. Subsequent studies (Seto et al., 2016; Erickson et al., 2015) have delved deeper into this phenomenon, exploring various global examples and factors influencing carbon lock-in. Furthermore, Hughes and Zabala (2023) explore the transition dynamics within the Scottish oil and gas industry, identifying drivers such as profitability, government policies, and access to capital as key factors influencing investment in renewable and low-carbon energy operations. Their findings suggest the critical role of government intervention in facilitating this transition, highlighting the need for effective policies that balance environmental goals with economic and social considerations. Additionally, Marcel et al. (2023) highlights the complex challenges faced by emerging oil and gas producers in developing countries, emphasizing the need for a just transition that considers equity issues and the lack of capacity for stringent emissions management. This perspective underlines the importance of supporting these countries in their transition efforts, particularly in avoiding economic and technological lock-in.

In contrast, the recent study by Madsen et al. (2023) provides a valuable case study in overcoming carbon lock-in. It examines Denmark's ambitious commitment to phase out all oil and gas extraction by 2050, a pioneering move towards achieving climate neutrality. This example is particularly instructive as it illustrates how policy decisions and governmental commitment can effectively disrupt the TIC, paving the way for alternative, low-carbon technologies. Denmark's approach, involving economic feasibility studies and setting a clear phase-out date, offers practical lessons on navigating the challenges of transitioning away from established fossil fuel-based systems. Additionally, Suskind et al. (2020) provides an insightful examination of Malaysia's

approach to breaking out of carbon lock-in. Despite facing challenges like federal-state friction and barriers to investment in renewable energy, Malaysia has made ambitious commitments to reduce its carbon emissions intensity. It is actively pursuing a decarbonized development path. Key strategies that have enabled Malaysia to begin this transition include behavioural transformations, institutional shifts, and actions by a broad network of actors, including the adoption of policies like the FIT and net energy metering that incentivize investment in renewable energy. These efforts, while challenging, highlight the potential for creating the necessary conditions to overcome carbon lock-in, particularly in a rapidly developing country context. Complementing the experience of Malaysia, Madsen et al. (2023) provide a valuable case study in overcoming carbon lock-in for Denmark. It examines Denmark's ambitious commitment to phase out all oil and gas extraction by 2050, a pioneering move towards achieving climate neutrality. This example is particularly instructive as it illustrates how policy decisions and governmental commitment can effectively disrupt the TIC, paving the way for alternative, low-carbon technologies. Denmark's approach, involving economic feasibility studies and setting a clear phase-out date, offers practical lessons on navigating the challenges of transitioning away from established fossil fuel-based systems. Together, these case studies from Denmark and Malaysia illustrate the diverse strategies and approaches that can be employed to overcome carbon lock-in. They provide valuable insights into how both developed and developing countries can navigate the complex interplay of policy, technology, and societal change necessary for a successful transition to low-carbon economies (Suskind et al., 2020; Madsen et al., 2023). However, these studies offer limited approach for the decarbonization of oil and gas industry, and they do not offer a comprehensive methodology for assessing and adopting low-carbon technologies within the oil and gas sector, marking a significant research gap. This research is designed to accomplish the following objectives:

Main objective:

- to develop a holistic framework that incorporates social, technical, environmental, economic, and political (STEEP) criteria for assessing the low-carbon energy technologies in the oil and gas industry to achieve the emission reduction goals and investigate the impact factors of each criterion to evaluate the best technology alternatives for strategic technology roadmapping activities.

Specific objectives:

- To identify and integrate a comprehensive set of STEEP criteria that influence the selection of clean technology alternatives within organizations operating in the oil and gas sector.

- To develop and apply a quantitative framework that weighs the multi-dimensional perspectives and criteria for evaluating low-carbon technology alternatives.
- To conduct a thorough analysis of the adoption rates and patterns of low-carbon technologies in the oil and gas industry, examining the factors such as industry policies, market dynamics, technological readiness, and organizational strategies that facilitate or impede their adoption.

3.2. Research GAP Analysis

Since the oil and gas companies are the main GHG emitters among the energy-intensive industries, their actions on GHG emission reduction are very significant for mitigating climate change. For that reason, adopting new low carbon energy technologies as R&D or innovation activities, making investments for the deployment of clean energy technologies should be assessed carefully. In this sense, companies mostly evaluate clean technologies in terms of economic perspectives and environmental perspectives, respectively (DNV GL, 2021). Techno-economic analysis (TEA), marginal abatement cost curve (MACC), life cycle assessment (LCA), and life cycle costing (LCC) are the most used tools in the energy sector (Shrivastava and Unnikrishnan, 2019; Blanco et al, 2020; Chen et al, 2020). While these methodologies provide valuable insights, they predominantly offer unidimensional evaluations. This inherent limitation restricts the scope of the information available to decision-makers, potentially overlooking critical multi-faceted aspects of technology adoption, such as social, regulatory, and technological dynamics. Consequently, there exists a significant research gap in developing more integrative assessment frameworks that can encapsulate the complex interplay of factors influencing the adoption and effectiveness of low-carbon technologies in the oil and gas sector.

Recent developments in research methodologies have seen a shift towards integrating established assessment tools with MCDM techniques. Notable among these is the work of Hasheminasab et al. (2018a; 2018b), who developed sustainability metrics rooted in the United Nations Sustainable Development Goals to evaluate petroleum refinery construction projects. Their hierarchical approach, however, primarily focused on the social, economic, and environmental dimensions, leaving technical and political factors relatively unexplored. Similarly, Gholipour et al. (2018) employed MCDM techniques in conjunction with LCA, but their framework was mainly supportive of LCA, without comprehensively addressing the technical and political aspects. This trend indicates a growing awareness of the need for multi-dimensional evaluation frameworks, yet there remains an apparent gap in the literature: a comprehensive, quantitative approach that fully

encompasses the diverse spectrum of factors influencing technology selection in the oil and gas industry. To address this shortfall, the proposed study introduces a STEEP perspective. This approach aims to encapsulate all critical criteria for technology selection, offering a more holistic and nuanced framework. By integrating these diverse perspectives, the research will provide a more complete and balanced assessment tool, capable of guiding the selection of technologies in a manner that aligns with the multifaceted challenges and opportunities faced by the oil and gas industry today.

Building on the recognition of multi-dimensional assessment in the oil and gas sector, several researchers have explored the drivers and factors influencing technology selection. For instance, Ahmad et al. (2017) highlighted the environmental and societal impacts of oil and gas companies, by identifying six key external forces that influence the sustainability of the sector: economic stability, political stability, stakeholder pressure, competition, energy transition, and regulations. While their study is insightful, this approach primarily emphasizes external market dynamics without delving deeply into internal organizational or technological considerations. Similarly, other researchers have narrowed their focus to specific aspects of technology evaluation. Talaei et al. (2020), for instance, concentrated on techno-economic factors, considering elements like capital cost, lifetime, and energy-saving potential. In a more environmentally focused study, Zhao et al. (2021) investigated energy efficiency improvements in petroleum refining, assessing factors such as total energy use and various emissions (CO_2, NO_x, SO_X, and PM_{10}). However, while all these studies are valuable and offer fragmented insights, each of them only addresses the certain facets of a complex decision-making landscape. The literature thus reveals a pattern: studies tend to specialize in one or two dimensions, such as economic, environmental, or political factors, but they seldom provide a holistic view that encompasses all critical factors affecting technology selection in the oil and gas industry. This indicates a significant research gap, underscoring the need for a more integrative approach. The proposed research aims to bridge this gap by adopting the STEEP perspective, ensuring a comprehensive and multi-faceted evaluation of clean energy technologies. Such an approach is vital for capturing the full spectrum of influences on technology selection, thereby enabling more informed and strategic decision-making within the oil and gas sector.

The discourse on technology selection in the oil and gas industry remains incomplete without addressing the actual adoption of low-carbon technologies. While there is a numerous of basic research and various projects in the demonstration phase globally, a critical question has not been answered: how extensively these innovative technologies are being adopted by the industry. A notable study by Green et al. (2020) sheds light on this issue. By analysing the earnings calls of 10

major oil companies from 2004 to 2019, they explored the companies' acceptance of climate science and policies, and their support for technologies like CCS. The findings were telling despite public narratives, these companies have largely maintained their focus on fossil fuels. Furthermore, the InfluenceMap report reveals that five of these companies (Exxon, Shell, Chevron, BP, and Total) have spent close to $1 billion on climate-related advertising and lobbying, raising questions about their real intentions behind such campaigns. Additionally, Breetz et al. (2018) examined the intersection of clean technology adoption and policy, suggesting that political factors might adversely influence the transition from technology development to deployment. This highlights a complex dynamic where political, economic, and technological dimensions intersect, potentially impeding the industry's progress towards net-zero emissions.

Therefore, it is crucial to delve into the mechanisms of low-carbon technology adoption within the petroleum industry. Understanding the barriers and facilitators in this process is key to identifying actionable strategies that can accelerate the industry's transition to sustainable practices. This study aims to fill this research gap, providing a comprehensive analysis of the factors impacting the adoption of clean energy technologies. Also, it contributes to a more nuanced understanding of the industry's journey towards achieving its net-zero emission targets.

Lastly, the existing studies in the literature have mainly focused on mature technologies and there is a lack of R&D perspective, particularly for emerging technologies. This oversight is significant, especially considering the United Nations Technology Executive Committee (TEC)'s report, which underscores the critical role of technological innovation and R&D in achieving climate goals. According to the UNFCCC (2017), 140 developing countries, in their Nationally Determined Contributions (NDCs), have stressed the importance of technological innovation in mitigating climate change. This reflects a growing recognition that emerging technologies are pivotal in shaping current global energy trends and that organizations must evaluate not only the present utility but also the future potential of these technologies.

This research aims to bridge this gap by focusing on the evaluation of emerging technologies from an R&D standpoint. It seeks to provide insights and answers for decision-makers grappling with strategic planning for their companies' future technological trajectories. By doing so, the study will contribute to a deeper understanding of how emerging technologies can be leveraged to not only meet current operational needs but also to strategically position organizations for future challenges and opportunities in the context of climate change mitigation.

To encapsulate the interplay between these research gaps, objectives, and the underlying questions, a detailed analysis is presented in Table 3.1. This table serves as a roadmap, linking the identified gaps in existing research with the specific objectives of this study, and it provides a clear framework for addressing these critical issues in the oil and gas industry.

Table 3.1. Connection between the research gaps and research questions

Research Gaps	**Research Goals**	**Research Questions**
Overemphasis on mature technologies, neglecting the R&D of emerging innovations.	Develop a framework for assessing low-carbon energy technologies in the oil and gas industry from an R&D perspective.	How can R&D for low-carbon energy technologies be effectively integrated into the strategic planning of oil and gas companies?
Unidimensional evaluation methods failing to capture the STEEP factors affecting technology adoption.	Create a multi-dimensional evaluation model that includes social, technical, environmental, economic, and political perspectives.	What multi-dimensional evaluation model can comprehensively assess the impact of STEEP factors on technology adoption in the oil and gas industry?
Insufficient understanding of the adoption mechanisms and barriers for low-carbon technologies.	Investigate the adoption process of low-carbon technologies in the oil and gas industry, focusing on barriers and enablers.	What are the main barriers and enablers to the adoption of low-carbon technologies in the oil and gas industry, and how can they be navigated?
Lack of studies on the factors influencing the diffusion of clean energy technologies.	Analyse the drivers affecting the diffusion of clean energy technologies within the oil and gas sector.	Which factors most significantly influence the diffusion of clean energy technologies in the oil and gas industry?

3.3. Research Design

The main target of this research is to create a systematic decision-making framework for the oil and gas industry, to achieve this research goal, developing a multi-perspective decision modelling approach is the main building block of this research. HDM methodology is applied as a decision-making tool. This research study unfolds across six phases. Each research phase addresses the research questions which are identified in the research gap analysis. The diagram in Figure 3.1, shows the general structure of the research plan and the main outputs.

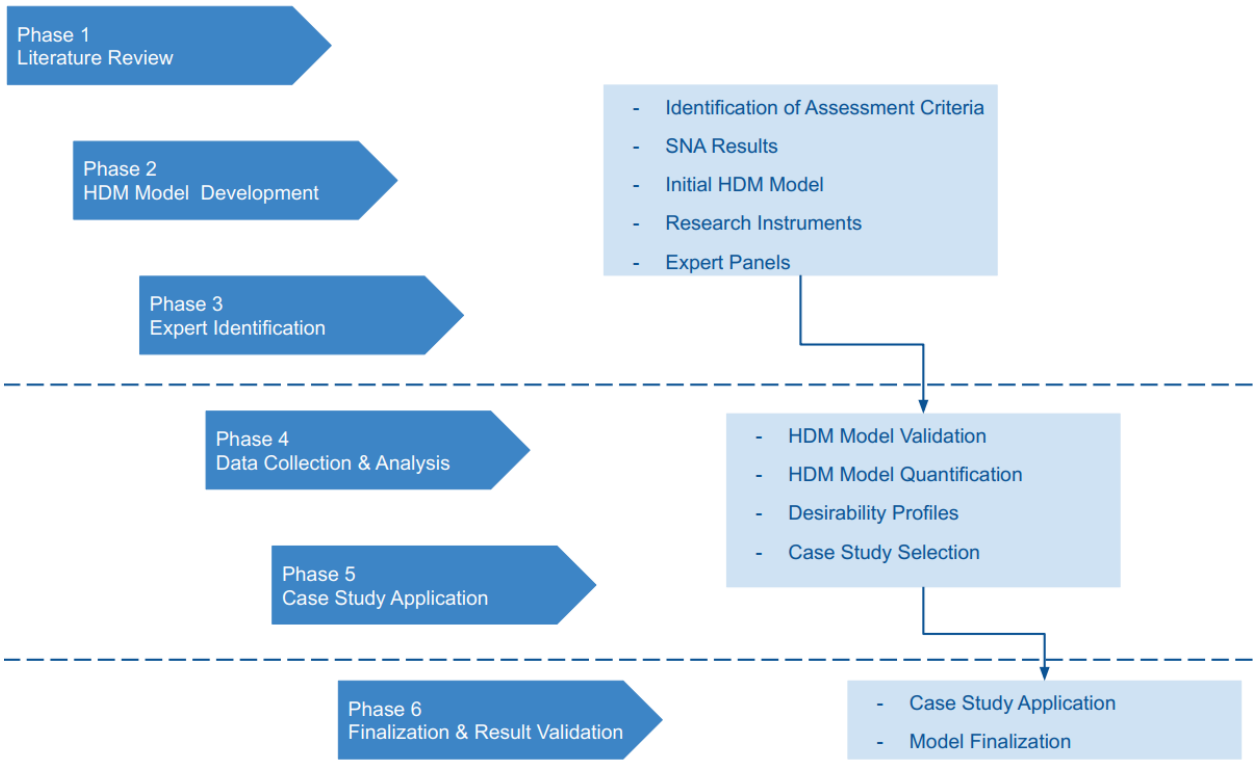

Figure 3.1. Research phases and primary deliverables of the study.

In the literature review phase, research objectives and motivation, research gaps are identified by investigating the sectoral reports and journal articles. The literature review is focused on mainly emerging low carbon energy technologies, factors, and barriers that affect the adoption of low - carbon energy technologies. The detailed literature review for each model element is accomplished for model development. Regarding the technology alternatives, one of the low-carbon energy technologies which are able to reduce emissions, can be deployed or have been already deployed in upstream and downstream oil and gas industry, are investigated.

In the second phase, the assessment criteria which are extracted from the literature review, incorporated into the HDM tool. Measurement units for each sub-criteria are defined, reflecting the insights obtained from the literature review phase.

The third phase of this research study includes the expert identification and preparation of survey instruments. In the expert identification step, a comprehensive expert list is prepared that includes the relevant information about the experts' background and qualifications. According to the rules on personal data protection, the personal information of experts such as name, surname, company name is not published, and the anonymization of expert data is made. During the expert finding period, literature review results, snowball method with the existent network, and

bibliometric analysis are used. The expert panels are formed with respect to experts' professional backgrounds and invitation letters are sent in order to invite the experts. After that, consent forms are sent in order to inform the experts about the research study and the rights for the withdrawal. The validation and quantification surveys are prepared in Qualtrics XM and published with this web-based platform.

The fourth phase of the study is the data collection and analysis. Firstly, each model element is validated by experts and the validated version of the model will be prepared. In the quantification phase, the pairwise comparison method will be used, and allocating weights for each element is requested from experts. A total of 100 points will be assigned between any two elements at the same level, by using the constant-sum method, and allocation of 100 points is requested with respect to their judgments. After quantification data are collected, the disagreement, inconsistency, and sensitivity analysis are performed and importance weights for each sub-criteria, criteria and perspectives are calculated. Desirability profiles are generated by experts' input.

In the fifth phase, technology alternatives are determined as a case study application. Regarding the case study application, research and innovation projects which are funded by European Commission (EC) Research and Innovation Funding Programme are investigated. In depth analysis of European R&D programs, specifically Framework Programme (FP) 7, Horizon 2020, and Horizon Europe is performed.

In the last phase of the study, the results are presented to the selected experts for validity purposes. It is expected that experts will provide their feedback about the decision model's which deliver predictable results. Improvement areas will be identified for further research.

3.4. Research Methodology

This research aims to design a multi-perspective technology assessment model in order to prioritize various low-carbon energy technologies for the oil and gas industry. The insights of a group of experts are the most critical input in a decision-making process. Although the criteria and expert opinions may inherently carry some degree of subjectivity, this study employs model development with HDM to solve this subjectivity issue. This approach systematically structures the decision-making process, reducing subjectivity and enhancing the reliability of the outcomes (Khanam and Daim, 2021). In the following sections, the intricate details of the research methodology are employed, and each component of the model is examined. This section includes

an exploration of HDM Components, Expert Identification, HDM Quantification, Inconsistency Analysis, Disagreement Analysis, Desirability Profiles, Technology Evaluation Score, and Sensitivity Analysis, providing a comprehensive understanding of the processes underpinning the technology assessment model.

3.4.1. HDM Components

The creation of the initial model was rooted in a comprehensive literature review, focusing on the factors, and challenges influencing the low-carbon energy technology assessment in the oil and gas industry. The model is composed of four layers: the perspectives, criteria, sub-criteria, and desirability curves. Each model layer was carefully designed to capture all the complexities and nuances of the oil and gas industry. After the design of the preliminary model, model components were evaluated by a selected group of experts from industry and academia. These panels played a pivotal role in validating the literature-derived findings. The feedback from these expert panels was instrumental in refining the model. Their insights led to the finalization of the factors influencing technology assessment in the oil and gas sector.

1) Perspectives: The model consists of five perspectives: social, economic, technical, environmental, and political. STEEP (Social, technical, economic, environmental, political) tool was used in this research to identify the complexity of multi-perspective technology assessment for low-carbon energy technologies in the oil and gas industry. STEEP Analysis is the most used strategic tool to identify the key macro-environmental factors that influence an organization and to assess the technology alternatives from various viewpoints (Sheikh et al., 2011; Iskin et al., 2012; Estep and Daim, 2018; Estep et al., 2021; Giadedi and Daim, 2021). Thus, it provides to build sustainable business models (Capobianco et al., 2021; Khanam and Daim, 2021).

2) Criteria: Each perspective is further broken down into specific criteria to ensure a comprehensive technology assessment. The social perspective encompasses criteria such as public acceptance, employment, working conditions, stakeholder pressure, and public health and safety. Regarding the economic perspectives, the model considers market adoption, R&D investments, plant cost, land usage, and location, and the type of final product. From a technical viewpoint, system efficiency, TRL, process safety, and integration capability are assessed. The environmental perspective evaluates air emissions, pollution, co-benefitting, and resource usage. Lastly, the political perspective examines the legal and regulatory instruments, market-based policy

instruments, and energy security. A detailed exploration of each criterion is presented in the literature review section.

3) Sub-Criteria: In the model, beyond the criteria, specific sub-criteria have been incorporated to enable a more comprehensive and in-depth evaluation of each criterion. The criterion of public acceptance, employment, working conditions, R&D investments, cost of the plant, land usage and location, system efficiency, process safety, air emissions, pollution, usage of resources, legal and regulatory instruments, and market-based policy instruments have sub-criteria. An in-depth exploration of each sub-criterion is provided in the literature review section.

4) Desirability Curves: To enhance the decision-making methodology, desirability curves have been developed in this study. These curves are a systematic tool designed to evaluate multiple alternatives in a repeatable and objective manner (Giadedi and Daim, 2021). The process of creating these curves begins with the identification of specific levels or metrics for each sub-criterion relevant to our study. Each metric is intrinsically linked to its respective sub-criterion, providing a quantifiable value on a scale from 0 to 100, where 0 represents the least desirable outcome and 100 the most desirable (Khanam and Daim, 2021; Shaygan and Daim, 2023). The process involves assessing each metric for every sub-criterion by experts, thereby allowing for a comprehensive and nuanced evaluation of each alternative. This standardized assessment framework facilitates a comparative analysis of different low-carbon technology alternatives, providing invaluable insights for decision-makers.

3.4.2. Expert Identification

Expert identification is a crucial step in this research, as the identified experts' judgments on technology assessment factors heavily influence the study's outcomes. Therefore, the selection of experts is conducted with thorough consideration of their scientific backgrounds, publications, projects, and professional experiences. Al-Taie et al. (2018) categorize expert finding techniques based on domain specificity. According to their classification, as illustrated in Figure 3.2 (Al-Taei et al., 2018), experts can be identified through an internal network within a company, involving direct contact with other employees, or through online community systems such as LinkedIn, ResearchGate, and scientific databases like Scopus, Web of Knowledge, and PubMed.

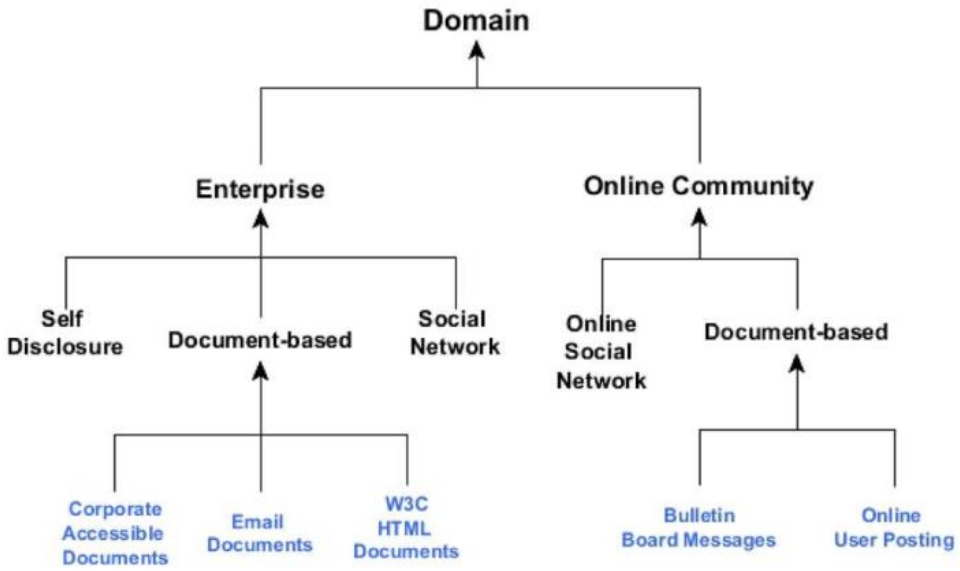

Figure 3.2. Categorization of domain-based expert identification techniques.

In this study, both domain-based and online community-based expert identification methods are employed. For the enterprise-based approach, the research team's background played a key role. In the online community-based method, it is focused on major oil and gas companies globally, 59 organizations are listed. LinkedIn was then utilized to identify employees working in these companies, using specific keywords such as R&D, innovation, carbon, LCA, CCUS, hydrogen, climate, renewable, and strategy to locate relevant experts. The snowball technique was subsequently applied for an expanded reach.

To further refine our expert selection, this study incorporated social network analysis and bibliometric analysis. Social network analysis provided insights into the interconnectedness and influence of potential experts within the field, while bibliometric analysis offered a systematic mapping of the specific research topic. This method revealed relationships between authors, highlighting key contributors in terms of centrality, betweenness, and affiliations with countries and institutions (Singh et al., 2020). In this research study, Bibliometrix tool was used and qualified experts were identified by reviewing a comprehensive scientific landscape from Web of Science and Scopus Database.

3.4.3. Expert Judgement Quantification

Expert judgment quantification technique is used in the model development. Expert judgment is also expressed as an expert elicitation technique. This method was developed in the 1950s in the field of decision theory in order to quantify uncertainty and estimate unattainable values to support

decision-making. In the 1970s, the expert judgment technique has been started to use by US Environmental Protection Agency (EPA). Firstly, it was applied to the air pollutant program and then it has been used by at least five other federal agencies and international organizations. US EPA used this technique in order to obtain quantitative judgments on scientific questions, complex environmental issues, probability of different events, relationships, and parameters. Expert judgment is a multidisciplinary and systematic process to obtain quantitative judgments. The expert knowledge with their experiences and judgments is the main input of the expert judgment process (US EPA, 2011).

The results of expert judgment quantification should not be processed or evaluated as a random statistical sample of the population. If experts are selected according to multiple rational perspectives and relevant expertise, expert judgment quantification can show logical results. Consequently, the selection of experts is critical to the success of an expert judgment quantification process (US EPA, 2011).

The number of experts who participated in the expert judgment study is determined with respect to the complexity of the problem, availability of experts, and perspectives that are examined. According to the literature, based on 38 studies, nearly 90 percent of expert panels performed with 11 or fewer experts. Approximately 60 percent of expert panels are performed with 6 to 8 experts (US EPA, 2011). According to Cooke and Goossens (2008), many experts show the difference in the structured expert judgment studies with respect to the complexity of the problem. For instance, in the chemical and gas industry number of experts in the study was 56 and they examined 403 variables, and 4491 elicitations were recorded. When the uncertainty in the problem increases, the expert numbers should be increased. For example, in the expert judgment study conducted for volcanoes, the expert numbers were 231 and they examined 673 variables in the study (Cooke and Goossens, 2008).

3.4.4. HDM Quantification

The HDM quantification is applied with selected experts. Generally, expert panels are organized as face-to-face meetings, however since the experts are located in different places, the data are collected virtually with the aid of web-based tools. Thirdly, inputs from decision makers are processed and the priorities of perspectives and criteria are calculated (Hallum and Daim, 2009; Fenwick and Daim, 2011; Hogaboam and Daim, 2018).

The pair-wise comparison method (PCM) which is also called the constant-sum method, is used in the quantification process. The experts allocate weights for each element (sub-criteria, criteria, and perspectives). By using the constant-sum method, a total of 100 points will be assigned between any two elements at the same level. The relative value of each criterion is determined in terms of their desirability for objective by using PCM. The judgmental value of the criteria for the objective is based on a scale of 0–100, and then it is normalized to be within the range of 0–1. In Figure 3.3 , a simple application of evaluating multiple objectives' contributions is explained (Gerdsi and Kocaoglu, 2007). Under Objective (O), quantifying expert judgment of relevant technology fields to obtain the value (F_k). For each factor F_k (k = 1, 2 …, k), using pair-wise comparison to determine the relative value of F_k in terms of their desirability for criterion. Judgmental value of the best F_k for O is based on a scale of 0–100, and then normalized to be within the range of 0–1 (Daim et al., 2018).

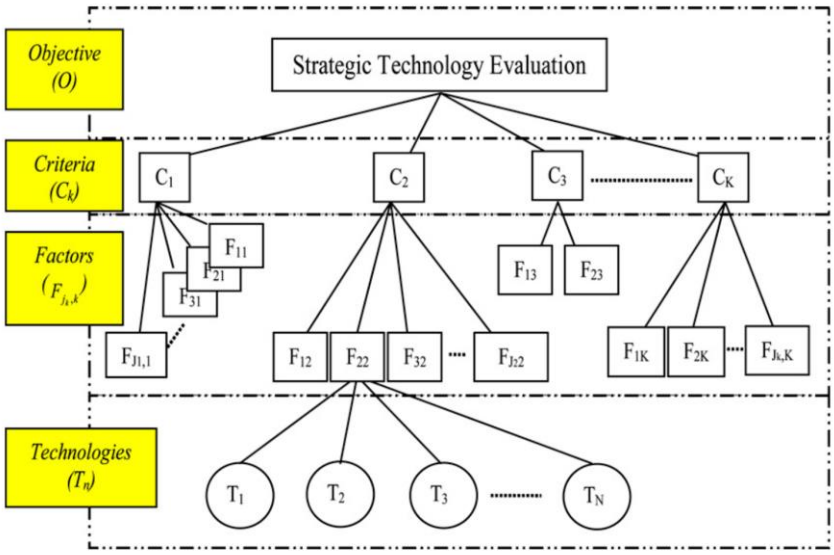

Figure 3.3. Hierarchical decision approach.

In summary, the experts quantify all elements in the HDM, employing methods such as pairwise comparisons and constant-sum techniques to determine the relative importance of each element. To identify potential biases, and ensure the model’s reliability, inconsistency and disagreement analysis is performed.

3.4.5. Inconsistency Analysis

Inconsistency analysis is very critical in this research since HDM methodology is based on expert judgment quantification and human judgment is subjective. In order to remove the subjectivity, inconsistency analysis is performed. Inconsistency analysis is a measurement method that explains the reliability and homogeneity of answers in the questionnaire. Since expert judgment quantification is a subjective method, the judgments may not be perfect and consistent at all times. Some inconsistencies can be measured and tolerated. The acceptable inconsistency value is known as ≤ 0.1 for each respondent. If any expert has an inconsistency indicator of more than 0.1, he or she can be asked to revise his or her answers and judgments until they reach the desired levels. Inconsistency analysis can be calculated as follows: for n decision variables there will be n! orientations with vectors $r_1, r_2 \ldots, r_n$. For four decision variables (n = 4) there will be 24 orientations such as; ABCD ABDC ACBD, ACDB, . . ., DBCA. If an expert will be consistent with all his or her judgments, all the orientations will have the same relative values. However, if the expert's response is inconsistent, each orientation has slightly different relative values assigned to each decision variable. Inconsistency in the HDM methodology is calculated by using the variance of the relative values of the elements in each orientation. The formula is given in Equation 3.1, is used for the inconsistency index (Abotah and Daim, 2017; Daim et al., 2018):

$$\overline{r_i} = \left(\frac{1}{n!}\right) \sum_{j=1}^{n!} r_{ij} \tag{3.1}$$

where:

r_{ij} : relative value of the ith element in the jth orientation of an expert

r_i : mean relative value of ith element

Variance in the relative value of ith element:

$$\left(\frac{1}{n!}\right) \sum_{j=1}^{n!} \left(\bar{r}_i - r_{ij}\right)^2 \qquad i = 1,2 \ldots n \tag{3.2}$$

The inconsistency index is the variance of the expert in providing relative values for n elements (Abotah and Daim, 2017):

$$Inconsistency = \left(\frac{1}{n}\right)\sum_{i=1}^{n}\sqrt{\frac{1}{n!}\sum_{i=1}^{n!}\left(\bar{r}_i - r_{ij}\right)^2} \quad (3.3)$$

In addition to the inconsistency index, Abbas (2016) introduced new measurement method for the calculation of inconsistency, named as Root Sum of the Variance (RSV) Method. Abbas proposed new specific thresholds which were designed according to number of decision variables, and desired alpha ($\boldsymbol{\alpha}$) levels. Thus, it offers flexibility and precision in assessing the decision consistency. The formula for RSV measurement is given in Equation 3.4 (Abbas, 2016; Hogaboam, 2018):

$$Inconsistency\ (RSV) = \sqrt{\sum_{i=1}^{n}(\alpha_i)^2} \quad (3.4)$$

where:

$\boldsymbol{\alpha}_i$: the variance of the mean of the ith decision element
n : the number of decision elements

3.4.6. Disagreement Analysis

After applying inconsistency analysis, disagreement analysis is conducted because experts have different opinions or judgments, therefore possible disagreements can be observed among themselves. The group disagreement index is used to investigate any experts' disagreements, and the hierarchical agglomerative clustering (HAC) analysis is used to identify clusters and new regrouping of experts. The threshold value is selected as 0.10 for the disagreement index is used to decide on any disagreement. If the value exceeds 0.10, then it is concluded that there is disagreement among the experts. This method provides the right categorization of the expert results. The formula is Equation 3.5, is used to calculate the disagreement index for j experts for n decision variables in each panel (Abotah and Daim, 2017):

$$d = \sqrt{\frac{1}{m}\sum_{J=1}^{m}\frac{1}{n}\sum_{i=1}^{n}\left(R_i - r_{ij}\right)^2} \quad (3.5)$$

where:

d: disagreement index

R_i: group relative value of ith element

m: the number of experts

n: the number of decision elements

r_{ij}: mean relative value of the ith element for j^{th} expert

When the group disagreement value surpassed the threshold value, it indicates that a notable divergence of opinions among the experts exist. To identify specific clusters of experts who demonstrate conflicting viewpoints, the hierarchical clustering method is performed. This technique aims to generate uniform decision clusters by analysing the defined attributes of each case. The process initiates by treating every individual case as a distinct cluster. In each iteration, clusters are formed by combining cases that the arithmetic distance between the newly formed and pre-existing clusters is minimized. This step-by-step procedure is carried out repetitively until all cases are consolidated into a solitary cluster. This method allows for a clear identification of agreement and disagreement patterns among the experts (Iskin, 2014; Estep, 2017).

3.4.7. Desirability Profiles

The desirability profiles are a unique feature and outcome of the HDM tool. These curves, or functions, serve as utility indicators, assisting in evaluating technology alternatives against varying degrees of influencing factors. The desirability values, ranging from 0 to 100, were derived from expert judgments and formed the desirability curve graphs (Estep, 2017).

3.4.8. Technology Evaluation Score

After the disagreement and inconsistency analysis is completed, the local importance of all elements is combined by using an additive relationship to calculate the overall importance values for the alternatives. These importance values are ranked afterward according to the degree of contribution to the mission.

In the four-layered HDM utilized in this study, the upmost layer is built as the mission. This is followed by the second layer, which represents the perspectives. The third layer comprises the criteria, and the fourth and final layer contains the sub-criteria. In order to calculate the relative

importance of each model elements, PCM is used. These comparisons are conducted between each model elements with respect to their hierarchical position. This process is vital for determining the relative importance of each perspective within the mission, each criterion within its perspective, and each sub-criterion within its respective criterion. In this research, the calculation of the criteria and sub-criteria's relative importance to the mission is represented by the Equation 3.6:

$$S_{k,kj}^{TE} = \sum_{k=1}^{N} \sum_{jk=1}^{jk} (P_k^{TE})(C_{k,jk}^{TE}) \left(C_{s_{k,jk}}\right) \quad (3.6)$$

where

$S_{k,kj}^{TE}$= relative value of the j_kth criteria under the kth perspective with respect to Technology Evaluation (TE) score.

P_k^{TE} = relative priority of the kth perspective with respect to the TE score, k= 1, 2, 3, …K

$C_{k,jk}^{TE}$= relative contribution of the j_kth criteria under kth perspective, k=1, 2, 3, …K

$C_{s_{k,jk}}$= relative contribution of the j_kth sub-criteria under kth criteria, k=1,2,3, …K

The final TE score is calculated by the multiplication of the importance of sub-criteria and its respective desirability value and then all calculated scores are summed to obtain TE score.

$$TE_{score} = \sum_{k=1}^{N} \sum_{jk=1}^{jk} (S_{k,jk}^{TE})(D_{k,jk}) \quad (3.7)$$

$S_{k,jk}^{TE}$= relative value of the j_kth criteria under the kth perspective with respect to Technology Evaluation (TE) score.

$D_{k,jk}$= Desirability value of the technology alternative corresponding to the j_k^{th} criteria under kth perspective.

3.4.9. Sensitivity Analysis

Sensitivity analysis (SA) is used to prove the robustness of the results. The SA provides to observe the effect of any changes to any level of the hierarchy of the alternatives. In the SA, the parameters will be calculated and called the tolerance. Tolerance is "the allowable range in which a contribution value can vary without changing the rank order of decision alternatives" (Chen and Kocaoğlu, 2008; Abotah and Daim, 2017). To conduct SA, various scenarios are utilized to determine the extent of alteration in the rankings under specific circumstances. In this research,

scenario analysis is employed to evaluate the resilience and responsiveness of the model under various and extreme conditions. In each distinct scenario, a single perspective is elevated to its maximum score to examine the impact of that factor assuming it becomes the most significant element in actual practice (Giadedi, 2020).

4. RESULTS AND DATA ANALYSIS

This section provides a detailed information for the validation study of the model, the quantification of its constituent elements and the creation of desirability curves that form an essential component of the technology assessment framework designed for decision-makers.

4.1. Initial Model

Through this research, the model was developed based on a thorough literature review that established key criteria for evaluating low carbon energy technologies in the oil and gas industry. This decision-making framework considers a range of criteria —social, economic, technical, environmental, and political—each broken down into detailed sub-criteria for in-depth evaluation. Figure 4.1 presents the initial model, which serves as a systematic and adaptable tool that assists stakeholders in weighing and prioritizing technologies amidst various, sometimes conflicting, considerations. The design of the model, as depicted in the figure, aids decision-makers in navigating through the evaluation process with clarity and impartiality.

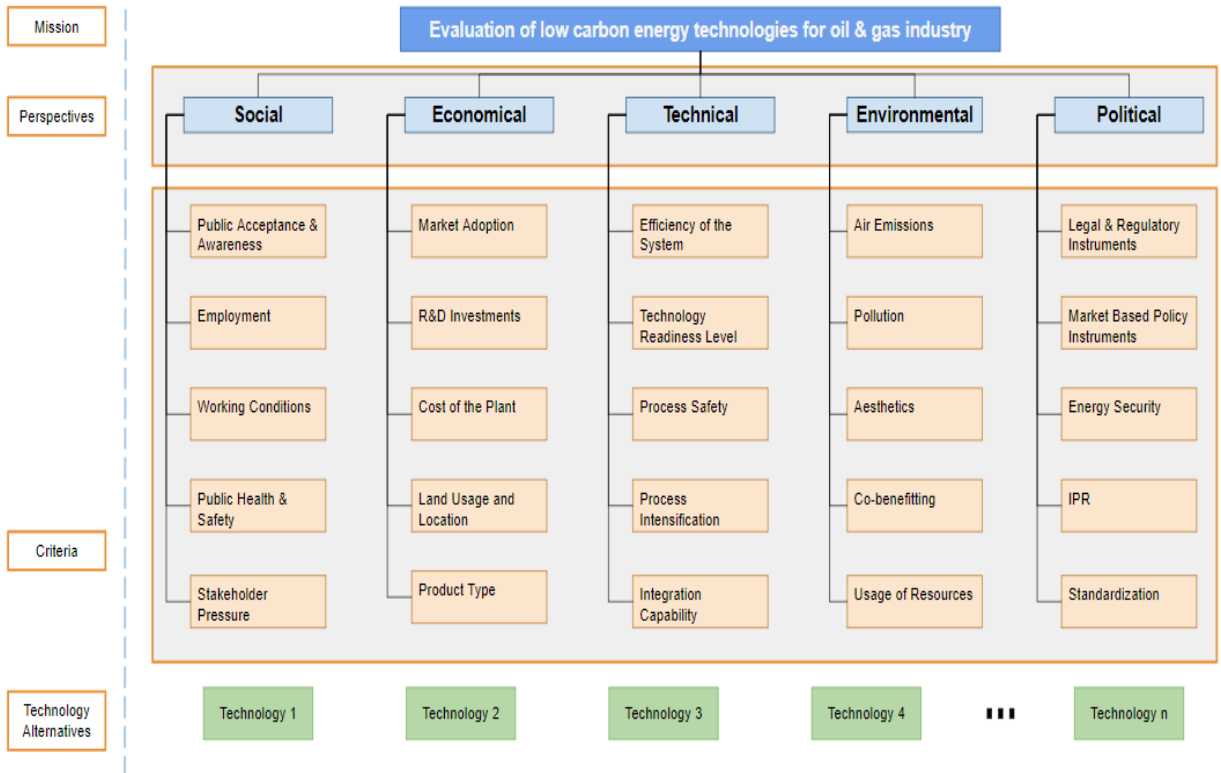

Figure 4.1. Initial Version of Model.

4.2. Expert Panels Formation

Expert identification is the most critical step of the study since the selected experts make the judgments for the technology assessment criteria and the research results directly reflect their opinions and knowledge. Therefore, the potential experts are investigated in detail with respect to their scientific backgrounds, publications, projects, and job experiences. Bibliometric analysis and snowball sampling were used for the expert identification. The consent form and invitation letter (seen in Appendix A and Appendix B) were sent to Subject matter experts (SMEs) and then participated SMEs were distributed to the panels with respect to their academic and professional experience.

Expert panels are categorized into three groups: panels for model validation, panels for model quantification with pairwise comparison, and panels for quantification of desirability curves, as shown in Table 4.1. A total of 188 experts from the oil and gas industry, research institutions, and associations were distributed on 13 panels. According to their field of expertise and willingness to participate, some experts attend more than one panel. The responses are collected from SMEs via Qualtrics web-based software. Online interviews and e-mailing are used for further discussion and feedback for the case study application.

Table 4.1. Expert panel distribution.

No.	Panel Name	Panel Description
P1	Expert Panel 1	Validation of perspectives
P2	Expert Panel 2	Validation of the criteria (social perspective)
P3	Expert Panel 3	Validation of the criteria (economic perspective)
P4	Expert Panel 4	Validation of the criteria (technical perspective)
P5	Expert Panel 5	Validation of the criteria (environmental perspective)
P6	Expert Panel 6	Validation of the criteria (political perspective)
P7	Expert Panel 7	Quantification of perspectives
P8	Expert Panel 8	Quantification of the criteria (social perspective)
P9	Expert Panel 9	Quantification of the criteria (economic perspective)
P10	Expert Panel 10	Quantification of the criteria (technical perspective)
P11	Expert Panel 11	Quantification of the criteria (environmental perspective)
P12	Expert Panel 12	Quantification of the criteria (political perspective)
P13	Expert Panel 13	Quantification of desirability curves

4.3. HDM Validation Results

The validation of the model was imperative to confirm that all critical aspects encapsulated with a comprehensive evaluation framework, thereby the decision makers ensure the model's compatibleness to real-world applications. To this end, domain experts from the oil and gas industry and innovators in low carbon energy technology have participated to validate the model elements. 41 domain experts from industry and academia participated in the validation study. The extensive information about the experts and panel distribution for HDM validation phase is given in the Table 4.2. These professionals were tasked with the evaluation of each sub-criterion, criterion, and perspective. A model element was retained only if it received validation from a minimum of 75% of the panel members, a benchmark informed by prior studies (Lavoie, 2019; Barham, 2019; Giadedi, 2020; Giadedi and Daim, 2021). The experts were also solicited for contributions regarding potential additions of new sub-criteria and criteria deemed critical to the model's comprehensiveness.

Table 4.2. Expert list for HDM Validation Study.

Expert No.	Title/Position	Organization Type	Country	P1	P2	P3	P4	P5	P6
Expert 01	R&D Director	Oil & Gas	Spain	X					
Expert 02	Projects & Technical Consulting Manager	Technology Provider	Egypt	X					
Expert 03	Chief Executive	Oil & Gas	Indonesia	X					
Expert 04	R&D Manager	Oil & Gas	Turkey	X					
Expert 05	Professor in Department of Human Ecology	Research Institution	USA	X					
Expert 06	Innovation Strategy Vice President	Technology Provider	Italy	X					
Expert 07	Chief Technology Officer	Oil & Gas	Turkey	X					
Expert 08	Power to X Director	Technology Provider	Belgium	X					
Expert 09	Professor in Public Relations Department	Research Institution	Romania		X				
Expert 10	Senior Researcher	Research Institution	Italy		X			X	
Expert 11	Principal Research Scientist	Research Institution	USA		X				
Expert 12	Associate Professor of Social Studies	Research Institution	Norway		X				
Expert 13	Researcher in Energy Policy Research Group	Research Institution	UK		X				X
Expert 14	Lead Advisor for Climate Technology	Others	USA		X				
Expert 15	Head of Downstream Innovation Team	Oil & Gas	Austria			X			
Expert 16	Procurement Advisor	Oil & Gas	UK			X			
Expert 17	Strategy Business Development Manager	Oil & Gas	Turkey			X			
Expert 18	Head of Energy and Environment Division	Association	France			X			
Expert 19	Economist	Governmental Organization	Norway			X			
Expert 20	Energy Transition Science Executive	Association	Belgium			X			
Expert 21	R&D Project Manager	Oil & Gas	Italy				X		
Expert 22	Principal Scientist	Oil & Gas	Norway				X		
Expert 23	Power Plant Manager	Oil & Gas	Portugal				X		
Expert 24	New Energy Projects Manager	Technology Provider	Portugal				X		
Expert 25	Research Scientist	Research Institution	Norway				X		
Expert 26	NET Power Systems Integration Leader	Technology Provider	Italy			X	X		
Expert 27	Director	Technology Provider	USA				X		
Expert 28	Professor of Systems for Energy and Environment	Research Institution	Italy				X		
Expert 29	Solar Energy R&D Knowledge Owner	Oil & Gas	Germany					X	
Expert 30	Product Design Advisor	Oil & Gas	Spain				X	X	
Expert 31	Strategy Consultant	Research Institution	The Netherlands					X	
Expert 32	Project Management Analyst	Oil & Gas	Nigeria					X	
Expert 33	Director	Association	Belgium					X	
Expert 34	Environmental Advisor	Oil & Gas	United Arab Emirates					X	
Expert 35	Policy Analyst	Association	Portugal						X
Expert 36	Principal Advisor	Governmental Organization	Greece						X
Expert 37	Head of EU Framework Programmes	Governmental Organization	Turkey						X
Expert 38	Assistant Professor of Environmental Planning	Research Institution	Sweden						X
Expert 39	Lawyer and Economist	Others	Norway						X
Expert 40	Researcher	Research Institution	The Netherlands						X
Expert 41	Sustainable Shipping Policy Officer	Association	Belgium						X

4.3.1. Perspective Level Validation Results

Eight experts participated in validation of the model perspectives. All experts, as shown in Figure 4.2., agreed on the identified perspectives.

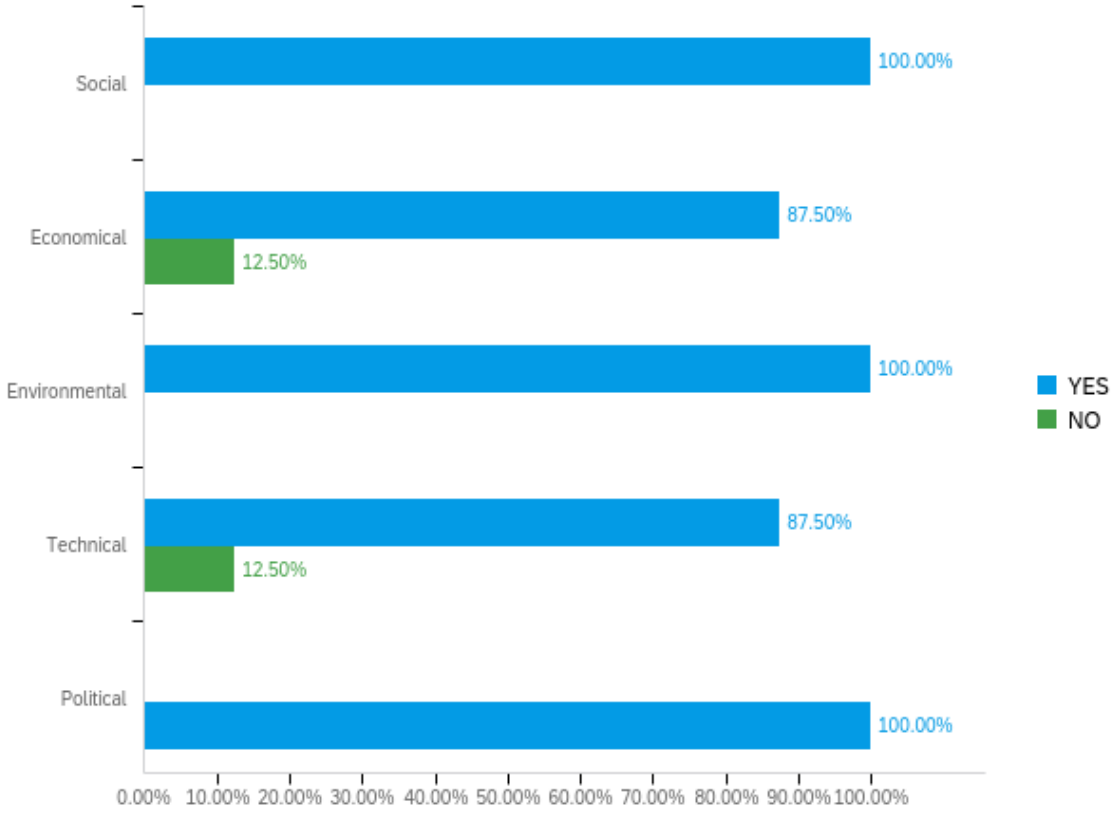

Figure 4.2. Perspective level validation results.

4.3.2. Validation Results of Social Criteria

Six experts participated in the validation of social criteria. All experts, except one, agreed on the identified factors as shown in Figure 4.3.

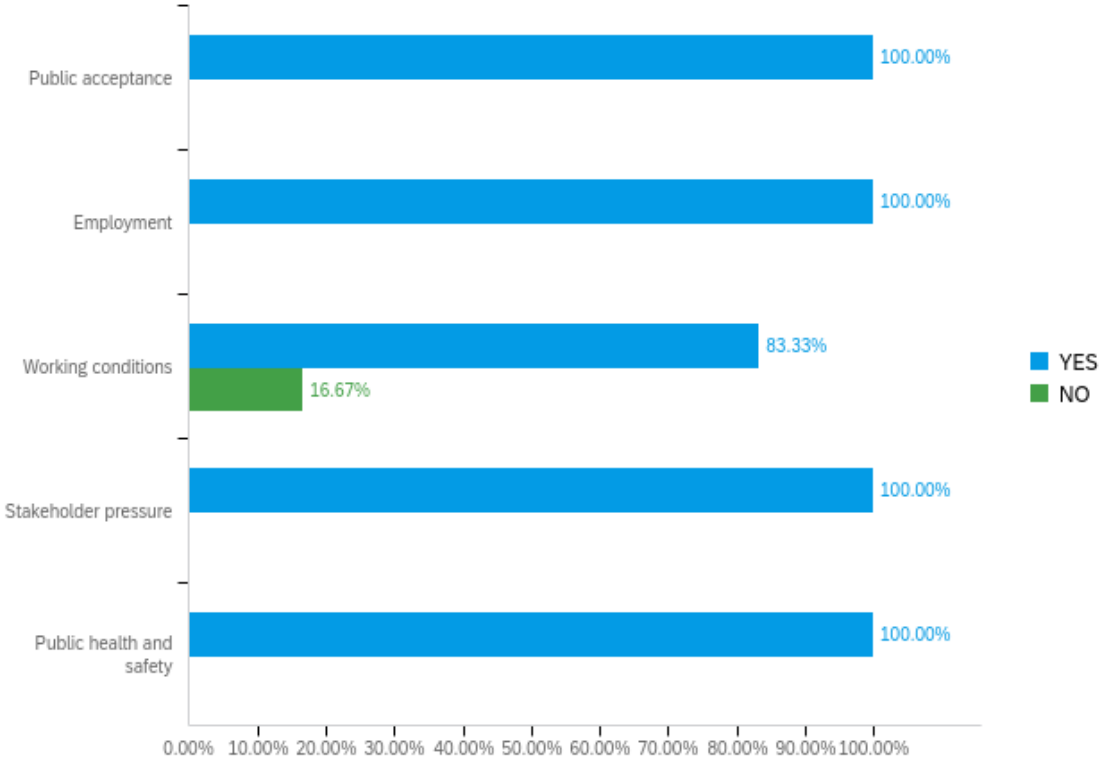

Figure 4.3. Validation of social criteria.

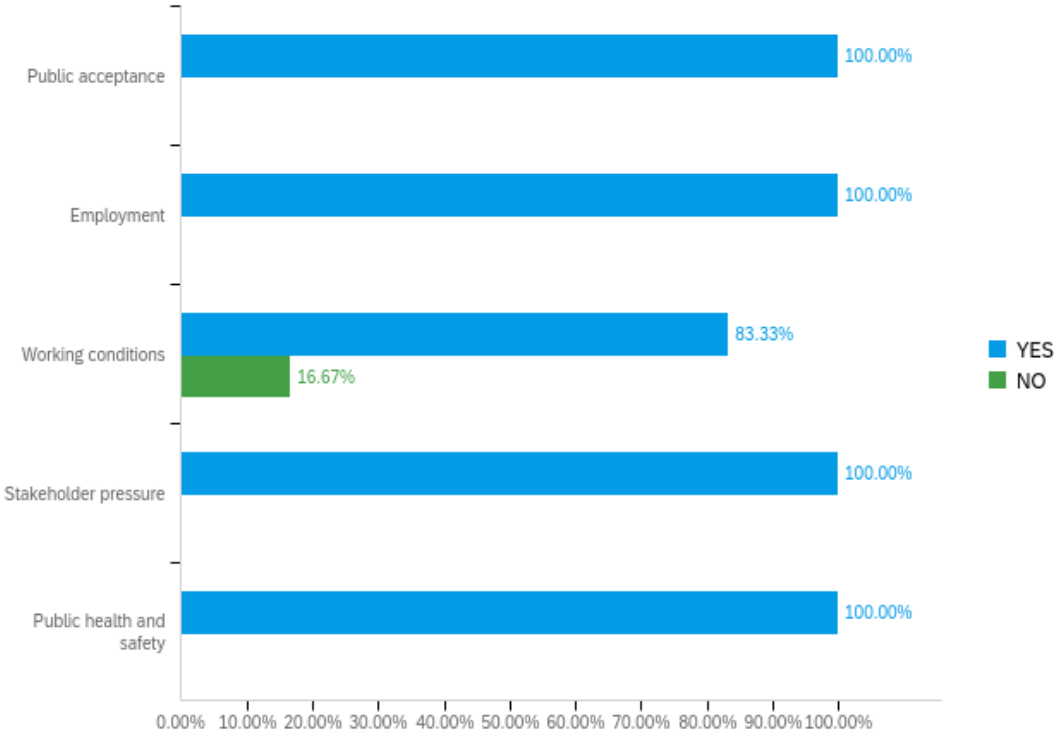

Figure 4.4. Validation results of "Public Awareness" sub-criteria.

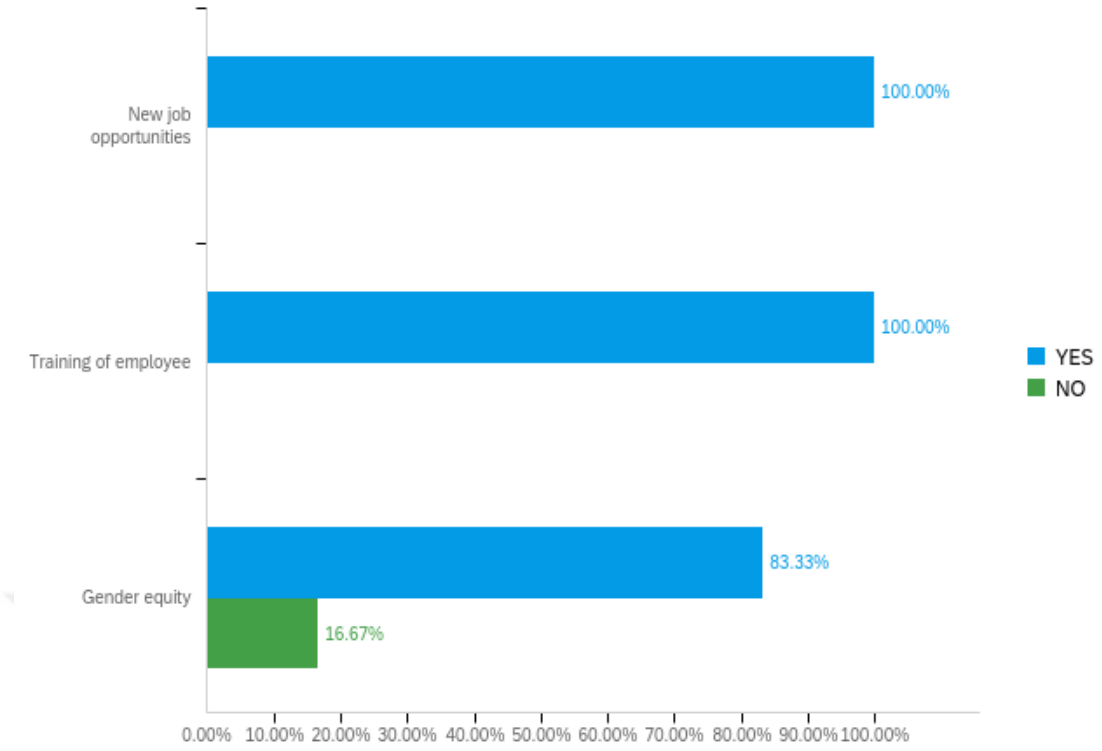

Figure 4.5. Validation results of "employment" sub-criteria.

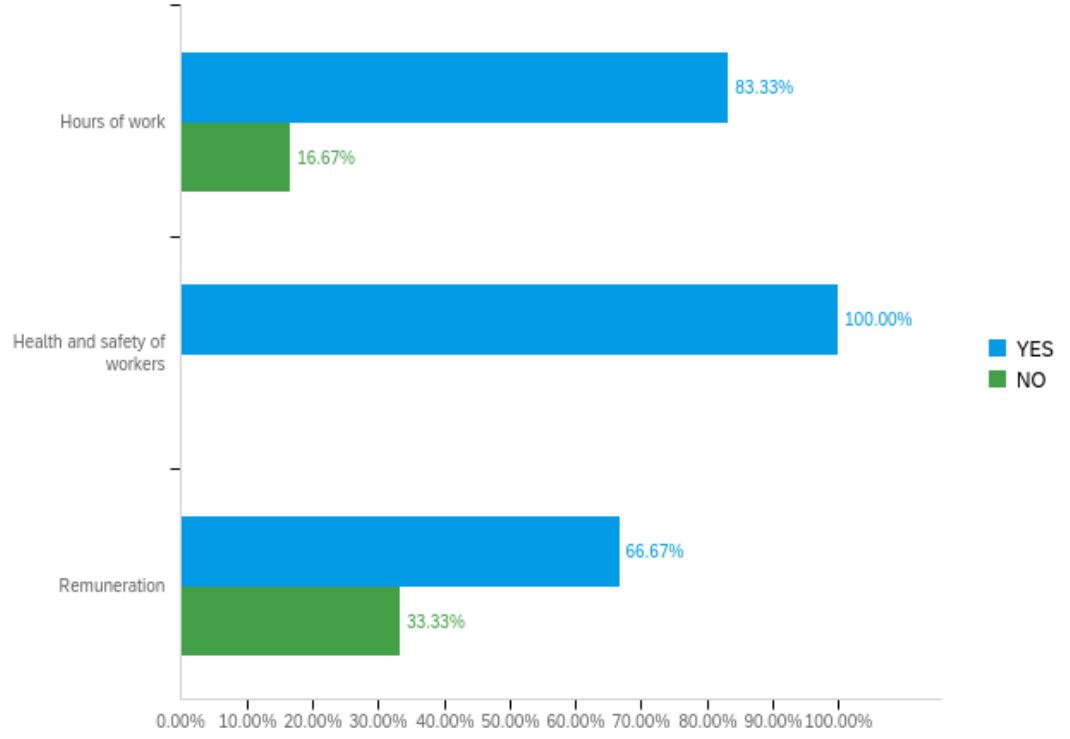

Figure 4.6. Validation results of "working conditions" sub-criteria.

Although experts agreed that all criteria and sub-criteria under the social perspective should exist in the model, they have commented on some sub-criteria. They stated that lack of knowledge and public awareness are on the same continuum (opposed). Public acceptance correlates with

awareness, for that reason lack of knowledge should be removed. The sub-criteria related to lack of knowledge will be removed from the final model. With regard to working conditions, they suggest that it might be more interesting or important to understand the potential opportunities for jobs, rather than working hours and remuneration. They proposed the removal of remuneration. The sub-criteria related to remuneration will be removed from the final model. The validation results of social sub-criteria are presented in Figure 4.4, Figure 4.5, Figure 4.6.

4.3.3. Validation Results of Economic Criteria

Seven experts have participated in the validation study of economic criteria. All experts agreed that the identified criteria and sub-criteria in the economic perspective should exist in the model. One expert suggested that instead of product costs and feedstock costs, the feasibility may cover the identified sub-criteria under the criteria of "Cost of Plant". The validation results can be shown in Figure 4.7, Figure 4.8, Figure 4.9, Figure 4.10.

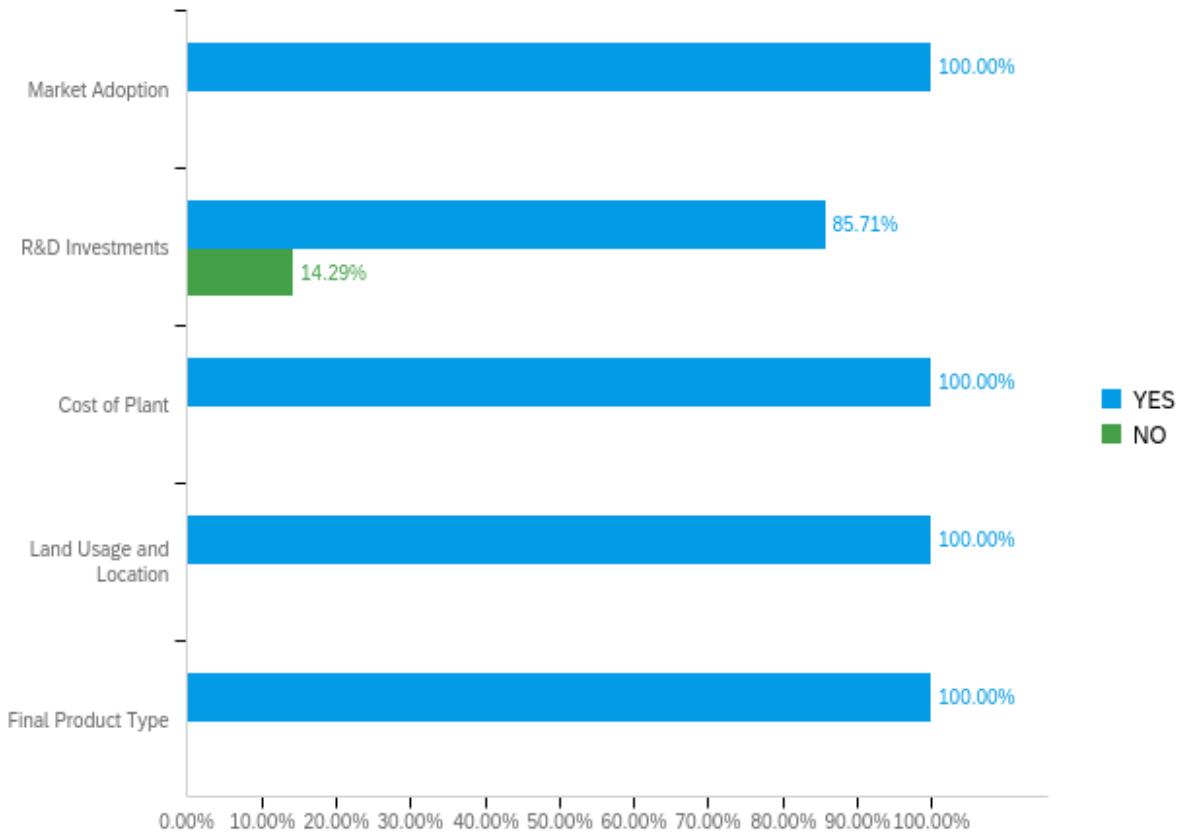

Figure 4.7. Validation results of economic perspective.

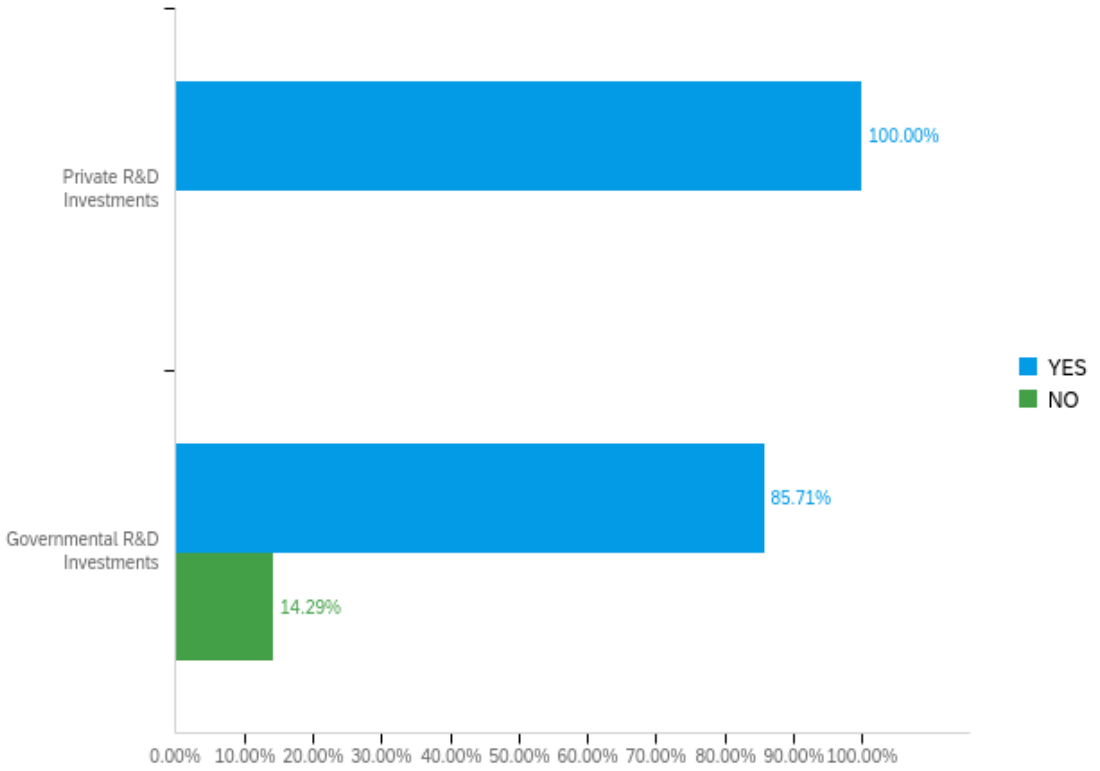

Figure 4.8. Validation results of "R&D investments" sub-criteria.

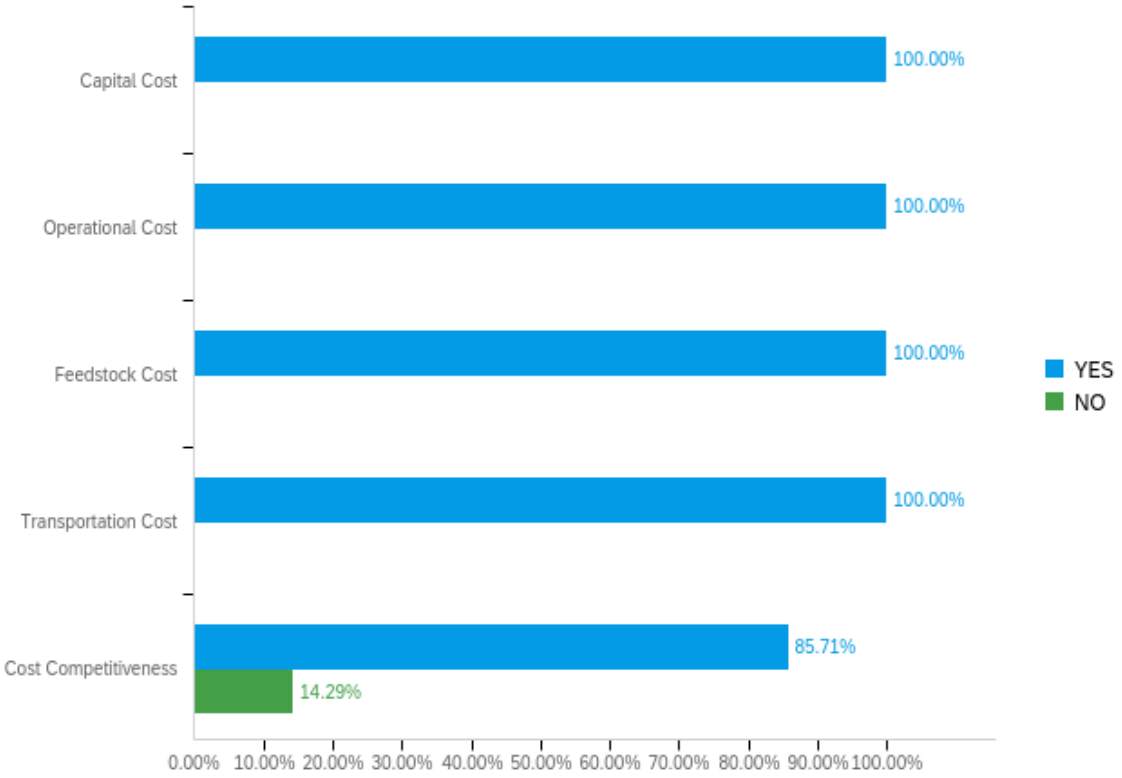

Figure 4.9. Validation results of "Cost of plant" sub-criteria.

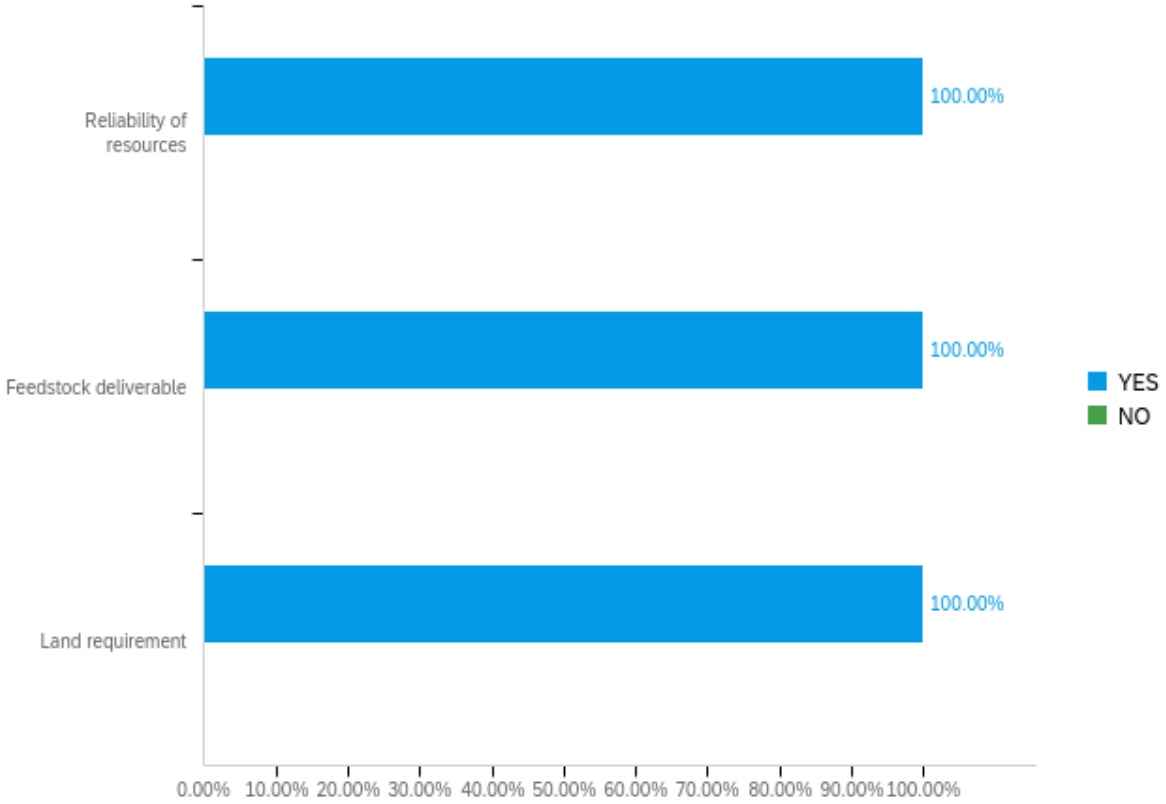

Figure 4.10. Validation results of "Land usage and location" sub-criteria.

4.3.4. Validation Results of Technical Criteria

Nine experts have participated in the validation study of technical perspectives so far. Three experts suggest that the criterion of process intensification should be removed from technical perspectives as shown in Figure 4.11. This criterion will be removed from the final model.

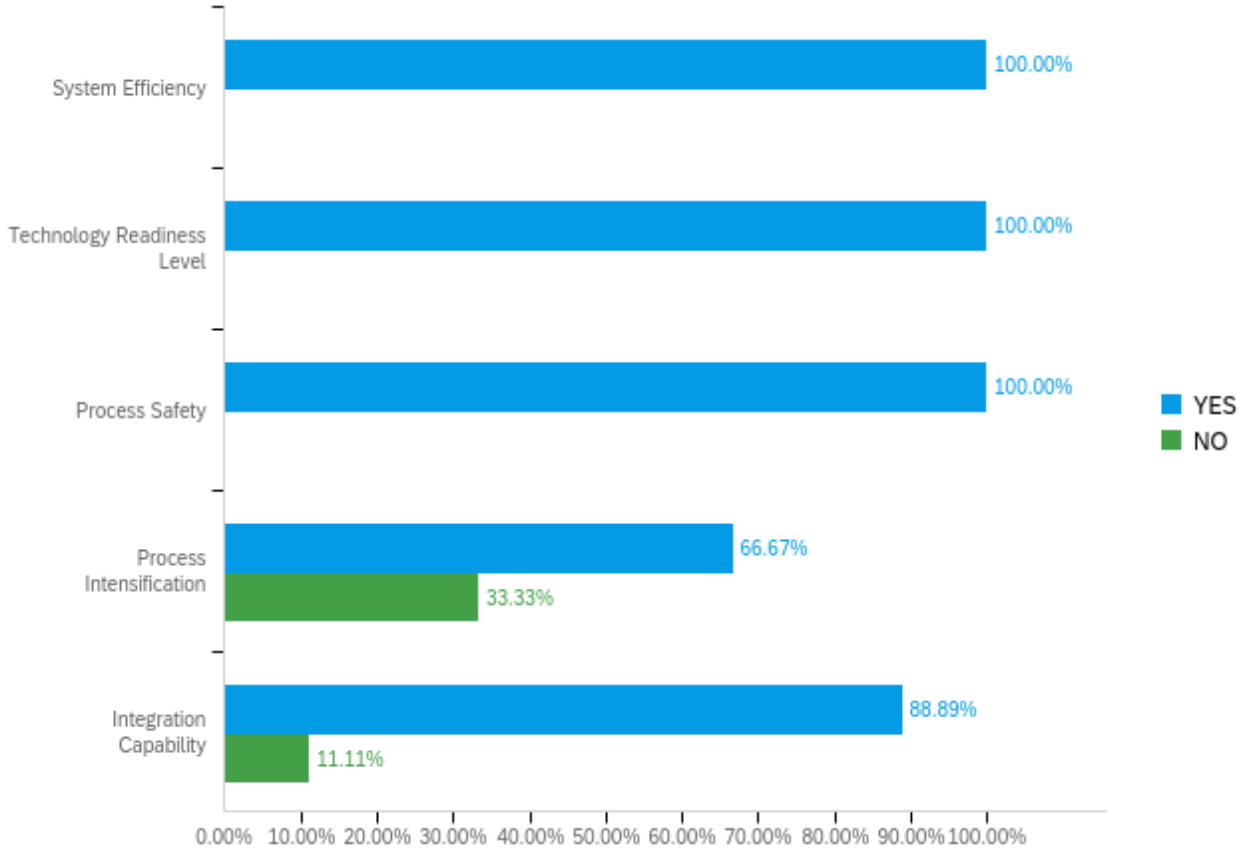

Figure 4.11. Validation results of technical perspective.

Three experts suggested that the sub-criterion of “materials of equipment” should be removed from the model. Two experts suggested that the sub-criteria of “ease of maintenance” should be removed from the model. Also, experts suggested that “risk” may be added to the criterion of process safety because the risk depends on the probability of the incident and the impact of the incident. The validation results of technical sub-criteria are presented in Figure 4.12, Figure 4.13.

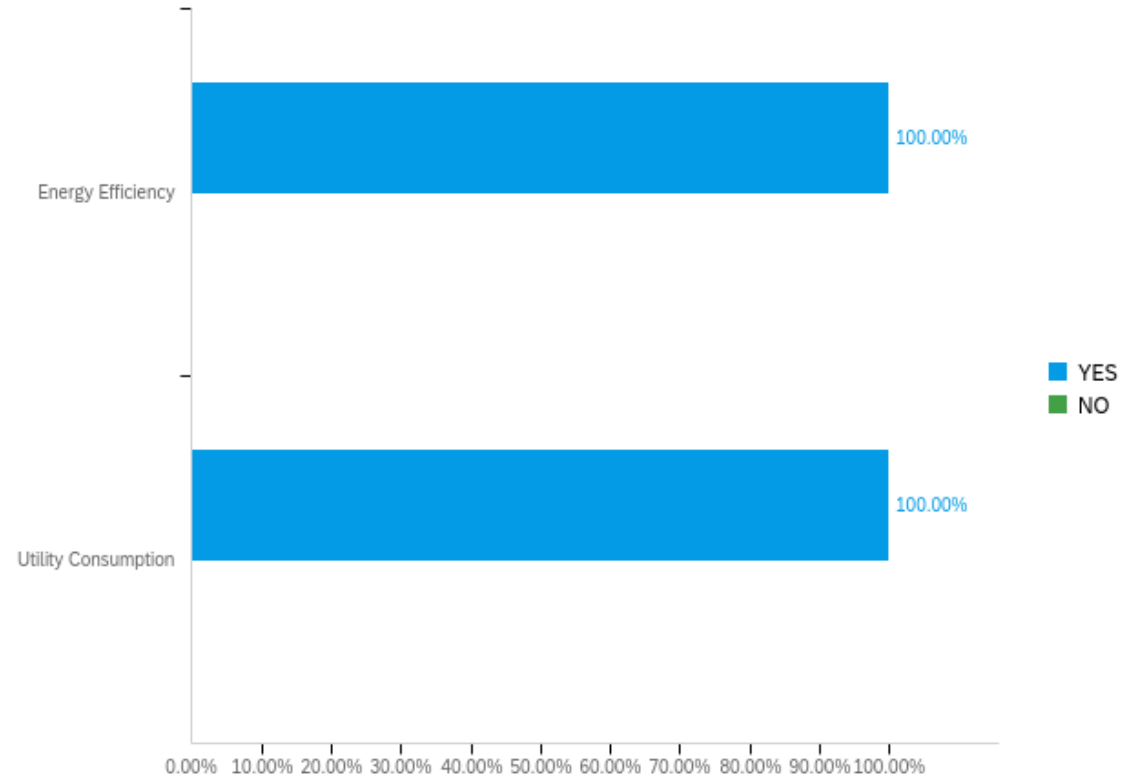

Figure 4.12. Validation results of "System Efficiency" sub-criteria.

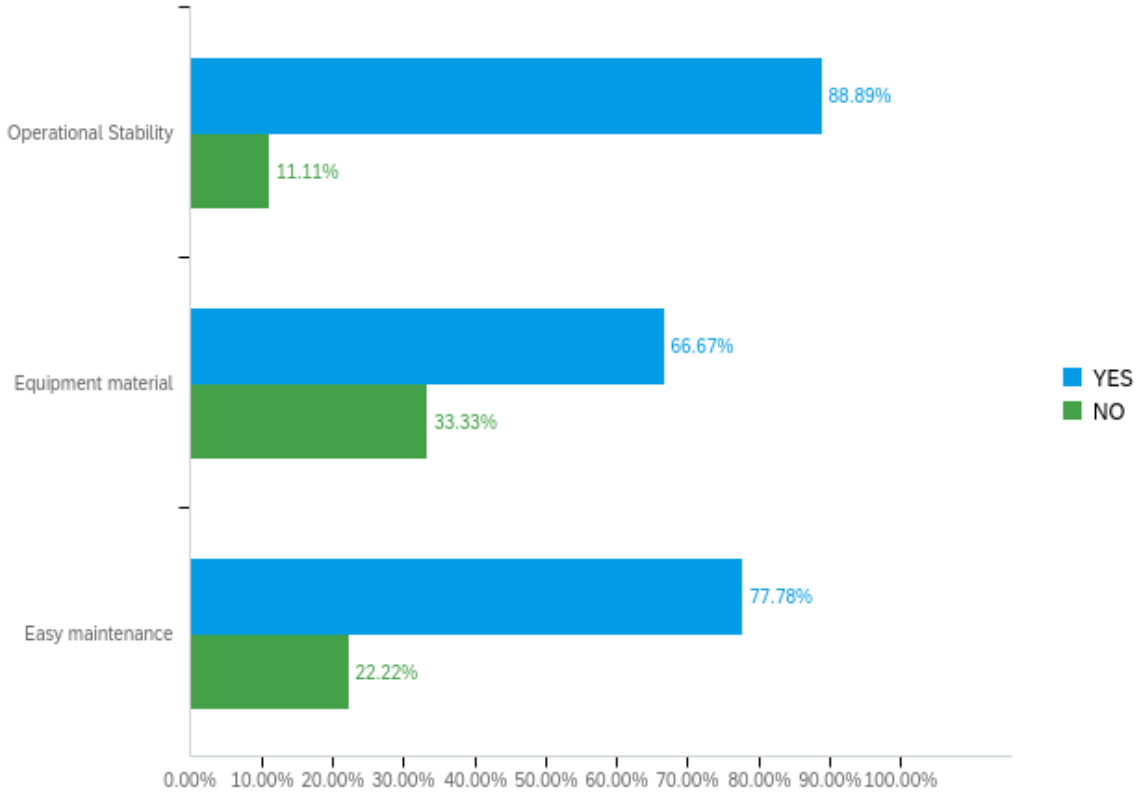

Figure 4.13. Validation results of "Process Safety" sub-criteria.

4.3.5. Validation Results of Environmental Criteria

Seven experts participated in the validation study of environmental perspectives. All experts agreed that the identified criteria except the criterion of “aesthetics” in the environmental perspective should exist in the model. Only, two experts suggests that aesthetics and co-benefitting should be removed from environmental perspectives as shown in Figure 4.14.

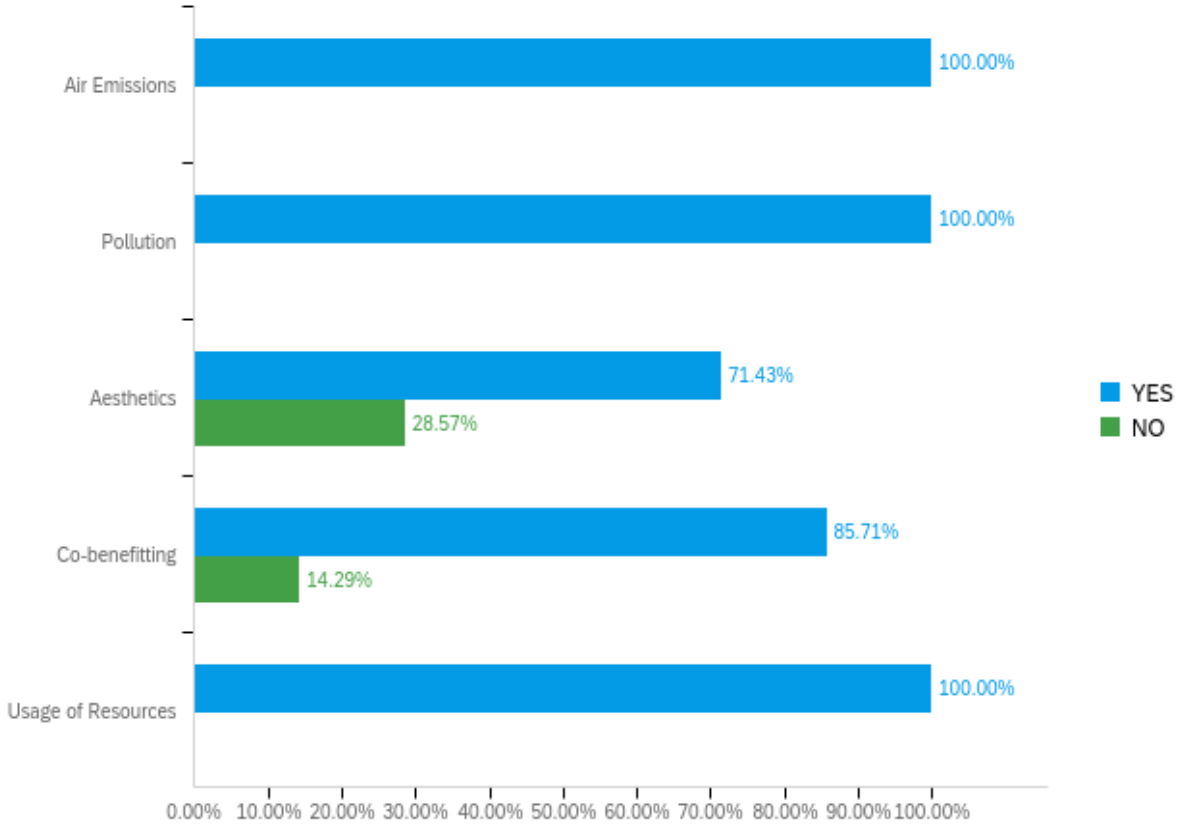

Figure 4.14. Validation results of environmental perspective.

According to the experts' opinions, the odor should be removed from the model. Also, they stated that the sub-criterion of noise is irrelevant to aesthetics and should be removed from the model. Effect on flora and fauna should be added to the environmental perspective because the presence and impact of technological activities on protected species are also important for the environmental perspective. However, since the criteria of pollution and air emission cover the topic of flora and fauna in terms of air pollution, water pollution, soil, and groundwater pollution. The suggested criterion was not added into the model. The validation results of environmental sub-criteria are presented in Figure 4.15, Figure 4.16, Figure 4.17, Figure 4.18.

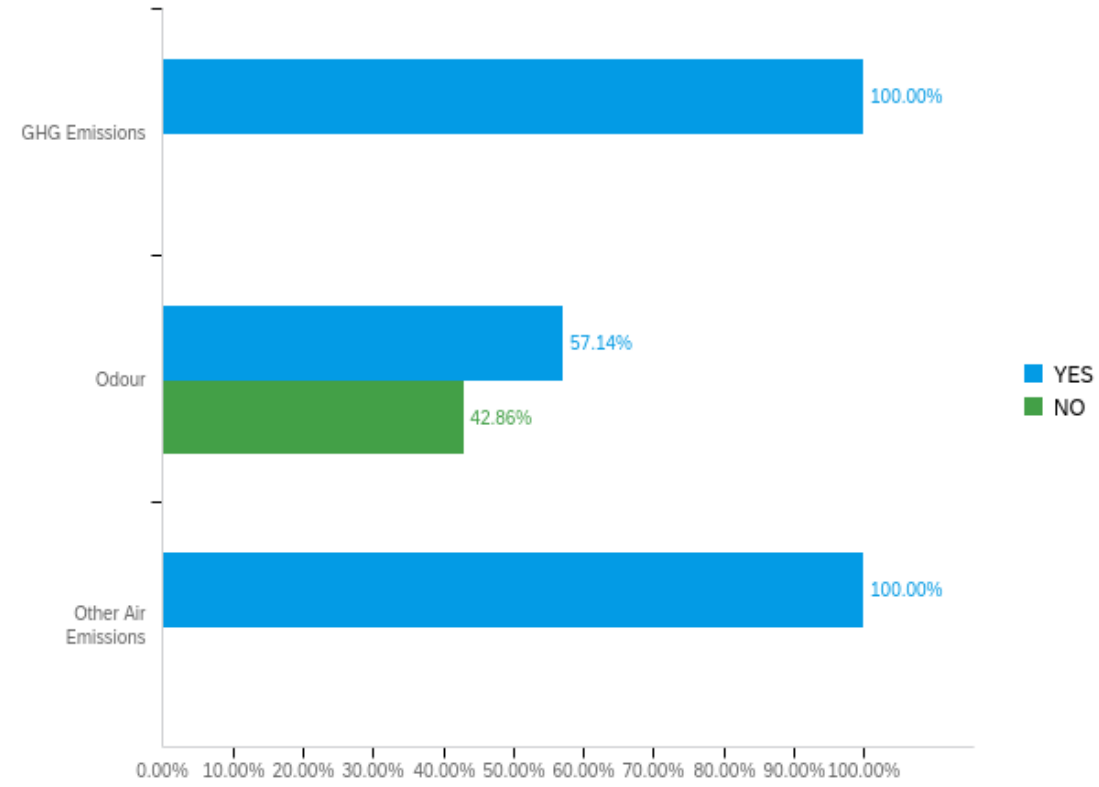

Figure 4.15. Validation results of "Air emissions" sub-criteria.

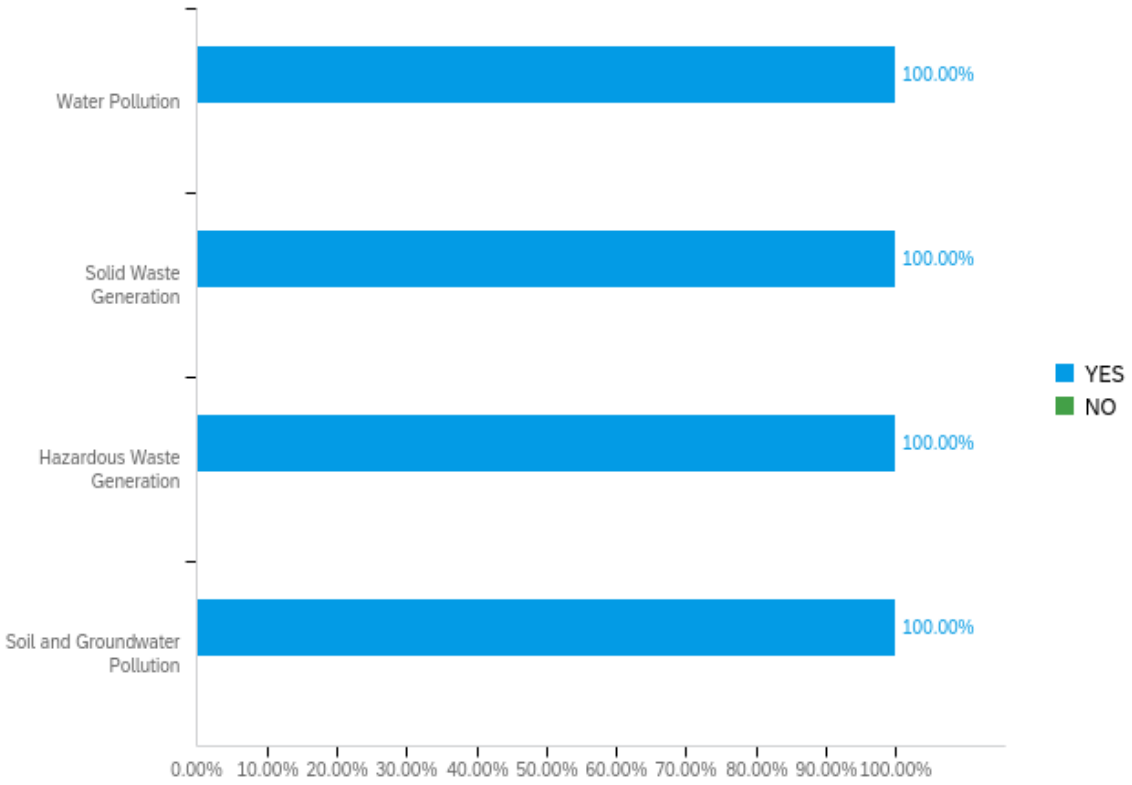

Figure 4.16. Validation results of "Pollution" sub-criteria.

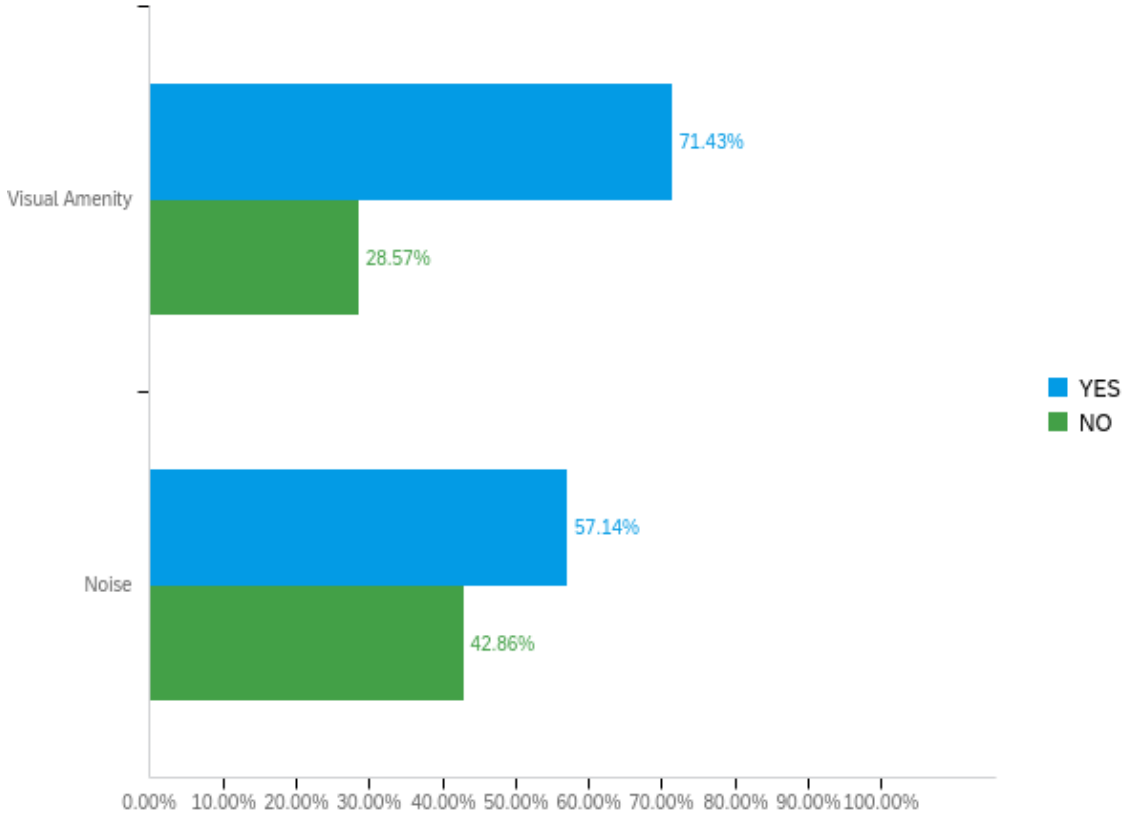

Figure 4.17. Validation results of "Aesthetics" sub-criteria.

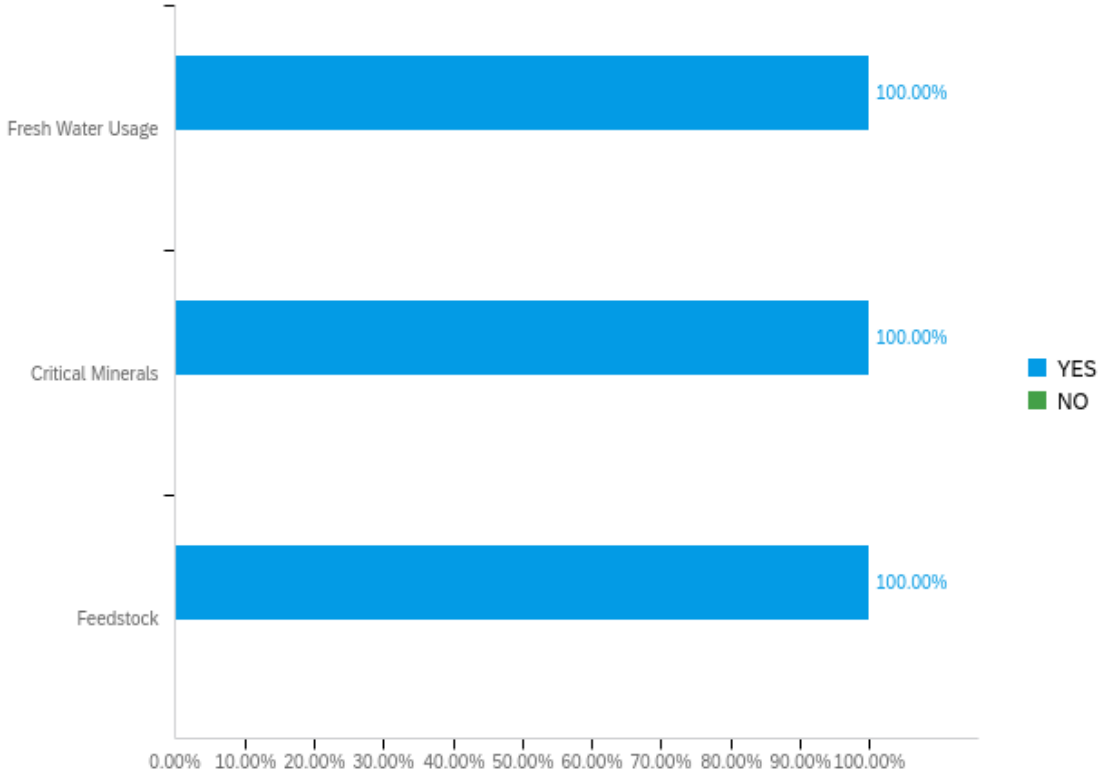

Figure 4.18. Validation results of "Usage of Resources" sub-criteria.

4.3.6. Validation Results of Political Criteria

Eight experts participated in the validation study of political perspectives. All experts agreed that legal and regulatory instruments should exist from the political perspective. On the other hand, all experts stated that IPR and standardization factors should be removed from political perspectives. One expert suggested that energy security and MBIs should not exist from the political perspective. Also, ETS should be removed from the factor of MBIs. The validation results can be shown in Figure 4.19, Figure 4.20, Figure 4.21.

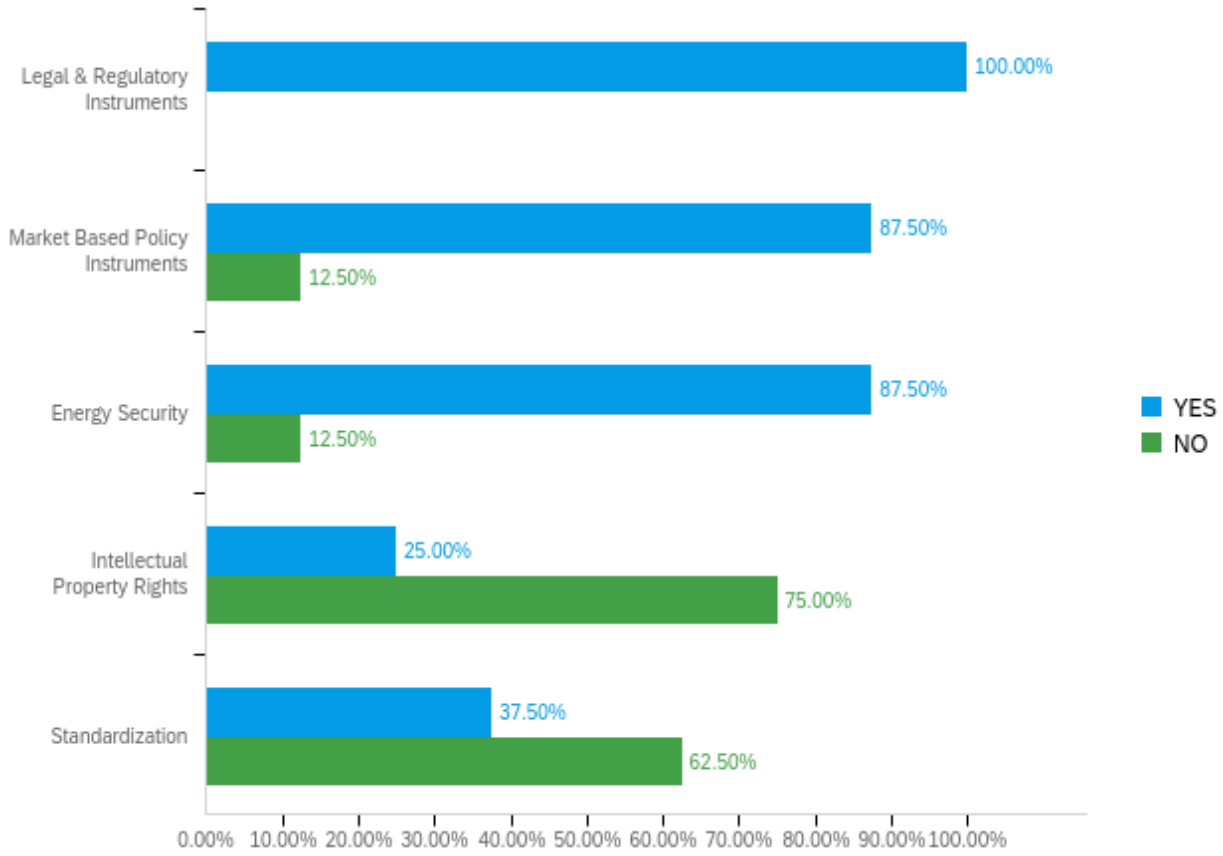

Figure 4.19. Validation results of political perspective.

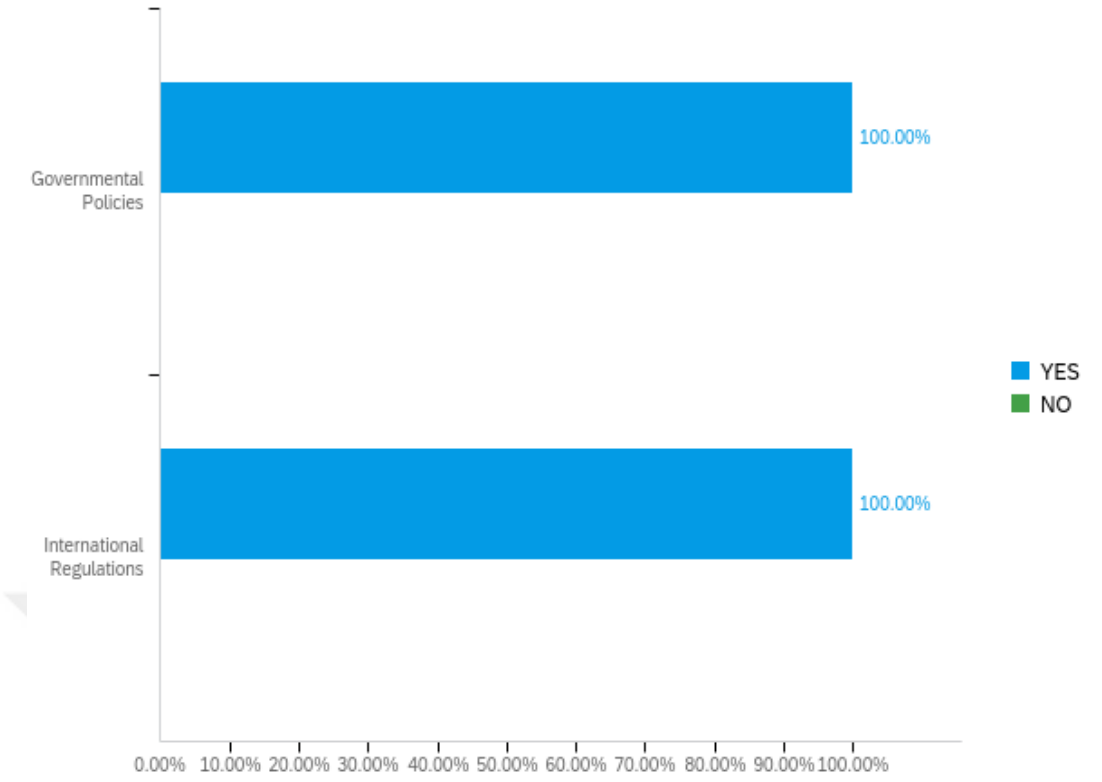

Figure 4.20. Validation results of "legal and regulatory policy instruments" sub-criteria.

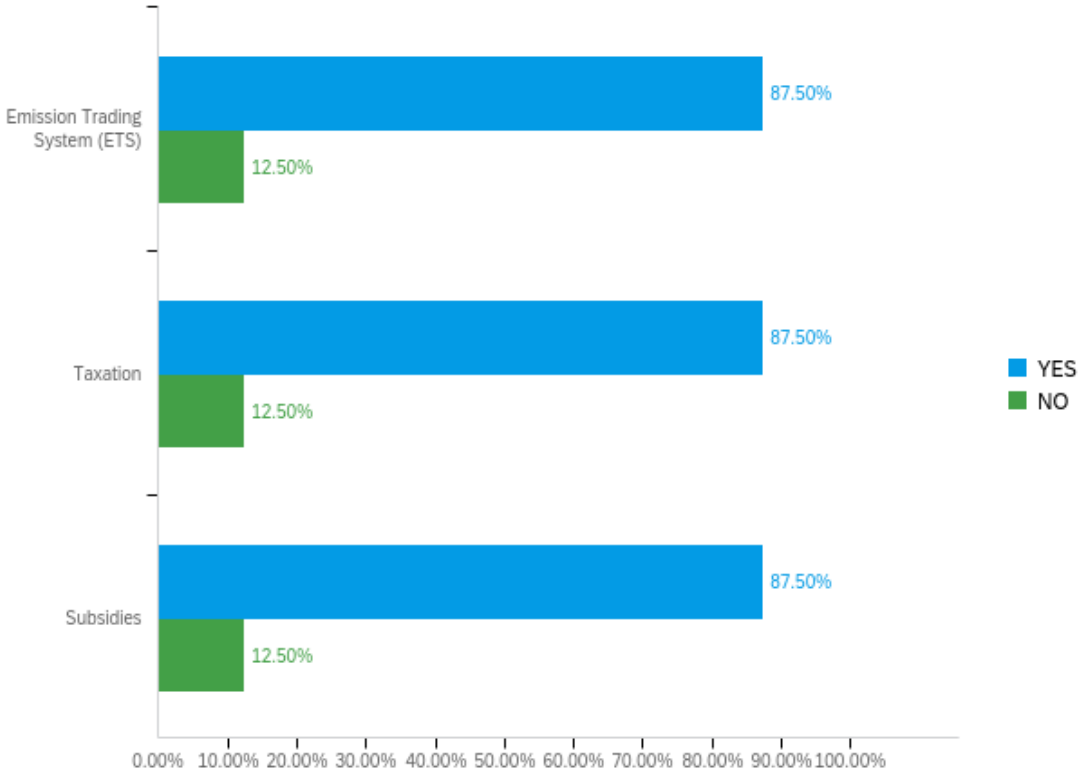

Figure 4.21. Validation results of "market-based policy instruments" sub-criteria.

4.3.7. Validated Model

In the validation phase, 41 experts participated, distributed across six expert panels as shown in Table 4.2. Their collective expertise facilitated a series of iterative refinements to the model. Based on their validation and collective feedback, certain criteria and sub-criteria were recalibrated or removed due to their relative acceptance rates. For instance, the 'Lack of Knowledge' sub-criterion was eliminated from the 'Public Awareness' criteria. Similarly, the 'Remuneration' sub-criterion was excised from the 'Working Conditions' criteria. From a technical perspective, the 'Process Intensification' criterion and the 'Equipment Material' sub-criterion were omitted. The 'Aesthetics' criterion and the 'Odor' sub-criterion were removed from environmental perspectives. The criteria pertaining to 'Intellectual Property Rights' and 'Standardization' were also excluded from the political perspectives under the model. The refined model was thus constituted of five perspectives, encompassing 21 criteria and 35 sub-criteria as seen in Appendix C. Figure 4.22 illustrates the validated model, which is designed to facilitate the evaluation of low-carbon energy alternatives for deployment in the oil and gas industry.

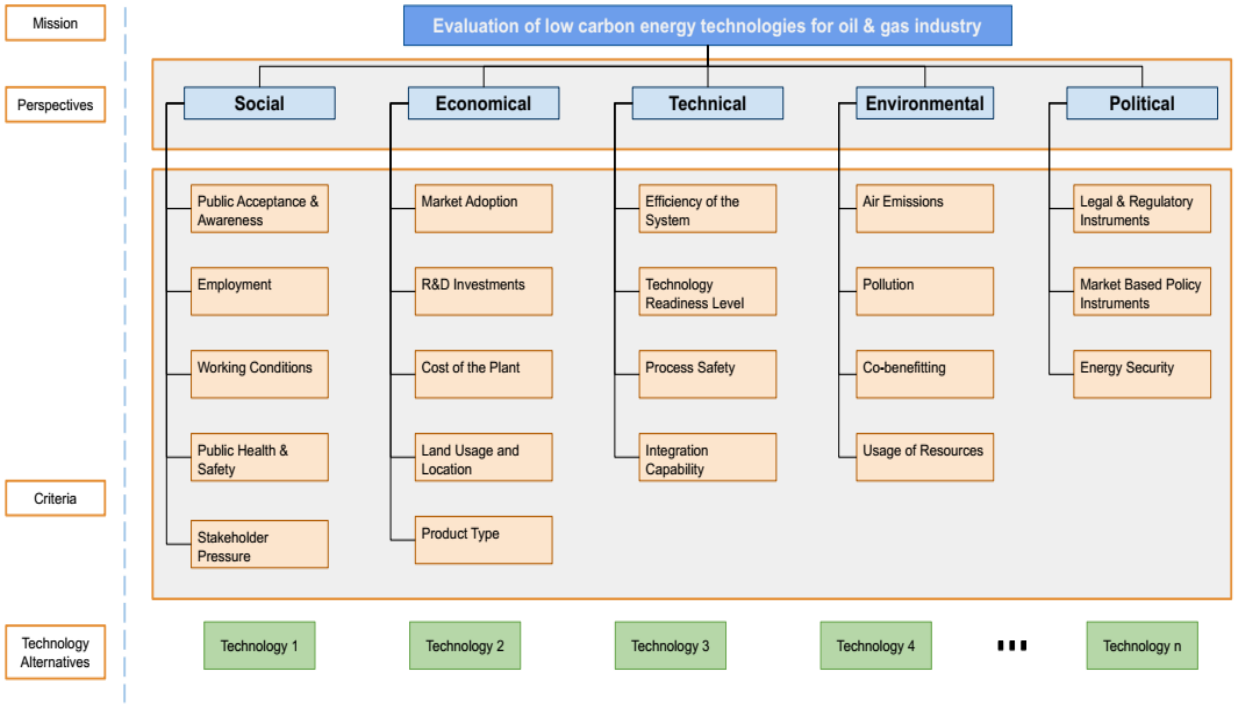

Figure 4.22. Validated model.

4.4. HDM Quantification Results

In this subsequent section, the findings derived from the quantification phase, are systematically presented. Six expert panels were formed in the quantification phase, and these are

the quantification of perspectives, quantification of social criteria, quantification of economic criteria, quantification of technical criteria, quantification of environmental criteria, and quantification of political criteria. The data collection for the quantification study was performed by QualtricsXM web-based survey program and the outcomes of the quantification phase were obtained by using HDM software. Input screens of HDM software were seen in Appendix C. A predetermined inconsistency threshold value of 0.1 was applied for this study in order to detect inconsistent responses (Gibson, 2016; Estep, 2017; Khanam, 2020). In the expert answers where inconsistencies exceeded the aforementioned threshold value, a more in-depth analysis was applied by using the RSV method. The RSV method was developed by Abbas (2016), enabling to examination of the inconsistency with respect to the number of variables and providing more flexibility for the inconsistency analysis.

The disagreement analysis was performed by using HDM software and the same threshold value 0.1 was applied to determine the group disagreements. In order to solve the disagreements in the expert panel, clustering analysis was performed and cluster dendrograms were generated as a visual representation that facilitated a deeper understanding of decisions.

4.4.1. Perspective Level Quantification Results

The experts in Expert Panel 7, were asked to compare each perspective to the research mission which is the evaluation of low-carbon energy technologies for the oil and gas industry. The arithmetic means of the relative importance of perspectives are shown in the following Figure 4.23. The results show that the environmental perspective has the most significant importance to the mission, with a weight of 0.234. This perspective examines the environmental impact of low-carbon energy technologies implementation in the oil and gas industry. Next in importance is the economic perspective at 0.223, followed by the technical perspective at 0.211. The political and social perspectives are less emphasized, with weights of 0.189 and 0.144, respectively.

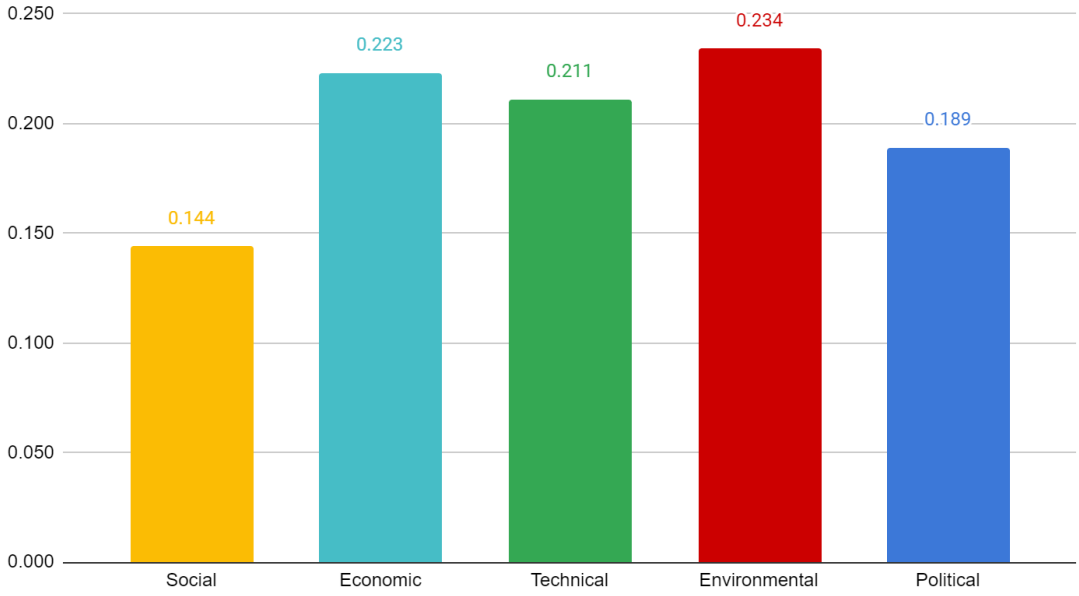

Figure 4.23. The importance weights of perspectives in the model

Expert Panel 7 was formed by 22 participants. Each expert examined the relative importance of perspectives to the mission and their results are tabulated in the following Table 4.3. Only consistent responses were considered in determining the relative significance of perspectives. The responses of 20 experts were consistent and inconsistency analysis results were below the threshold value of 0.10. 2 experts; Expert 43, and Expert 59, had inconsistency levels above the threshold value of 0.10 and the RSV method was applied. According to Abbas (2016), the threshold value of acceptable inconsistency for five decision variables at 85 % confidence interval is 0.3789 (Abbas, 2016). RSV values of Expert 43 and Expert 59 were 0.28 and 0.35, respectively. Since the RSV values of the two experts were less than 0.3789, we assume that the responses of these two experts were assumed as consistent. The data of Expert 43 and Expert 59 are included in the data repository.

Table 4.3. Perspectives level quantification results.

Expert No.	PERSPECTIVES LEVEL					
	Social	Economic	Technical	Environmental	Political	Inconsistency
Expert 50	0.19	0.17	0.23	0.27	0.14	0.01
Expert 44	0.28	0.15	0.24	0.19	0.14	0.01
Expert 46	0.02	0.33	0.15	0.08	0.43	0.04
Expert 47	0.18	0.27	0.17	0.17	0.20	0.02
Expert 48	0.05	0.05	0.22	0.27	0.41	0.08
Expert 55	0.14	0.16	0.23	0.2	0.27	0.07
Expert 42	0.20	0.18	0.18	0.17	0.27	0.02
Expert 54	0.09	0.14	0.26	0.27	0.24	0.06
Expert 57	0.05	0.42	0.25	0.13	0.15	0.07
Expert 45	0.18	0.20	0.14	0.26	0.21	0.01
Expert 51	0.15	0.34	0.10	0.18	0.24	0.00
Expert 53	0.21	0.15	0.25	0.27	0.13	0.00
Expert 49	0.07	0.31	0.41	0.13	0.08	0.05
Expert 52	0.17	0.17	0.13	0.47	0.07	0.02
Expert 43	0.23	0.08	0.18	0.32	0.19	0.10
Expert 58	0.05	0.22	0.37	0.26	0.10	0.02
Expert 59	0.19	0.46	0.09	0.20	0.06	0.15
Expert 56	0.12	0.17	0.18	0.42	0.12	0.04
Expert 154	0.21	0.15	0.32	0.22	0.10	0.00
Expert 155	0.19	0.26	0.13	0.12	0.30	0.04
Expert 157	0.05	0.24	0.23	0.24	0.24	0.03
Expert 158	0.15	0.28	0.19	0.30	0.07	0.05
Mean	0.144	0.223	0.211	0.234	0.189	
Minimum	0.02	0.05	0.09	0.08	0.06	
Maximum	0.28	0.46	0.41	0.47	0.43	
Std. Deviation	0.07	0.10	0.08	0.09	0.10	
Disagreement						0.083

The expert panel exhibited a disagreement value of 0.083. The threshold value for group disagreement within this research is set as 0.10. Thus, the observed value of 0.083 falls well within the acceptable limit, and it indicates a relatively high level of consensus among the experts.

Table 4.4 provides a comprehensive overview of the experts who participated in Expert Panel 7. It categorizes them based on their professional titles or positions, the type of organizations they are affiliated with, and their respective countries of operation or residence. This table offers a snapshot of the diverse backgrounds and expertise of the individuals whose insights contributed to the Expert Panel 7, ensuring a broad and representative perspective.

Table 4.4. Composition of Expert Panel 7.

Expert No.	Title/Position	Organization Type	Country
Expert 50	Technical Services and R&D Director (Former)	Oil & Gas	Turkey
Expert 44	R&D Center Manager	Oil & Gas	Spain
Expert 46	Strategic Planning Director	Oil & Gas	Turkey
Expert 47	Vice President, Energies & Chemicals Strategy	Technology Provider	France
Expert 48	Project Office Manager, Sustainable Development	Oil & Gas	Bulgaria
Expert 55	Strategy Advisor	Oil & Gas	Portugal
Expert 42	Management Partner, Executive Office	Oil & Gas	United Arab Emirates
Expert 54	Head of Department	Research Institution	Denmark
Expert 57	Digital Transformation Manager	Oil & Gas	Turkey
Expert 45	Head of Industrial Development Department	Oil & Gas	Italy
Expert 51	Managing Director	Technology Provider	Germany
Expert 53	Head of Power Systems Group	Research Institution	Spain
Expert 49	Operations Director	Oil & Gas	Azerbaijan
Expert 52	Project Coordinator	Governmental Organization	Norway
Expert 43	Vice President, CO2 Management Product Line	Technology Provider	France
Expert 58	Director, Energy Transition Research Initiative	Research Institution	UK
Expert 59	Process Director	Oil & Gas	Turkey
Expert 56	Head of Technology Planning and R&D Services	Oil & Gas	Italy
Expert 154	Environment, Health, and Safety Manager	Oil & Gas	Turkey
Expert 155	Senior Consultant of Low Carbon Generation	Oil & Gas	Spain
Expert 157	Environmental Manager	Oil & Gas	Turkey
Expert 158	Head of R&D Laboratories	Oil & Gas	Turkey

4.4.2. Quantification Results of Social Criteria

The experts in Expert Panel 8, were asked to compare the social criteria in terms of significance that affect the implementation of low-carbon energy technologies for the oil and gas industry. The arithmetic means of the relative importance of social criteria are shown in the following Figure 4.24.

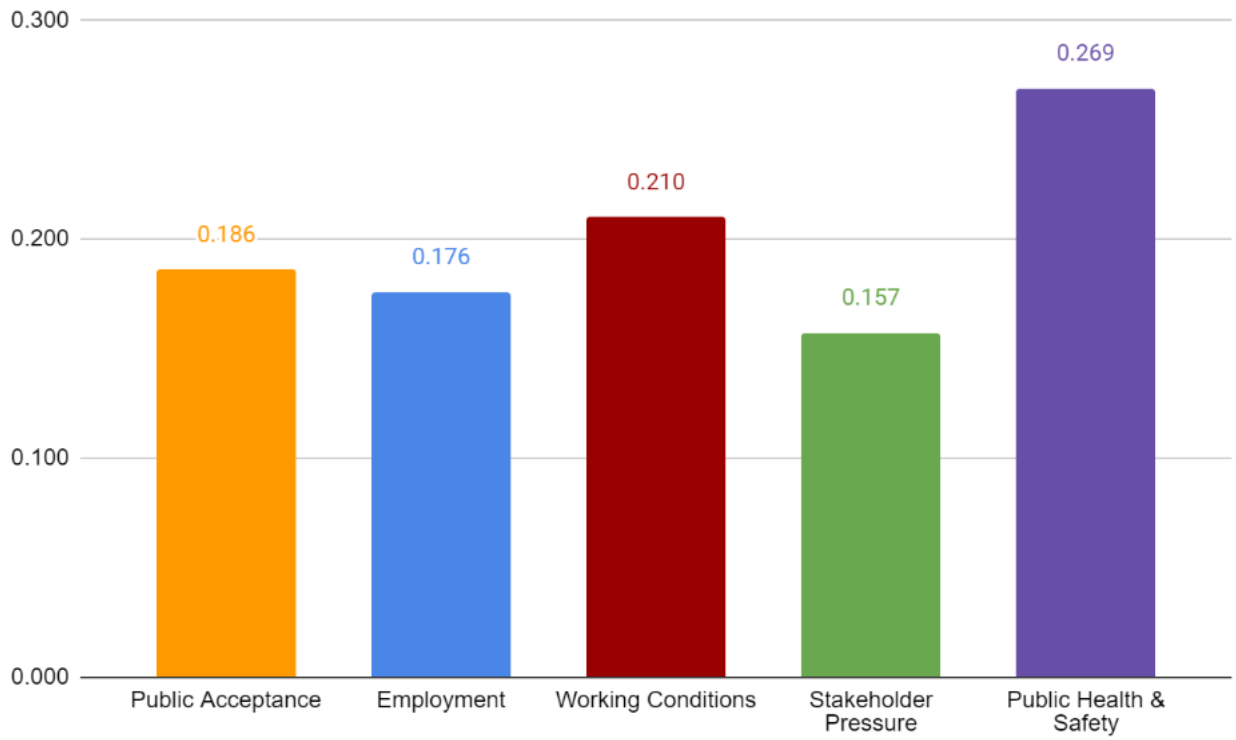

Figure 4.24. The importance weights of social criteria in the model.

The results show that public health and safety is the most important criterion with a weight of 0.269. The second most important criterion is the working conditions of employees. The criterion of public acceptance is the third most significant criterion with a weight of 0.186. The least important criteria are employment and stakeholder pressure, with a weight of 0.176 and 0.157, respectively. Additionally, public acceptance, employment, and working conditions criterion have their sub-criteria. According to panel results, public awareness with an importance weight of 0.537, is more important than the public concern sub-criterion (importance weight is 0.463), as seen in Figure 4.25. There are 3 sub-criteria under the employment criterion: new job opportunities, training of employees, and gender equity. Their importance weights are 0.394, 0.354, and 0.251, respectively. The results of employment are presented in Figure 4.26. Working conditions criterion has two sub-criteria: working hours and health and safety of workers. Health and safety of workers has higher

importance with a weight of 0.603 and working hours have lower importance with a weight of 0.397. The results of working conditions are presented in Figure 4.27.

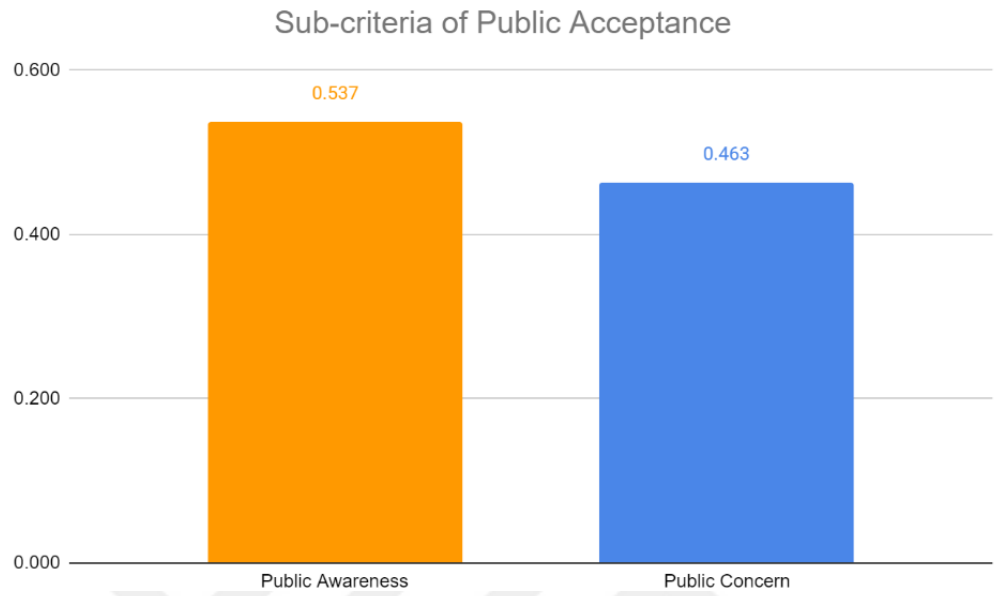

Figure 4.25. The importance weights of public acceptance sub-criteria in the model.

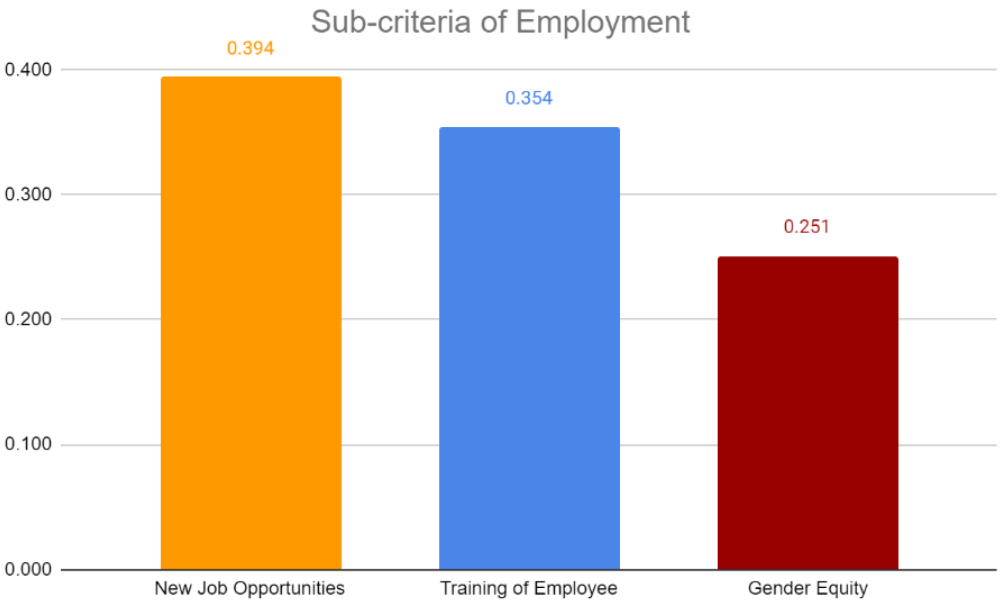

Figure 4.26. The importance weights of employment's sub-criteria in the model.

30 Experts participated in Expert Panel 8. Each expert systematically compared the social criteria and their corresponding sub-criteria against one another. Following this comparative analysis, the results were then computed and consolidated for further interpretation.

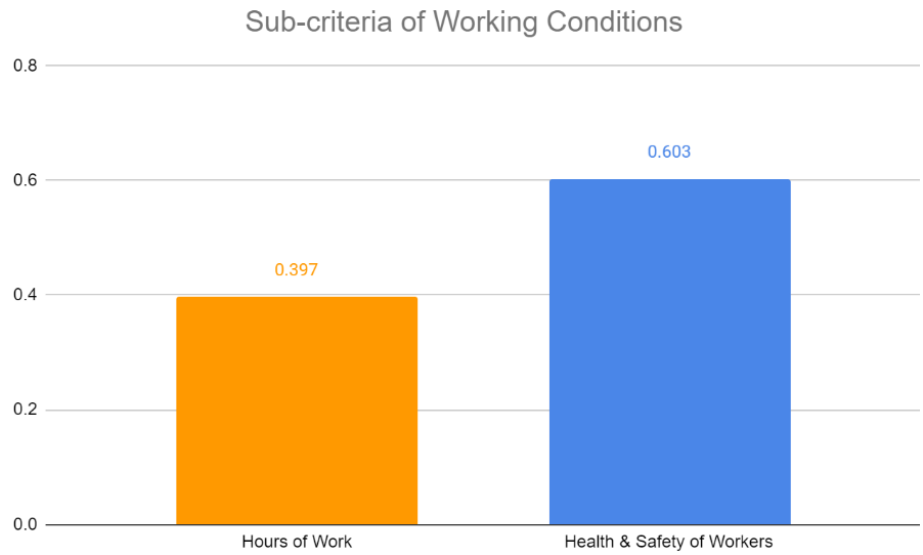

Figure 4.27. The importance weights of working conditions' sub-criteria in the model.

During the data collection phase, it was observed that one participant (Expert 63), did not complete the entire quantification survey. Consequently, the data from Expert 63 was excluded from the repository to maintain the integrity of the analysis. Out of the remaining data, the responses from 24 experts were found to be consistent, with inconsistency values registering below the threshold of 0.10. However, 5 experts, namely Expert 60, Expert 61, Expert 68, Expert 71, and Expert 73, had high inconsistency values of 0.26, 0.19, 0.13, 0.22, and 0.12, respectively. To further examine these inconsistencies, RSV calculation was performed for these experts. According to graphs plotted by Abbas (2016), an RSV value for 5 variables should remain below 0.3789 at an 85% confidence level. The computed RSV values for the aforementioned experts were 0.39, 0.67, 0.44, 0.51, and 0.25, respectively. Given these findings, experts with RSV values exceeding 0.3789, which includes Expert 60, Expert 61, Expert 68, and Expert 71 were subsequently removed from the data repository to ensure the robustness of the subsequent analyses. Also, Expert 60 and Expert 73 had inconsistent responses for the comparison of employment's sub-criteria. Their respective inconsistency values were 0.39 and 0.21. According to Abbas (2016), an RSV value for 3 variables should not exceed 0.0129 for an 85 % confidence level. While Expert 60 had already been excluded from the dataset for previous inconsistencies, a dedicated RSV calculation was conducted for Expert 73. The resulting RSV value for Expert 73 was found to be 0.20, which surpasses the threshold of 0.0129. In light of this finding, and to maintain the integrity of the dataset, Expert 73 was subsequently removed from the data repository.

Table 4.5. Quantification results of social criteria

Expert No.	SOCIAL CRITERIA					
	Public Acceptance	**Employment**	**Working Conditions**	**Stakeholder Pressure**	**Public Health & Safety**	**Inconsistency**
Expert 62	0.19	0.33	0.18	0.16	0.14	0.02
Expert 64	0.17	0.32	0.23	0.09	0.20	0.04
Expert 65	0.21	0.09	0.15	0.16	0.39	0.04
Expert 66	0.18	0.20	0.17	0.25	0.19	0.04
Expert 67	0.13	0.14	0.36	0.06	0.30	0.07
Expert 69	0.06	0.39	0.31	0.04	0.20	0.02
Expert 70	0.18	0.09	0.18	0.16	0.39	0.09
Expert 75	0.12	0.38	0.14	0.22	0.14	0.05
Expert 76	0.20	0.12	0.08	0.24	0.36	0.01
Expert 72	0.09	0.41	0.12	0.16	0.21	0.03
Expert 74	0.35	0.07	0.19	0.12	0.26	0.07
Expert 77	0.20	0.09	0.29	0.14	0.27	0.01
Expert 78	0.06	0.25	0.23	0.05	0.40	0.09
Expert 79	0.39	0.03	0.18	0.08	0.32	0.06
Expert 80	0.11	0.11	0.24	0.10	0.44	0.04
Expert 158	0.13	0.10	0.20	0.26	0.31	0.09
Expert 163	0.25	0.05	0.03	0.41	0.27	0.05
Expert 164	0.18	0.14	0.28	0.11	0.28	0.01
Expert 174	0.15	0.17	0.22	0.21	0.25	0.09
Expert 178	0.19	0.29	0.20	0.09	0.22	0.03
Expert 179	0.42	0.08	0.06	0.32	0.13	0.02
Expert 185	0.15	0.14	0.34	0.11	0.25	0.03
Expert 186	0.17	0.14	0.40	0.07	0.21	0.06
Expert 187	0.18	0.09	0.25	0.15	0.33	0.08
Mean	**0.186**	**0.176**	**0.210**	**0.157**	**0.269**	
Minimum	0.06	0.03	0.03	0.04	0.13	
Maximum	0.42	0.41	0.40	0.41	0.44	
Std. Deviation	0.09	0.12	0.09	0.09	0.09	
Disagreement						0.088

Table 4.6. Quantification results of public acceptance and employment sub-criteria.

Expert No.	SUB-CRITERIA of PUBLIC ACCEPTANCE			SUB-CRITERIA of EMPLOYMENT			
	Public Awareness	Public Concern	Inconsistency	New Job Opport.	Training of Employee	Gender Equity	Inconsistency
Expert 62	0.61	0.39	0.00	0.48	0.31	0.21	0.00
Expert 64	0.62	0.38	0.00	0.43	0.23	0.34	0.03
Expert 65	0.50	0.50	0.00	0.38	0.29	0.33	0.00
Expert 66	0.40	0.60	0.00	0.48	0.28	0.24	0.01
Expert 67	0.51	0.49	0.00	0.33	0.33	0.33	0.00
Expert 69	0.50	0.50	0.00	0.46	0.44	0.10	0.00
Expert 70	0.70	0.30	0.00	0.38	0.56	0.06	0.00
Expert 75	0.50	0.50	0.00	0.62	0.26	0.12	0.00
Expert 76	0.55	0.45	0.00	0.20	0.54	0.26	0.00
Expert 72	0.30	0.70	0.00	0.64	0.26	0.10	0.05
Expert 74	0.61	0.39	0.00	0.46	0.24	0.30	0.03
Expert 77	0.60	0.40	0.00	0.33	0.43	0.25	0.00
Expert 78	0.90	0.10	0.00	0.33	0.33	0.33	0.00
Expert 79	0.50	0.50	0.00	0.14	0.53	0.34	0.00
Expert 80	0.60	0.40	0.00	0.33	0.29	0.38	0.00
Expert 158	0.50	0.50	0.00	0.43	0.32	0.24	0.02
Expert 163	0.30	0.70	0.00	0.53	0.30	0.17	0.02
Expert 164	0.60	0.40	0.00	0.35	0.36	0.29	0.00
Expert 174	0.69	0.31	0.00	0.47	0.29	0.24	0.07
Expert 178	0.50	0.50	0.00	0.38	0.29	0.33	0.00
Expert 179	0.50	0.50	0.00	0.41	0.41	0.18	0.00
Expert 185	0.60	0.40	0.00	0.23	0.54	0.23	0.00
Expert 186	0.40	0.60	0.00	0.23	0.23	0.54	0.00
Expert 187	0.40	0.60	0.00	0.44	0.44	0.11	0.00
Mean	**0.537**	**0.463**		**0.394**	**0.354**	**0.251**	
Minimum	0.30	0.10		0.14	0.23	0.06	
Maximum	0.90	0.70		0.64	0.56	0.54	
Std. Deviation	0.13	0.13		0.12	0.11	0.11	
Disagreement	0.098			0.098			

Table 4.7. Quantification results of working conditions sub-criteria.

Expert No.	SUB-CRITERIA of WORKING CONDITIONS		
	Hours of Work	**Health & Safety of Workers**	**Inconsistency**
Expert 62	0.50	0.50	0.00
Expert 64	0.55	0.45	0.00
Expert 65	0.50	0.50	0.00
Expert 66	0.41	0.59	0.00
Expert 67	0.49	0.51	0.00
Expert 69	0.50	0.50	0.00
Expert 70	0.09	0.91	0.00
Expert 75	0.71	0.29	0.00
Expert 76	0.30	0.70	0.00
Expert 72	0.20	0.80	0.00
Expert 74	0.47	0.53	0.00
Expert 77	0.40	0.60	0.00
Expert 78	0.20	0.80	0.00
Expert 79	0.20	0.80	0.00
Expert 80	0.40	0.60	0.00
Expert 158	0.40	0.60	0.00
Expert 163	0.50	0.50	0.00
Expert 164	0.41	0.59	0.00
Expert 174	0.38	0.62	0.00
Expert 178	0.01	0.99	0.00
Expert 179	0.50	0.50	0.00
Expert 185	0.40	0.60	0.00
Expert 186	0.50	0.50	0.00
Expert 187	0.50	0.50	0.00
Mean	**0.397**	**0.603**	
Minimum	0.01	0.29	
Maximum	0.71	0.99	
Std. Deviation	0.16	0.16	
Disagreement			0.124

Upon refining the dataset of social criteria, pairwise comparison results of 24 experts and group disagreement value are shown in Table 4.5, Table 4.6, Table 4.7. The group disagreement value for social criteria was 0.088, showing the alignment among expert opinions on this aspect. Additionally, the disagreement analysis was performed for the sub-criteria of public acceptance, employment, and working conditions. Both public acceptance and employment had the same disagreement value of 0.098. However, the results of the working conditions' sub-criteria presented a higher disagreement value of 0.124. Since this value exceeded the threshold limit of 0.1, the statistical F-test data which was obtained from HDM software were examined.

F-test is a statistical test method that is used to compare the variances between two or more groups. In the context of disagreement analysis, it is performed to identify the disagreement among the experts. A hypothesis is set for the F-test. The null hypothesis (H_0) implies that there is an absolute disagreement in the expert panel and the alternative hypothesis (H_1) shows that there is some level of agreement or correlation among the judgments. In order to test these hypotheses, an F-test value is calculated. The computed F-test value is then compared with critical F-values for specific degrees of freedom at a chosen significance level. If the F-test value exceeds the critical F-value, the null hypothesis is rejected indicating that there is statistically significant agreement among the experts' judgments. Table 4.8 below shows the F-test results of the disagreement assessment of the working conditions sub-criteria. The F-test value of the working conditions sub-criteria is 8.04. The critical F-value at a significance level of 0.01 (1 %) is 7.88. Since the F-test value is greater than the critical F-value, it can be concluded that there is no statistically significant disagreement among the experts in the expert panel 8 for the pairwise comparison of working conditions sub-criteria.

Table 4.8. F-test results of working conditions sub-criteria.

Source of Variation	Sum of Square	Degree of freedom	Mean Square	F-test value
Between Subjects:	0.43	1	0.433	**8.04**
Between Conditions:	0	23	0	
Residual:	1.24	23	0.054	
Total:	**1.67**	**47**		
Critical F-value with degrees of freedom 1 & 23 at 0.01 level:				**7.88**
Critical F-value with degrees of freedom 1 & 23 at 0.025 level:				**5.75**
Critical F-value with degrees of freedom 1 & 23 at 0.05 level:				**4.28**
Critical F-value with degrees of freedom 1 & 23 at 0.1 level:				**2.94**

Table 4.9 presents the list of experts who participated in Expert Panel 8 and information about their backgrounds, expertise, and regions. These experts are from the academic and industrial sectors, predominantly from research institutions and the oil and gas industry. Their roles range from senior academic positions, such as professors and lecturers, to specialized roles in health, safety, and environment within the oil and gas industry. Representing a global perspective, these experts are from countries spanning North America, Europe, Asia, and Africa, ensuring a broad and inclusive viewpoint on the subject matter.

Table 4.9. Composition of Expert Panel 8.

Expert No.	Title/Position	Organization Type	Country
Expert 62	Senior Lecturer	Research Institution	Ghana
Expert 64	Researcher	Research Institution	Malaysia
Expert 65	Senior Lecturer	Research Institution	Malaysia
Expert 66	Associate Lecturer	Research Institution	UK
Expert 67	Professor in the School of Public Affairs	Research Institution	USA
Expert 69	Senior Toxicologist	Oil & Gas	Netherlands
Expert 70	Research Assistant in the Faculty of Economics	Research Institution	Russia
Expert 75	Post Doctoral Research Fellow	Research Institution	UK
Expert 76	Researcher in the Department of HSE	Research Institution	Iran
Expert 72	Lecturer in Organisational Behaviour and Entrepreneurship	Research Institution	UK
Expert 74	Associate Professor	Research Institution	Greece
Expert 77	Operating Superintendent	Oil & Gas	Turkey
Expert 78	Professor and Head of the Department of Economics	Research Institution	Russia
Expert 79	Professor in the Department of Occupational Health	Research Institution	USA
Expert 80	Assoc. Professor in the Department of Political Science	Research Institution	Canada
Expert 158	Head of R&D Laboratories	Oil & Gas	Turkey
Expert 163	Building Information Modelling (BIM) Director	Oil & Gas	Spain
Expert 164	Senior Health Advisor	Oil & Gas	USA
Expert 174	Industrial Hygiene Manager	Oil & Gas	Italy
Expert 178	Exploration Team Lead	Oil & Gas	Ghana
Expert 179	Process Safety Engineer	Oil & Gas	Italy
Expert 185	Safety Specialist	Oil & Gas	Italy
Expert 186	Head of Impact Assessment, Monitoring & Reporting	Oil & Gas	Italy
Expert 187	Health and Safety Specialist	Oil & Gas	Italy

4.4.3. Quantification Results of Economic Criteria

The experts in Expert Panel 9, were asked to compare the economic criteria and sub-criteria in terms of significance that affect the implementation of low-carbon energy technologies for the oil and gas industry. The arithmetic means of the relative importance of economic criteria are shown in Figure 4.28.

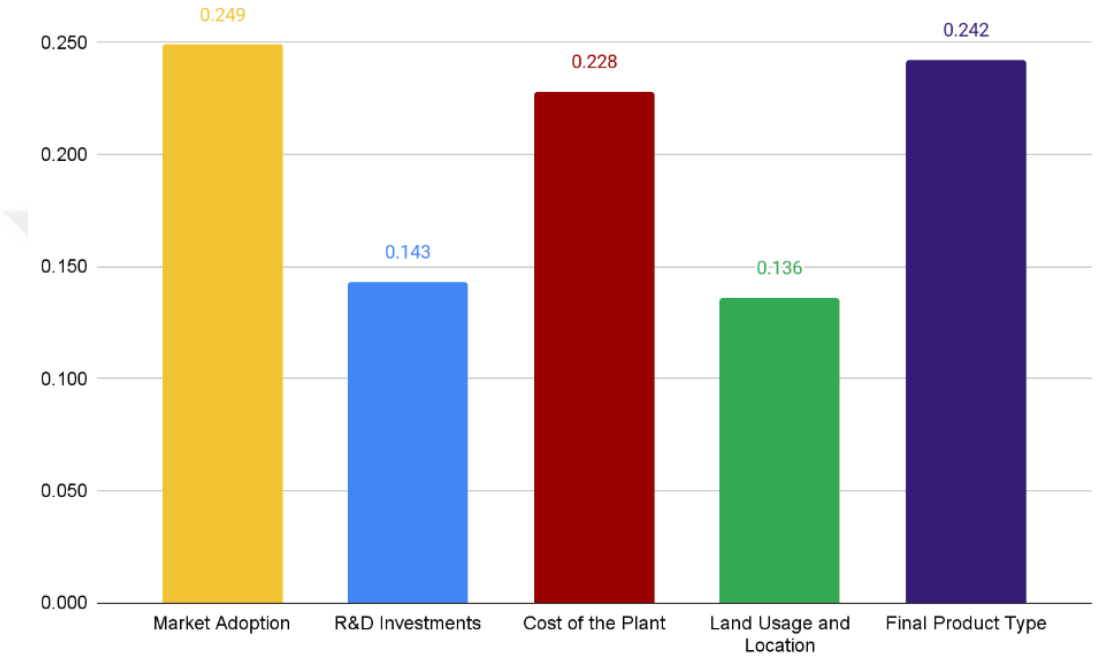

Figure 4.28. The importance weights of economic criteria in the model.

The results show that market adoption and final product type are the most important criteria with a weight of 0.249, and 0.242, respectively. The third most important criterion is the plant cost with a weight of 0.228. The criterion of R&D investments follows the plant cost criterion with a lower degree of importance, 0.143. Lastly, the less important criterion is land usage and location with a weight of 0.136.

In Expert Panel 9, sub-criteria of R&D investments, plant cost, land usage and location were also assessed. The results of relative importance are shown in Figure 4.29, Figure 4.30, and Figure 4.31. R&D investment criterion has two sub-criteria: private and governmental R&D investments. Experts in Panel 9 stated that private R&D investment is more important than governmental R&D investment with a weight of 0.534. The criterion of plant cost has five sub-criteria, namely, capital cost, operational cost, feedstock cost, transportation cost, and cost competitiveness. Cost competitiveness is the most important criterion with a weight of 0.256 among the other sub-criteria.

The second important criterion is the feedstock cost with a weight of 0.245. Capital cost and operational cost follow as third and fourth important criterion with a weight of 0.227, and 0.155, respectively. Lastly, transportation cost is the least important criterion with a weight of 0.121. Criterion of land usage and location has three sub-criteria, and the most important sub-criterion is the reliability of resources with a weight of 0.469. The second most important sub-criterion is the delivery of feedstock with a weight of 0.272. The least important criterion is the required area with a weight of 0.258 for providing feedstock and plant construction area.

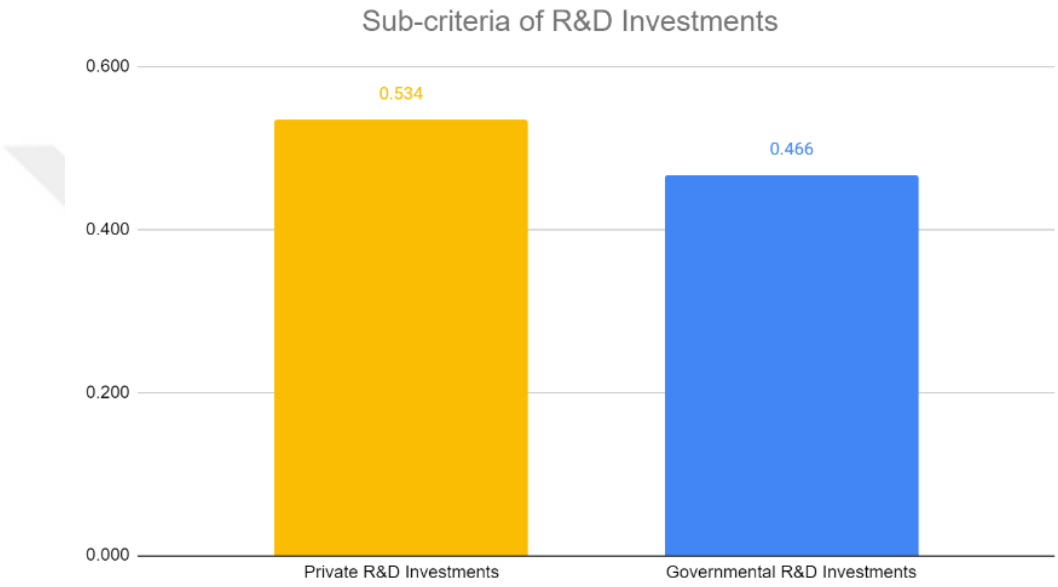

Figure 4.29. The importance weights of R&D investments sub-criteria in the model.

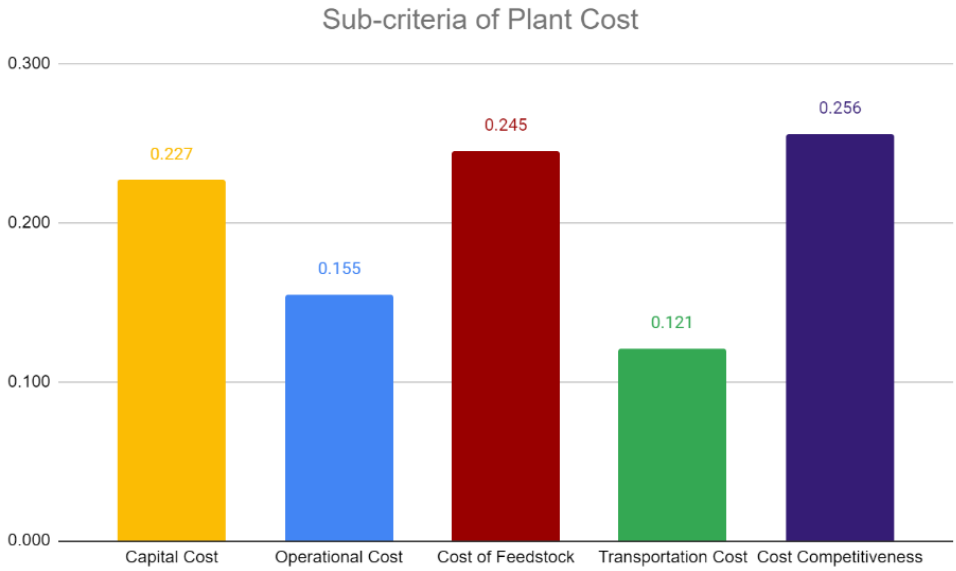

Figure 4.30. The importance weights of plant cost sub-criteria in the model.

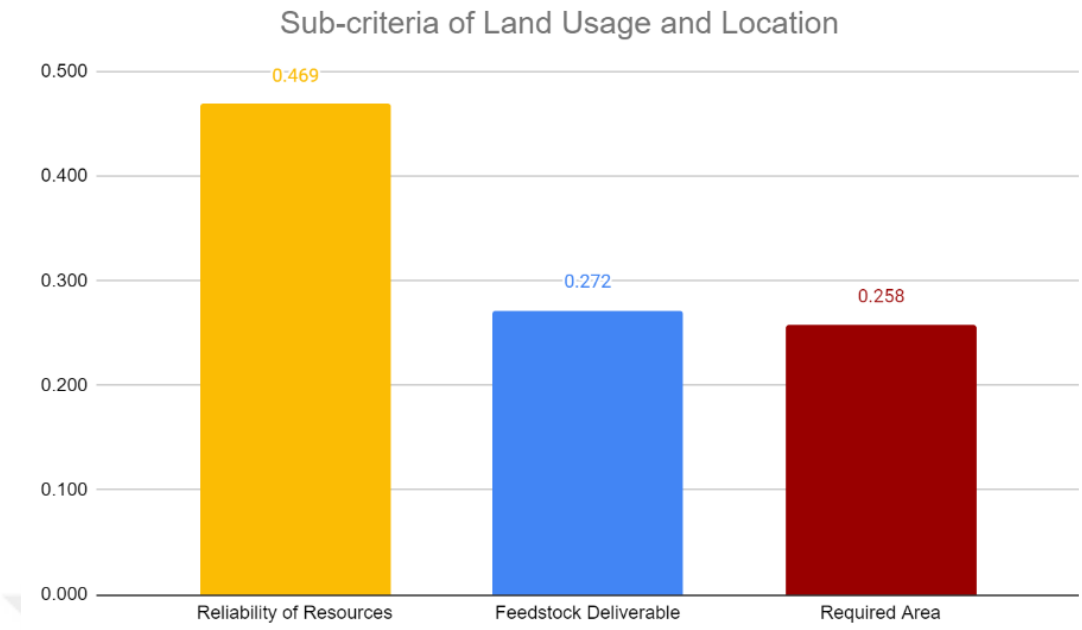

Figure 4.31. The importance weights of land usage and location sub-criteria in the model.

22 experts attended Expert Panel 9 for the assessment of economic criteria that affect the implementation of low-carbon energy technologies in oil and gas industry. Each expert responded to the pairwise comparison questions and the data were consolidated for interpretation. Among the 22 experts, five experts have inconsistent responses. Expert 92, Expert 93, Expert 84, Expert 89, and Expert 94 had high inconsistency values of 0.13, 0.10, 0.26, 0.16, and 0.10, respectively. RSV calculations were applied to investigate whether the inconsistency values were at an acceptable level or not. According to Abbas (2016), the RSV value for five variables should remain below 0.3789 at an 85 % confidence level. The RSV values of Expert 92, Expert 93, Expert 84, Expert 89, Expert 94 were 0.31, 0.29, 0.49, 0.69 and 0.28, respectively. Given these results, the expert responses that had higher RSV values than 0.3789, Expert 84 and Expert 89 were removed from the data repository. In addition to that, Expert 94 had a high inconsistency value in the pairwise comparison of land usage and location sub-criteria (0.10). According to Abbas (2016), the RSV value for three variables should not exceed 0.0129 for an 85 % confidence level. The RSV calculation of Expert 94 for land usage and location sub-criteria, was 0.15 which exceeds the threshold of 0.0129. In light of these result, Expert 94 were also removed from the data repository to maintain treated results.

Table 4.10. Quantification results of economic criteria.

Expert No.	CRITERIA LEVEL					
	Market Adoption	**R&D Investments**	**Cost of the Plant**	**Land Usage and Location**	**Final Product Type**	**Inconsistency**
Expert 86	0.23	0.15	0.35	0.12	0.15	0.03
Expert 85	0.20	0.16	0.27	0.16	0.20	0.04
Expert 82	0.35	0.13	0.17	0.17	0.17	0.04
Expert 83	0.22	0.09	0.22	0.22	0.24	0.04
Expert 87	0.22	0.13	0.29	0.09	0.28	0.01
Expert 88	0.19	0.18	0.18	0.16	0.30	0.04
Expert 90	0.35	0.05	0.30	0.09	0.19	0.03
Expert 91	0.30	0.11	0.21	0.16	0.23	0.06
Expert 92	0.36	0.12	0.33	0.11	0.08	0.13
Expert 93	0.17	0.06	0.16	0.20	0.40	0.10
Expert 95	0.11	0.12	0.20	0.24	0.33	0.05
Expert 96	0.28	0.20	0.22	0.09	0.21	0.01
Expert 81	0.09	0.51	0.11	0.08	0.21	0.05
Expert 97	0.25	0.15	0.22	0.12	0.26	0.09
Expert 98	0.27	0.15	0.20	0.09	0.29	0.01
Expert 07	0.29	0.04	0.33	0.19	0.15	0.09
Expert 99	0.32	0.09	0.21	0.06	0.32	0.06
Expert 160	0.23	0.14	0.17	0.17	0.29	0.00
Expert 04	0.31	0.14	0.19	0.07	0.29	0.06
Mean	**0.249**	**0.143**	**0.228**	**0.136**	**0.242**	
Minimum	0.09	0.04	0.11	0.06	0.08	
Maximum	0.36	0.51	0.35	0.24	0.40	
Std. Deviation	0.08	0.10	0.07	0.05	0.08	
Disagreement						0.063

Table 4.11. Quantification results of R&D investment sub-criteria.

Expert No.	SUB-CRITERIA of R&D INVESTMENTS		
	Private R&D Investments	**Governmental R&D Investments**	**Inconsistency**
Expert 86	0.50	0.50	0.00
Expert 85	0.34	0.66	0.00
Expert 82	0.61	0.39	0.00
Expert 83	0.40	0.60	0.00
Expert 87	0.40	0.60	0.00
Expert 88	0.50	0.50	0.00
Expert 90	0.50	0.50	0.00
Expert 91	0.50	0.50	0.00
Expert 92	0.50	0.50	0.00
Expert 93	0.60	0.40	0.00
Expert 95	0.50	0.50	0.00
Expert 96	0.64	0.36	0.00
Expert 81	0.70	0.30	0.00
Expert 97	0.40	0.60	0.00
Expert 98	0.70	0.30	0.00
Expert 07	0.40	0.60	0.00
Expert 99	0.46	0.54	0.00
Expert 160	0.80	0.20	0.00
Expert 04	0.70	0.30	0.00
Mean	**0.534**	**0.466**	
Minimum	0.34	0.20	
Maximum	0.80	0.66	
Std. Deviation	0.128	0.128	
Disagreement			0.106

After the data refinement, three experts were removed from the panel, and the data of 19 experts were used for determining the relative importance weights of economic criteria and sub-criteria. The criteria and sub-criteria level results of each expert and the group disagreement value of 19 experts are shown in Table 4.10, Table 4.11, Table 4.12, Table 4.13 presents the F-test results of the R&D investment sub-criteria. The F-test value of this sub-criteria was 1.35. The critical value

at a significance level of 0.1, 0.05, 0.025, and 0.01 was 3.01, 4.41, 5.98, and 8.29 respectively. Since the F-test value is lower than the critical F-value, it can be stated that a statistically significant disagreement exists among the experts and further disagreement analysis should be performed in order to solve the disagreement and identify the decision groups.

Table 4.12. Quantification results of plant cost sub-criteria.

Expert No.	SUB-CRITERIA of PLANT COST					
	Capital Cost	**Operational Cost**	**Cost of Feedstock**	**Transportation Cost**	**Cost Competitiveness**	**Inconsistency**
Expert 86	0.31	0.11	0.21	0.06	0.31	0.08
Expert 85	0.20	0.25	0.20	0.18	0.18	0.00
Expert 82	0.33	0.11	0.23	0.10	0.23	0.05
Expert 83	0.15	0.25	0.20	0.17	0.23	0.00
Expert 87	0.39	0.25	0.14	0.09	0.14	0.04
Expert 88	0.23	0.15	0.21	0.14	0.27	0.02
Expert 90	0.18	0.24	0.26	0.08	0.24	0.01
Expert 91	0.23	0.12	0.23	0.15	0.28	0.01
Expert 92	0.13	0.08	0.23	0.37	0.19	0.06
Expert 93	0.08	0.15	0.42	0.07	0.29	0.03
Expert 95	0.34	0.10	0.17	0.16	0.24	0.00
Expert 96	0.20	0.23	0.14	0.07	0.35	0.04
Expert 81	0.09	0.07	0.62	0.03	0.20	0.07
Expert 97	0.18	0.12	0.19	0.04	0.47	0.06
Expert 98	0.34	0.12	0.25	0.04	0.25	0.02
Expert 07	0.16	0.04	0.44	0.18	0.19	0.05
Expert 99	0.19	0.22	0.07	0.14	0.38	0.01
Expert 160	0.28	0.14	0.22	0.14	0.22	0.00
Expert 04	0.30	0.19	0.22	0.09	0.21	0.00
Mean	**0.227**	**0.155**	**0.245**	**0.121**	**0.256**	
Minimum	0.08	0.04	0.07	0.03	0.14	
Maximum	0.39	0.25	0.62	0.37	0.47	
Std. Deviation	0.09	0.07	0.12	0.08	0.08	
Disagreement						0.077

The group disagreement value of economic criteria was 0.063, proving that the experts' decisions were in a consensus. Also, the disagreement values of plant cost and land usage and location were 0.077 and 0.091, respectively. The disagreement values were well below the threshold value of 0.10. However, the disagreement value of the R&D investments sub-criteria was 0.106, which exceeded the threshold limit of 0.1, and the statistical F-test data was investigated.

Table 4.13 presents the F-test results of the R&D investment sub-criteria. The F-test value of this sub-criteria was 1.35. The critical value at a significance level of 0.1, 0.05, 0.025, and 0.01 was 3.01, 4.41, 5.98, and 8.29 respectively. Since the F-test value is lower than the critical F-value, it can be stated that a statistically significant disagreement exists among the experts and further disagreement analysis should be performed in order to solve the disagreement and identify the decision groups.

Table 4.13. F-test results of R&D investments

Source of Variation	**Sum of Square**	**Degree of freedom**	**Mean Square**	**F-test value**
Between Subjects:	0.04	1	0.044	1.35
Between Conditions:	0	18	0	
Residual:	0.59	18	0.033	
Total:	0.64	37		
Critical F-value with degrees of freedom 1 & 23 at 0.01 level:				8.29
Critical F-value with degrees of freedom 1 & 23 at 0.025 level:				5.98
Critical F-value with degrees of freedom 1 & 23 at 0.05 level:				4.41
Critical F-value with degrees of freedom 1 & 23 at 0.1 level:				3.01

Table 4.14. Quantification results of land usage and location sub-criteria

Expert No.	SUB-CRITERIA of LAND USAGE & LOCATION			
	Reliability of Resources	**Feedstock Deliverable**	**Required Area**	**Inconsistency**
Expert 86	0.32	0.22	0.46	0.04
Expert 85	0.29	0.39	0.32	0.02
Expert 82	0.54	0.16	0.30	0.02
Expert 83	0.25	0.38	0.38	0.00
Expert 87	0.48	0.31	0.21	0.00
Expert 88	0.34	0.33	0.33	0.05
Expert 90	0.48	0.31	0.21	0.00
Expert 91	0.49	0.32	0.19	0.00
Expert 92	0.68	0.16	0.16	0.00
Expert 93	0.59	0.15	0.26	0.07
Expert 95	0.33	0.33	0.33	0.00
Expert 96	0.57	0.28	0.15	0.00
Expert 81	0.48	0.31	0.21	0.00
Expert 97	0.43	0.29	0.29	0.00
Expert 98	0.47	0.33	0.19	0.06
Expert 07	0.53	0.30	0.17	0.02
Expert 99	0.61	0.10	0.29	0.03
Expert 160	0.33	0.33	0.33	0.00
Expert 04	0.70	0.17	0.13	0.02
Mean	**0.469**	**0.272**	**0.258**	
Minimum	0.25	0.10	0.13	
Maximum	0.70	0.39	0.46	
Std. Deviation	0.13	0.08	0.09	
Disagreement				0.091

Hierarchical agglomerative clustering (HAC) analysis was applied in order to identify subgroups within the Expert Panel 9 and understand the nuances of their differing decisions. HAC analysis was performed in R. R codes for HAC analysis is seen in Appendix D. Euclidean method is used for computing the pairwise distances and several trials were conducted in order to find the subgroups that had low disagreement values. The trials were performed by changing the linkage method and number of clusters. The average linkage method was used for identifying the

subgroups. The outcome of this analysis showed the formation of two distinct subgroups and clustering results in the form of a dendrogram are shown in Figure 4.32. Notably, both subgroups exhibited low disagreement values, indicating a higher degree of consensus within each subgroup. Table 4.15 and Table 4.16 show the relative priorities of experts, inconsistency values, and disagreement values of Subgroup A and Subgroup B, respectively.

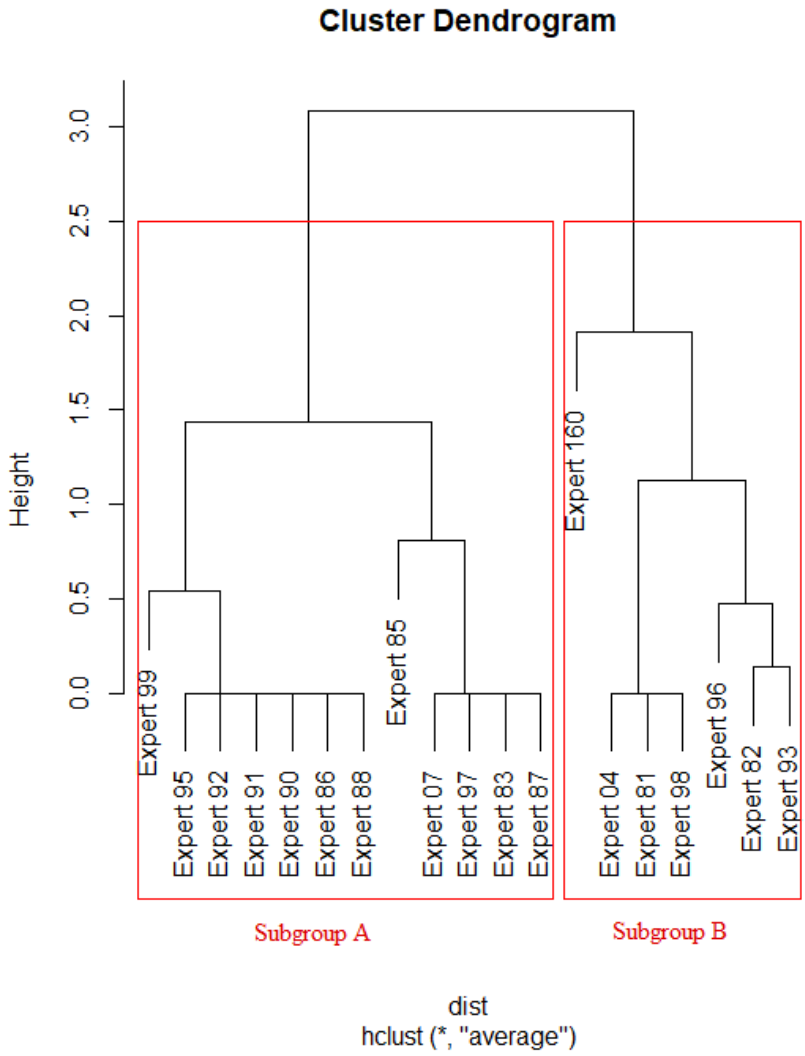

Figure 4.32. Dendrogram of subgroups of Expert Panel 9 for the assessment of R&D investment sub-criteria

Subgroup A, comprised of 12 experts, demonstrated a slight preference for governmental R&D investments over private R&D investments in their evaluations. The overall low disagreement value of 0.052 further shows a general alignment in expert perspectives, suggesting that while they lean towards the importance of governmental investments, the difference in preference is not substantial.

Table 4.15. Analysis of the results of Subgroup A in Expert Panel 9

Expert No.	SUB-CRITERIA of R&D INVESTMENTS		
	Private R&D Investments	Governmental R&D Investments	Inconsistency
Expert 86	0.50	0.50	0.00
Expert 85	0.34	0.66	0.00
Expert 83	0.40	0.60	0.00
Expert 87	0.40	0.60	0.00
Expert 88	0.50	0.50	0.00
Expert 90	0.50	0.50	0.00
Expert 91	0.50	0.50	0.00
Expert 92	0.50	0.50	0.00
Expert 95	0.50	0.50	0.00
Expert 97	0.40	0.60	0.00
Expert 07	0.40	0.60	0.00
Expert 99	0.46	0.54	0.00
Mean	0.450	0.550	
Minimum	0.34	0.50	
Maximum	0.50	0.66	
Std. Deviation	0.058	0.058	
Disagreement			0.052

Subgroup B, composed of seven experts, present a distinct trend compared to the previous group. The data shows that this subgroup displays a clearer preference for Private R&D investments with a weight of 0.679. Probably, they perceive private investments as playing a more dominant role in the R&D. The group disagreement value stands at 0.053, which shows that there is some variation in opinions, the experts in Subgroup B are largely in agreement.

Table 4.16. Analysis of the results of Subgroup B in Expert Panel 9

Expert No.	SUB-CRITERIA of R&D INVESTMENTS		
	Private R&D Investments	**Governmental R&D Investments**	**Inconsistency**
Expert 82	0.61	0.39	0.00
Expert 93	0.60	0.40	0.00
Expert 96	0.64	0.36	0.00
Expert 81	0.70	0.30	0.00
Expert 98	0.70	0.30	0.00
Expert 160	0.80	0.20	0.00
Expert 04	0.70	0.30	0.00
Mean	0.679	0.321	
Minimum	0.60	0.20	
Maximum	0.80	0.40	
Std. Deviation	0.069	0.069	
Disagreement			0.053

Expert Panel 9 is composed of professionals from diverse backgrounds and regions, each bringing a unique perspective to the table. The panel includes representatives from the USA, Brazil, Italy, the Netherlands, France, the UK, Spain, the United Arab Emirates, and Turkey, as shown in Table 4.17. Their affiliations span a range of sectors, including governmental organizations, research institutions, technology providers, and the oil and gas industry.

Table 4.17. Composition of Expert Panel 9.

Expert No.	Title/Position	Organization Type	Country
Expert 86	Full Professor of Energy Economics	Research Institution	Brazil
Expert 85	Assistant Professor in Economics	Research Institution	Italy
Expert 82	CCS Advisor	Governmental Organization	Netherlands
Expert 83	Researcher	Research Institution	USA
Expert 87	Sales Application Manager	Technology Provider	Italy
Expert 88	Technology Manager	Technology Provider	Netherlands
Expert 90	Hydrogen Country Lead	Oil & Gas	Netherlands
Expert 91	Technology Governance and Reporting Head	Technology Provider	Italy
Expert 92	Technology Lead Advisor, Gas Chain	Oil & Gas	France
Expert 93	Senior Chemical Engineer	Research Institution	USA
Expert 95	Engineering Advisor	Oil & Gas	Spain
Expert 96	Manager	Technology Provider	United Arab Emirates
Expert 81	R&D Experimental Chapter Lead	Oil & Gas	Turkey
Expert 97	Chief Scientist	Oil & Gas	Netherlands
Expert 98	Head of Department of Chemical Engineering	Research Institution	UK
Expert 07	Chief Technology Officer	Oil & Gas	Turkey
Expert 99	Investment & Project Development Chief	Oil & Gas	Turkey
Expert 160	R&D Renewable Energies Senior Scientist	Oil & Gas	Italy
Expert 04	R&D Manager	Oil & Gas	Turkey

4.4.4. Quantification Results of Technical Criteria

The experts in Expert Panel 10, were asked to evaluate the technical criteria in terms of significance that affect the implementation of low-carbon energy technologies for the oil and gas industry. The arithmetic means of the relative importance of technical criteria are shown in Figure 4.33.

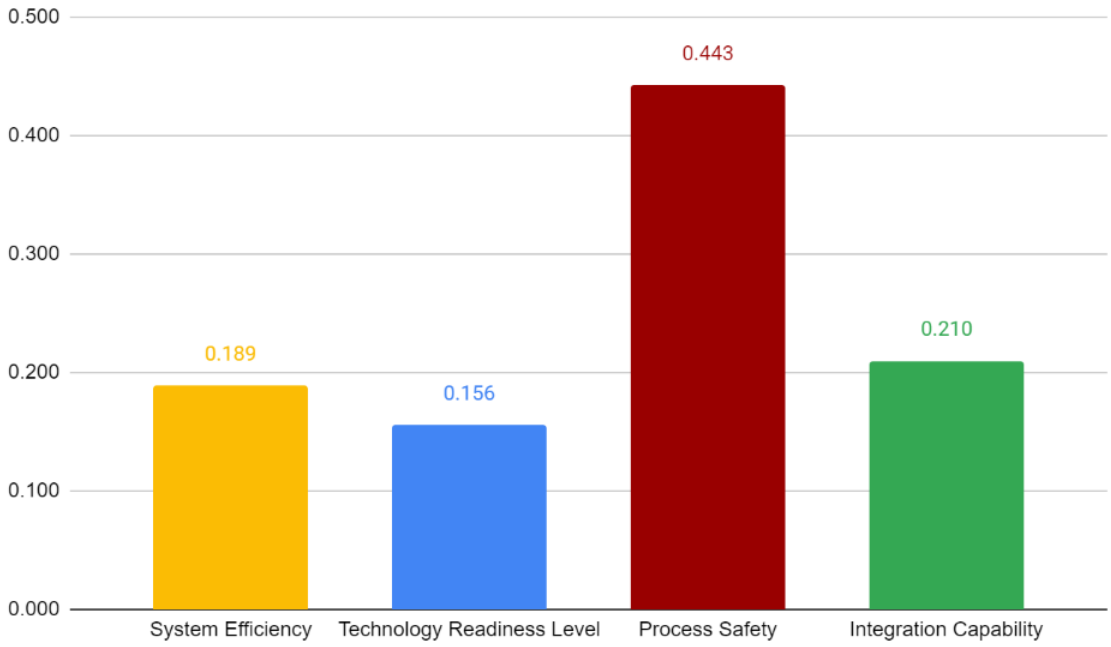

Figure 4.33. The importance weight of technical criteria in the model.

The criterion of process safety emerges as the most critical criterion with a weight of 0.443 in Expert Panel 10. These results can be interpreted as ensuring the safe operation and handling of the system or technology is of paramount importance, likely due to the potential risks and consequences associated with safety breaches. The second most significant criterion is the integration capability with a weight of 0.210. The importance of this criterion shows that technology's ability to seamlessly integrate with existing processes or systems in the oil and gas industry also ensures smooth operations and minimizes disruptions. The system efficiency criterion is in third place with a weight of 0.189. With a weight of 0.156, TRL is the least emphasized criterion among the technical criteria. However, it holds significance since this criterion also highlights the importance of the maturity and reliability of technology. A higher readiness level generally indicates that the technology is more developed, tested, and closer to deployment in real-world scenarios.

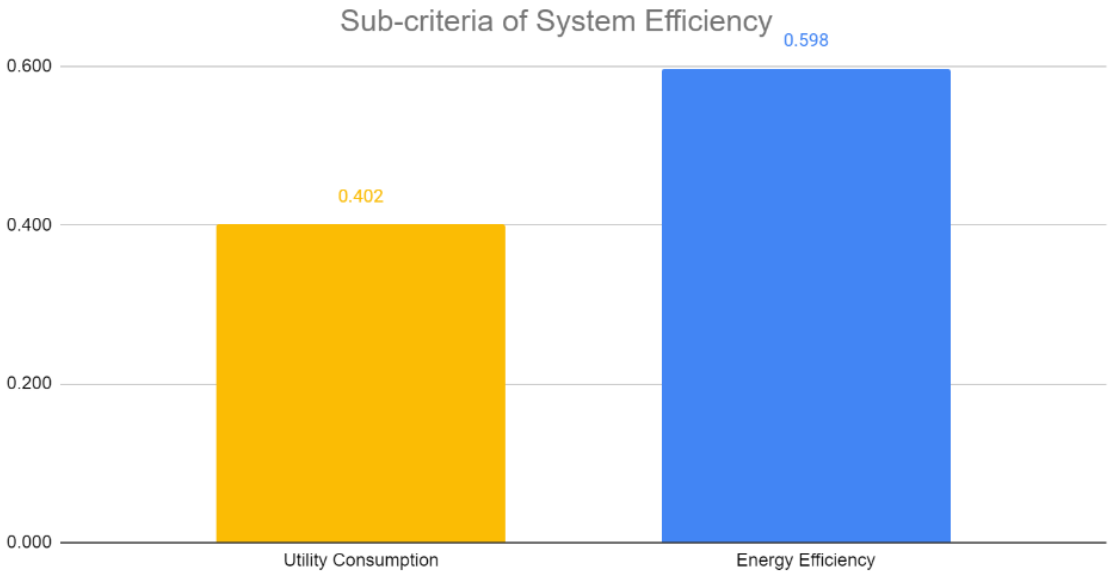

Figure 4.34. The importance weights of system efficiency sub-criteria in the model.

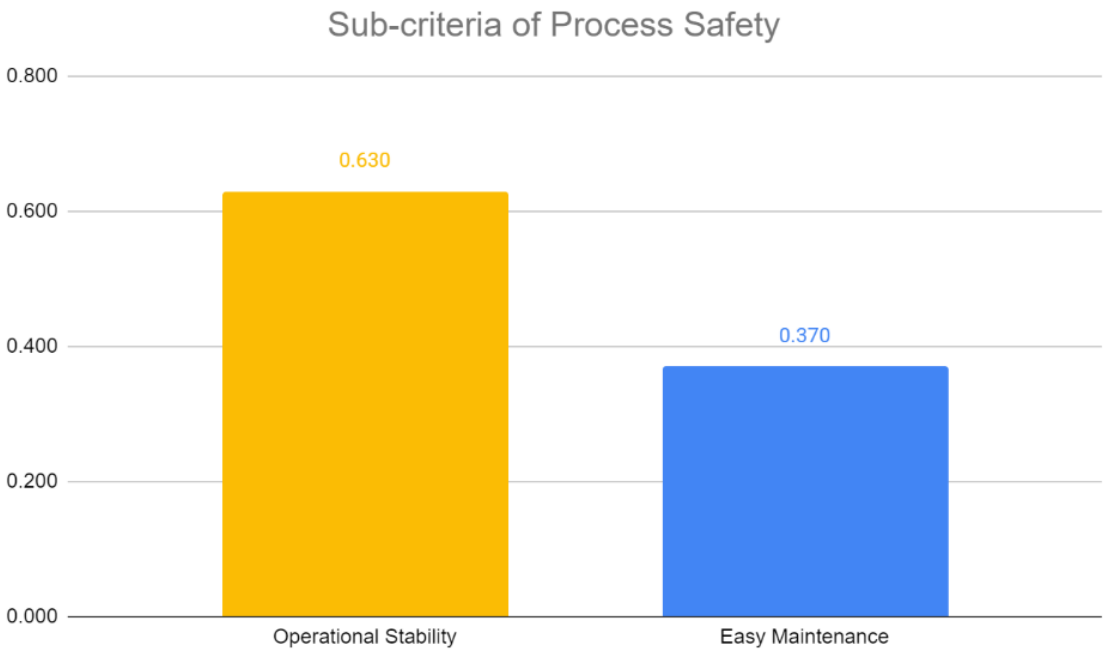

Figure 4.35. The importance weights of process safety sub-criteria in the model.

The pairwise comparison assessment of two sets of sub-criteria: system efficiency and process safety were also performed in Expert Panel 10. The system efficiency has two sub-criteria: energy efficiency and utility consumption. According to the results, energy efficiency is highlighted as the most important sub-criterion with a weight of 0.598, as shown in Figure 4.34. Emphasizing energy efficiency can lead to cost savings, reduced environmental impact, and more sustainable operations. The utility consumption sub-criterion with a weight of 0.402 is also important but it is slightly less emphasized than the energy efficiency sub-criterion. Process safety has two sub-criteria: operational

stability and easy maintenance. With a weight of 0.630, operational stability ranked as the predominant sub-criterion over easy maintenance. The results of process safety sub-criteria are presented in Figure 4.35. Experts in Panel 10 suggested that the operation of a system or a technology consistently and, the reliability of the system without frequent disruptions or failures has the utmost importance. Stability in the operation also leads to productivity, provides better performance, and reduces sudden shutdowns. The ease of maintenance sub-criterion was slightly less emphasized by experts with a weight of 0.370. In conclusion, while operational stability and ease of maintenance are vital operational sub-criteria, the experts focus on ensuring consistent and reliable operations.

29 experts participated in Expert Panel 10 for the assessment of technical criteria that affect the implementation of low-carbon energy technologies in the oil and gas industry. Pairwise comparison questions were responded to by the experts, and then the data were consolidated by calculating the importance weights of the criteria and sub-criteria. Among the 29 experts, two experts had inconsistent quantification responses. Expert 161 and Expert 184 had high inconsistency values of 0.11 and 0.10, respectively. RSV calculations were performed to examine further whether the inconsistency values were at an acceptable level or not. According to Abbas (2016), the RSV value for four variables should remain below 0.1886 at an 85 % confidence level. The RSV values of Expert 161 and Expert 184 were 0.28 and 0.44, respectively. Since the expert responses had higher RSV values than the limit of 0.1886, the data of Expert 161 and Expert 184 were not included in the data repository. The criteria and sub-criteria level results of each expert and group disagreement value of Expert Panel 10 are presented in Table 4.18 and Table 4.19. Group disagreement values of Expert Panel 10 for criteria level, system efficiency sub-criteria level, and process safety sub-criteria level are 0.123, 0.170, and 0.111, respectively. Since the group disagreement values were higher than the threshold value of 0.1, the statistical F-test was performed. Table 4.20 shows the F-test results of technical criteria, system efficiency sub-criteria, and process safety sub-criteria. Since the F-test values are lower than the critical F-value at a considerable significance level, it can be stated that a statistically significant agreement exists among the experts and further disagreement analysis is not needed to be performed to solve the disagreement and identify the decision groups.

Table 4.18. Quantification results of technical criteria.

Expert No.	CRITERIA LEVEL				
	System Efficiency	**TRL**	**Process Safety**	**Integration Capability**	**Inconsistency**
Expert 102	0.14	0.06	0.73	0.06	0.03
Expert 100	0.50	0.07	0.23	0.20	0.04
Expert 105	0.17	0.09	0.56	0.17	0.02
Expert 104	0.17	0.07	0.68	0.07	0.00
Expert 109	0.14	0.12	0.43	0.31	0.03
Expert 57	0.29	0.27	0.18	0.25	0.04
Expert 103	0.13	0.09	0.63	0.16	0.01
Expert 83	0.10	0.14	0.53	0.23	0.00
Expert 111	0.15	0.35	0.18	0.32	0.07
Expert 107	0.20	0.06	0.58	0.16	0.02
Expert 108	0.23	0.08	0.57	0.12	0.01
Expert 110	0.15	0.33	0.30	0.22	0.05
Expert 106	0.09	0.60	0.21	0.10	0.07
Expert 112	0.17	0.08	0.29	0.45	0.02
Expert 113	0.13	0.10	0.38	0.39	0.00
Expert 114	0.13	0.20	0.44	0.23	0.06
Expert 59	0.26	0.32	0.23	0.19	0.03
Expert 101	0.22	0.08	0.59	0.10	0.03
Expert 115	0.33	0.18	0.30	0.20	0.00
Expert 81	0.19	0.09	0.45	0.26	0.04
Expert 162	0.24	0.04	0.34	0.37	0.02
Expert 167	0.23	0.19	0.32	0.26	0.01
Expert 168	0.21	0.12	0.58	0.09	0.03
Expert 170	0.05	0.04	0.88	0.03	0.03
Expert 171	0.26	0.26	0.30	0.18	0.01
Expert 176	0.09	0.06	0.77	0.08	0.01
Expert 180	0.13	0.11	0.29	0.47	0.00
Mean	**0.189**	**0.156**	**0.443**	**0.210**	
Minimum	0.05	0.04	0.18	0.03	
Maximum	0.50	0.60	0.88	0.47	
Std. Deviation	0.09	0.13	0.20	0.12	
Disagreement					0.123

Table 4.19. Quantification results of system efficiency's and process safety's sub-criteria.

Expert No.	SUB-CRITERIA of SYST. EFFICIENCY			SUB-CRITERIA of PROCESS SAFETY		
	Utility Consum.	En. Eff.	Inconsistency	Oper. Stability	Ease of Main.	Inconsistency
Expert 102	0.30	0.70	0.00	0.50	0.50	0.00
Expert 100	0.08	0.92	0.00	0.50	0.50	0.00
Expert 105	0.25	0.75	0.00	0.75	0.25	0.00
Expert 104	0.50	0.50	0.00	0.60	0.40	0.00
Expert 109	0.09	0.91	0.00	0.81	0.19	0.00
Expert 57	0.25	0.75	0.00	0.50	0.50	0.00
Expert 103	0.50	0.50	0.00	0.70	0.30	0.00
Expert 83	0.50	0.50	0.00	0.70	0.30	0.00
Expert 111	0.50	0.50	0.00	0.30	0.70	0.00
Expert 107	0.25	0.75	0.00	0.50	0.50	0.00
Expert 108	0.40	0.60	0.00	0.70	0.30	0.00
Expert 110	0.60	0.40	0.00	0.50	0.50	0.00
Expert 106	0.20	0.80	0.00	0.80	0.20	0.00
Expert 112	0.20	0.80	0.00	0.80	0.20	0.00
Expert 113	0.61	0.39	0.00	0.57	0.43	0.00
Expert 114	0.30	0.70	0.00	0.50	0.50	0.00
Expert 59	0.85	0.15	0.00	0.90	0.10	0.00
Expert 101	0.64	0.36	0.00	0.60	0.40	0.00
Expert 115	0.40	0.60	0.00	0.60	0.40	0.00
Expert 81	0.30	0.70	0.00	0.70	0.30	0.00
Expert 162	0.02	0.98	0.00	0.80	0.20	0.00
Expert 167	0.51	0.49	0.00	0.44	0.56	0.00
Expert 168	0.29	0.71	0.00	0.61	0.39	0.00
Expert 170	0.52	0.48	0.00	0.64	0.36	0.00
Expert 171	0.60	0.40	0.00	0.60	0.40	0.00
Expert 176	0.60	0.40	0.00	0.70	0.30	0.00
Expert 180	0.60	0.40	0.00	0.70	0.30	0.00
Mean	**0.402**	**0.598**		**0.630**	**0.370**	
Minimum	0.02	0.15		0.30	0.10	
Maximum	0.85	0.98		0.90	0.70	
Std. Deviation	0.20	0.20		0.137	0.137	
Disagreement		0.170		0.111		

Table 4.20. F-test results of Expert Panel 10.

Panel Description	Disagreement	F-test Value	F-Critical (0.1)	F-Critical (0.05)	F-Critical (0.025)	F-Critical (0.01)
Technical Perspectives	**0.123**	18.25	2.16	2.72	3.29	4.04
System Efficiency	**0.170**	6.31	2.91	4.23	5.66	7.72
Process Safety	**0.111**	24.36	2.91	4.23	5.66	7.72

Expert Panel 10 is composed of professionals from various regions and expertise, each bringing a unique perspective to the table. The panel includes representatives from the USA, Italy, the Netherlands, Finland, the UK, Spain, Norway, and Turkey as seen in Table 4.21. Their affiliations span a range of sectors, including governmental organizations, research institutions, technology providers, and the oil and gas industry.

Table 4.21. Composition of Expert Panel 10.

Expert No.	Title/Position	Organization Type	Country
Expert 102	Professor in Chemical Reaction Engineering	Research Institution	Slovenia
Expert 100	Advisor	Technology Provider	UK
Expert 105	CO2 Storage Development Manager	Oil & Gas	UK
Expert 104	Professor in Petroleum Engineering	Research Institution	USA
Expert 109	Senior Consultant	Technology Provider	Netherlands
Expert 57	Digital Transformation Manager	Oil & Gas	Turkey
Expert 103	Advisor	Governmental Organization	Norway
Expert 83	Researcher	Research Institution	USA
Expert 111	Principal Account Manager	Technology Provider	Turkey
Expert 107	Research Associate	Research Institution	Greece
Expert 108	Senior Researcher	Research Institution	Germany
Expert 110	Project Manager	Technology Provider	Germany
Expert 106	Researcher	Oil & Gas	Finland
Expert 112	Professor in Chemical Technology	Research Institution	Portugal
Expert 113	Technology Specialist	Technology Provider	UK
Expert 114	Projects Director	Technology Provider	Italy
Expert 59	Process Director	Oil & Gas	Turkey
Expert 101	Head of Operations	Oil & Gas	Italy
Expert 115	Technical Services Director	Oil & Gas	Turkey
Expert 81	R&D Experimental Chapter Lead	Oil & Gas	Turkey
Expert 162	Process & Technologies Vice President	Oil & Gas	Italy
Expert 167	Technology Manager	Oil & Gas	Italy
Expert 168	Process Engineer	Oil & Gas	Netherlands
Expert 170	Technical Advisor	Oil & Gas	Spain
Expert 171	Operations & Production Engineer	Oil & Gas	Italy
Expert 176	GHG Technical Advisor	Oil & Gas	Spain
Expert 180	R&D Project Manager	Oil & Gas	Italy

4.4.5. Quantification Results of Environmental Criteria

The experts in Expert Panel 11, were asked to compare the environmental criteria in terms of significance that affect the implementation of low-carbon energy technologies for the oil and gas industry. The arithmetic means of the relative importance of environmental criteria are shown in Figure 4.36. The criterion of air emissions is the most significant criterion with a weight of 0.283 in Expert Panel 11. This result shows that the mitigation of atmospheric pollutants is the primary concern for experts. The second most important criterion is the usage of resources with a weight of 0.264, it accentuates the significance of sustainable resource management. The pollution criterion is in the third place with a weight of 0.255, it emphasizes the broader environmental challenge of addressing contaminants across diverse mediums; water, soil, and groundwater. Lastly, co-benefitting at a weight of 0.200, shows the benefits and positive contributions to environmental initiatives.

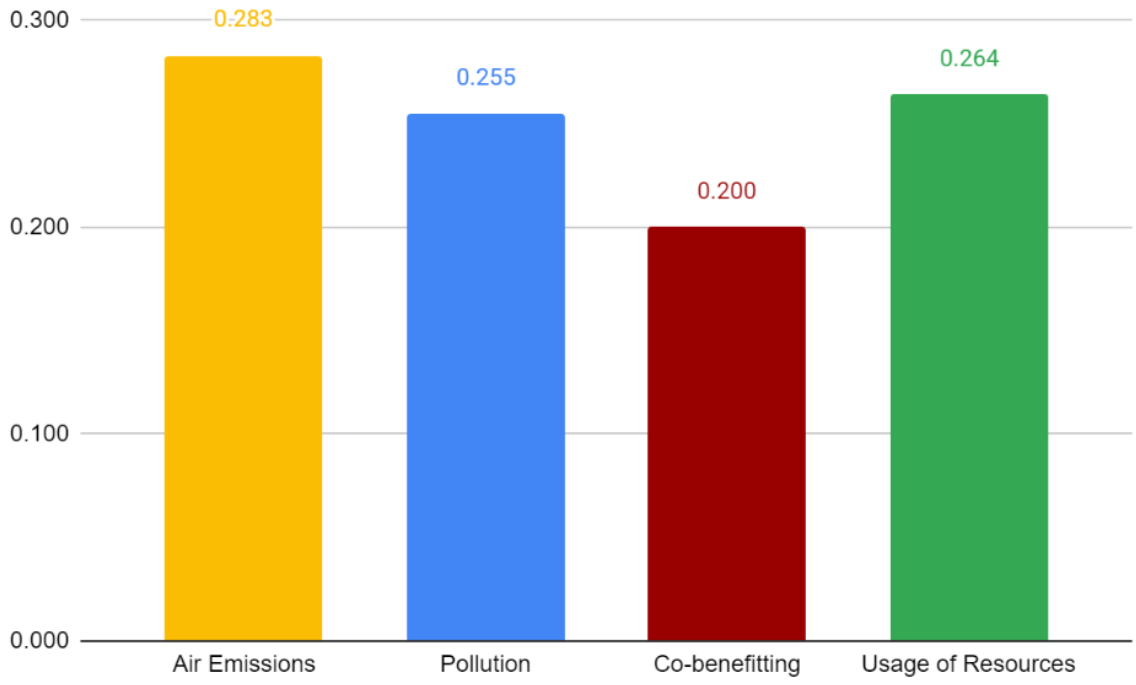

Figure 4.36. The importance weights of environmental criteria in the model

In Expert Panel 11, sub-criteria set of air emissions, pollution, and usage of resources were also investigated. The results of the relative importance of each sub-criteria are shown in Figure 4.37, Figure 4.38, Figure 4.39. Air emissions have two sub-criteria: GHG emissions and other air emissions. According to the panel results, GHG emissions stand the most important sub-criterion with a weight of 0.678 and the relative importance of other air emissions is less than GHG emissions with a weight of 0.323. The pollution criterion has four sub-criteria, namely, water

pollution, solid waste generation, hazardous waste generation, soil and groundwater pollution. Foremost, the sub-criterion of soil and groundwater pollution is ranked as the most important sub-criterion since the remediation of subsurface water resources from contaminants is a very challenging issue. This is followed by the water pollution sub-criterion with a weight of 0.298. The sub-criterion of hazardous waste generation is allocated as the third important sub-criterion with a weight of 0.213. Experts highlighted the significance of managing and mitigating hazardous wastes with potentially detrimental environmental and health effects. Lastly, the sub-criterion of solid waste generation ranked as the least important sub-criterion with a weight of 0.138. The usage of resources criterion has three sub-criteria that assess the usage of freshwater, the demand for critical minerals for producing clean energy technologies, and the type of feedstock. At the forefront, freshwater usage is ranked as the most important sub-criterion with a weight of 0.457. Following this, the sub-criterion of critical minerals is ranked as the second most important sub-criterion with a weight of 0.282. Lastly, the sub-criterion of feedstock type is placed as a less important sub-criterion with a weight of 0.262, this sub-criterion highlights raw materials input and sustainable management.

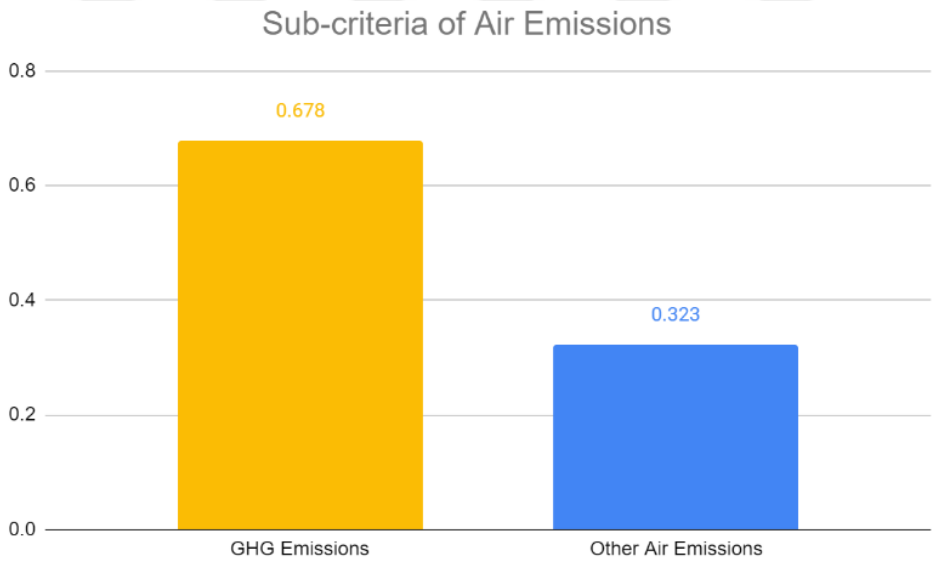

Figure 4.37. The importance weights of air emissions sub-criteria in the model.

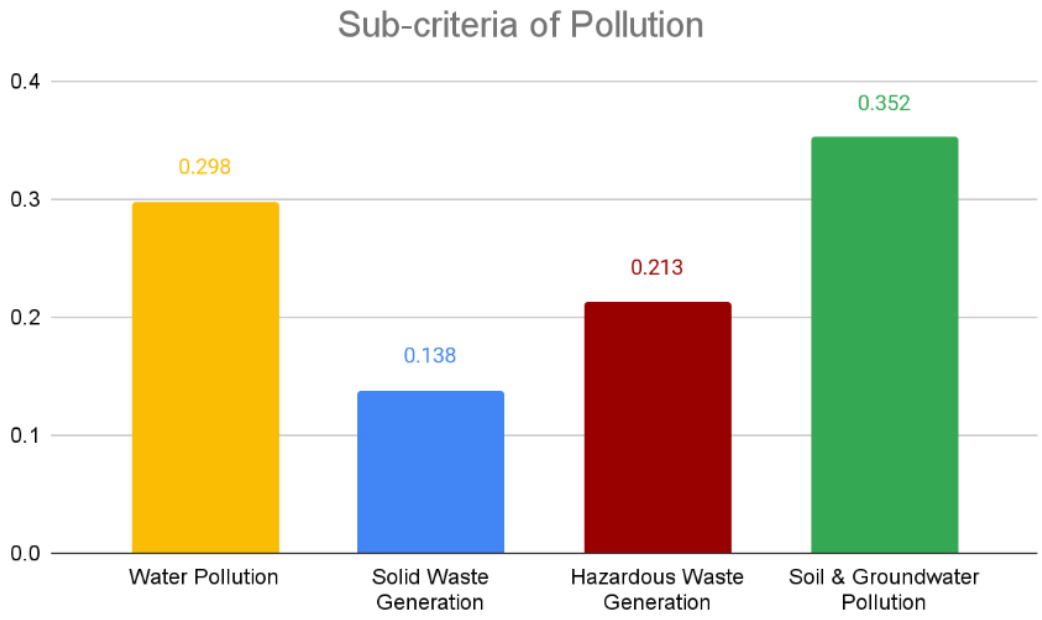

Figure 4.38. The importance weights of pollution sub-criteria in the model.

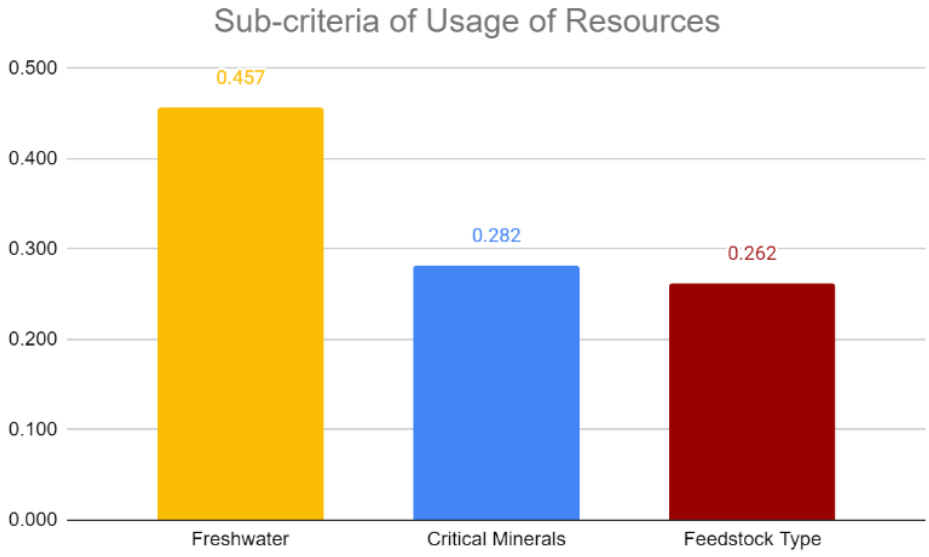

Figure 4.39. The importance weights of usage of resources sub-criteria in the model.

29 experts participated in Expert Panel 11 for the assessment of environmental criteria that play role in the implementation of low-carbon energy technologies in oil and gas industry. Each expert answered the pairwise comparison questions and the data were consolidated for further investigation. Among the 29 experts, five experts have inconsistent responses. Expert 126, Expert 129, Expert 136, Expert 137 and Expert 169 had high inconsistency values of 0.10, 0.15, 0.18, 0.14, and 0.10, respectively. RSV calculations were applied to investigate whether the inconsistency values were at an acceptable level or not. According to Abbas (2016), the RSV value for 4 variables should remain below 0.1886 at an 85 % confidence level. The RSV values of Expert 126, Expert

129, Expert 136, Expert 137 and Expert 169 were 0.37, 0.40, 0.38, 0.32 and 0.26, respectively. Given these results, the expert responses that had higher RSV values than 0.1886, Experts 126, Expert 129, Expert 136, Expert 137, and Expert 169 were removed from the data repository.

The criteria and sub-criteria level results of each expert and group disagreement value of Expert Panel 11 are presented in Table 4.22 to Table 4.25. Group disagreement values of Expert Panel 11 for criteria level, air emissions sub-criteria level, pollution sub-criteria level, and usage of resources sub-criteria level are 0.085, 0.109, 0.080, and 0.104, respectively. The group disagreement values of the air emissions sub-criteria and usage of resources sub-criteria were higher than the threshold value of 0.1, the statistical F-test performed.

Table 4.26 shows the F-test results of air emissions sub-criteria and usage of resources sub-criteria. Since the F-test values are lower than the critical F-values at all significance levels, it can be stated that a statistically significant agreement exists among the experts and further disagreement analysis is not needed to be performed to solve the disagreement and identify the decision groups.

Table 4.22. Quantification results of environmental criteria.

Expert No.	CRITERIA LEVEL				
	Air Emissions	**Pollution**	**Co-benefitting**	**Usage of Resources**	**Inconsistency**
Expert 118	0.25	0.24	0.25	0.26	0.00
Expert 122	0.35	0.35	0.02	0.29	0.01
Expert 124	0.22	0.25	0.28	0.25	0.01
Expert 119	0.26	0.32	0.17	0.26	0.01
Expert 123	0.44	0.19	0.29	0.08	0.04
Expert 128	0.29	0.29	0.29	0.13	0.00
Expert 130	0.31	0.31	0.08	0.31	0.00
Expert 131	0.25	0.25	0.25	0.25	0.00
Expert 132	0.34	0.41	0.12	0.13	0.03
Expert 125	0.16	0.17	0.23	0.44	0.08
Expert 77	0.22	0.38	0.16	0.24	0.01
Expert 117	0.23	0.12	0.21	0.44	0.07
Expert 133	0.31	0.31	0.14	0.24	0.03
Expert 127	0.27	0.21	0.37	0.16	0.03
Expert 134	0.20	0.20	0.33	0.27	0.04
Expert 116	0.33	0.33	0.16	0.19	0.01
Expert 135	0.22	0.42	0.09	0.28	0.01
Expert 120	0.48	0.11	0.14	0.27	0.06
Expert 159	0.21	0.13	0.26	0.4	0.02
Expert 165	0.38	0.17	0.22	0.23	0.08
Expert 172	0.19	0.35	0.13	0.33	0.03
Expert 173	0.46	0.16	0.20	0.18	0.03
Expert 175	0.11	0.18	0.33	0.38	0.01
Expert 183	0.32	0.28	0.09	0.32	0.01
Mean	**0.283**	**0.255**	**0.200**	**0.264**	
Minimum	0.11	0.11	0.02	0.08	
Maximum	0.48	0.42	0.37	0.44	
Std. Deviation	0.093	0.092	0.091	0.093	
Disagreement					0.085

Table 4.23. Quantification results of air emissions sub-criteria.

Expert No.	SUB-CRITERIA of AIR EMISSIONS		
	GHG Emissions	**Other Air Emissions**	**Inconsistency**
Expert 118	0.50	0.50	0.00
Expert 122	0.60	0.40	0.00
Expert 124	0.81	0.19	0.00
Expert 119	0.61	0.39	0.00
Expert 123	0.80	0.20	0.00
Expert 128	0.60	0.40	0.00
Expert 130	0.50	0.50	0.00
Expert 131	0.50	0.50	0.00
Expert 132	0.49	0.51	0.00
Expert 125	0.60	0.40	0.00
Expert 77	0.70	0.30	0.00
Expert 117	0.80	0.20	0.00
Expert 133	0.60	0.40	0.00
Expert 127	0.75	0.25	0.00
Expert 134	0.80	0.20	0.00
Expert 116	0.75	0.25	0.00
Expert 135	0.80	0.20	0.00
Expert 120	0.55	0.45	0.00
Expert 159	0.71	0.29	0.00
Expert 165	0.90	0.10	0.00
Expert 172	0.70	0.30	0.00
Expert 173	0.90	0.10	0.00
Expert 175	0.69	0.31	0.00
Expert 183	0.60	0.40	0.00
Mean	**0.678**	**0.323**	
Minimum	0.49	0.10	
Maximum	0.90	0.51	
Std. Deviation	0.127	0.127	
Disagreement			0.109

Table 4.24. Quantification results of pollution sub-criteria.

Expert No.	SUB-CRITERIA of POLLUTION				
	Water Pollution	**Solid Waste Generation**	**Hazardous Waste Generation**	**Soil & Groundwater Pollution**	**Inconsistency**
Expert 118	0.25	0.09	0.31	0.35	0.01
Expert 122	0.29	0.14	0.36	0.21	0.02
Expert 124	0.18	0.22	0.33	0.27	0.02
Expert 119	0.40	0.12	0.24	0.23	0.02
Expert 123	0.16	0.24	0.33	0.27	0.04
Expert 128	0.28	0.11	0.33	0.28	0.01
Expert 130	0.19	0.15	0.14	0.52	0.03
Expert 131	0.23	0.12	0.33	0.33	0.05
Expert 132	0.31	0.04	0.05	0.60	0.03
Expert 125	0.38	0.22	0.09	0.31	0.01
Expert 77	0.30	0.12	0.21	0.38	0.01
Expert 117	0.40	0.13	0.07	0.40	0.03
Expert 133	0.30	0.05	0.19	0.46	0.09
Expert 127	0.28	0.27	0.15	0.30	0.00
Expert 134	0.32	0.14	0.27	0.27	0.02
Expert 116	0.27	0.16	0.24	0.33	0.00
Expert 135	0.46	0.14	0.11	0.30	0.02
Expert 120	0.41	0.09	0.20	0.30	0.04
Expert 159	0.35	0.10	0.26	0.28	0.03
Expert 165	0.35	0.06	0.06	0.53	0.02
Expert 172	0.31	0.13	0.19	0.37	0.00
Expert 173	0.30	0.11	0.24	0.35	0.00
Expert 175	0.17	0.27	0.03	0.53	0.06
Expert 183	0.26	0.10	0.37	0.27	0.02
Mean	**0.298**	**0.138**	**0.213**	**0.352**	
Minimum	0.16	0.04	0.03	0.21	
Maximum	0.46	0.27	0.37	0.60	
Std. Deviation	0.079	0.064	0.106	0.105	
Disagreement					0.080

Table 4.25. Quantification results of usage of resources sub-criteria.

Expert No.	SUB-CRITERIA of USAGE of RESOURCES			
	Freshwater	**Critical Minerals**	**Feedstock Type**	**Inconsistency**
Expert 118	0.48	0.18	0.36	0.00
Expert 122	0.54	0.05	0.41	0.00
Expert 124	0.33	0.33	0.33	0.00
Expert 119	0.55	0.28	0.17	0.00
Expert 123	0.28	0.59	0.13	0.00
Expert 128	0.38	0.25	0.38	0.00
Expert 130	0.67	0.17	0.17	0.00
Expert 131	0.33	0.33	0.33	0.00
Expert 132	0.48	0.32	0.20	0.03
Expert 125	0.45	0.26	0.28	0.00
Expert 77	0.45	0.28	0.26	0.00
Expert 117	0.55	0.31	0.14	0.02
Expert 133	0.29	0.38	0.34	0.03
Expert 127	0.49	0.27	0.24	0.03
Expert 134	0.41	0.18	0.41	0.00
Expert 116	0.29	0.43	0.29	0.00
Expert 135	0.33	0.33	0.33	0.00
Expert 120	0.47	0.42	0.11	0.00
Expert 159	0.76	0.15	0.09	0.00
Expert 165	0.21	0.37	0.42	0.01
Expert 172	0.40	0.27	0.33	0.01
Expert 173	0.76	0.11	0.13	0.01
Expert 175	0.64	0.21	0.15	0.00
Expert 183	0.43	0.29	0.29	0.00
Mean	**0.457**	**0.282**	**0.262**	
Minimum	0.21	0.05	0.09	
Maximum	0.76	0.59	0.42	
Std. Deviation	0.147	0.115	0.105	
Disagreement				0.104

Table 4.26. F-test results of Expert Panel 11.

Panel Description	Disagreement	F-test Value	F-Critical (0.1)	F-Critical (0.05)	F-Critical (0.025)	Fcritical (0.01)
Air Emissions	**0.109**	47.02	2.94	4.28	5.75	7.88
Usage of Resources	**0.104**	12.10	2.42	3.2	4	5.1

Table 4.27. Composition of Expert Panel 11.

Expert No.	Title/Position	Organization Type	Country
Expert 118	Climate Expert	Technology Provider	Germany
Expert 122	Sustainability and Climate Change Coordinator	Oil & Gas	Turkey
Expert 124	Professor in Department of Chemical Engineering	Research Institution	Nigeria
Expert 119	Sustainability Group Manager	Technology Provider	Turkey
Expert 123	Key Researcher	Research Institution	Austria
Expert 128	Expert in Green Hydrogen (Ph.D.)	Technology Provider	Sweden
Expert 130	Collaborating Professor in Chemical Engineering	Research Institution	Brazil
Expert 131	Professor in Chemical and Biomolecular Engineering	Research Institution	USA
Expert 132	Senior Research Executive	Oil & Gas	USA
Expert 125	Head of Renewable Energy & Environmental R&D	Oil & Gas	Italy
Expert 77	Operating Superintendent	Oil & Gas	Turkey
Expert 117	Head of Magnetic Fusion Initiatives	Oil & Gas	Italy
Expert 133	Professor in Chemical and Biological Engineering	Research Institution	USA
Expert 127	Senior Research Director	Research Institution	Qatar
Expert 134	Professor in Chemical Engineering	Research Institution	Brazil
Expert 116	LCA Lead	Oil & Gas	UK
Expert 135	Environmental Analyst	Governmental Organization	Brazil
Expert 120	LCA Expert	Oil & Gas	Turkey
Expert 159	Sustainability Strategy Senior Manager	Oil & Gas	Spain
Expert 165	Senior Scientist in Circular Economy Technologies	Oil & Gas	Spain
Expert 172	Environmental Engineer	Oil & Gas	Italy
Expert 173	Carbon & Sustainability Advisor	Oil & Gas	Netherlands
Expert 175	R&D Project Engineer	Oil & Gas	Italy
Expert 183	Researcher	Oil & Gas	Italy

The expert panel 11 assembled for this study represents diverse and comprehensive professionals from various regions and oil and gas sector. Experts from 15 different countries,

contributed to this panel as seen in Table 4.27. Additionally, a significant portion of the experts are affiliated with the oil and gas industry, holding positions such as sustainability and climate change coordinators, LCA leads, and environmental engineers. A few experts also come from governmental organizations, adding a dimension of regulatory and policy understanding to this panel. Collectively, the panel's composition ensures a holistic perspective on the environmental topic under consideration.

4.4.6. Quantification Results of Political Criteria

The experts in Expert Panel 12, were asked to compare the political criteria in terms of significance that affect the implementation of low-carbon energy technologies for the oil and gas industry. The arithmetic means of the relative importance of political criteria are shown in Figure 4.40.

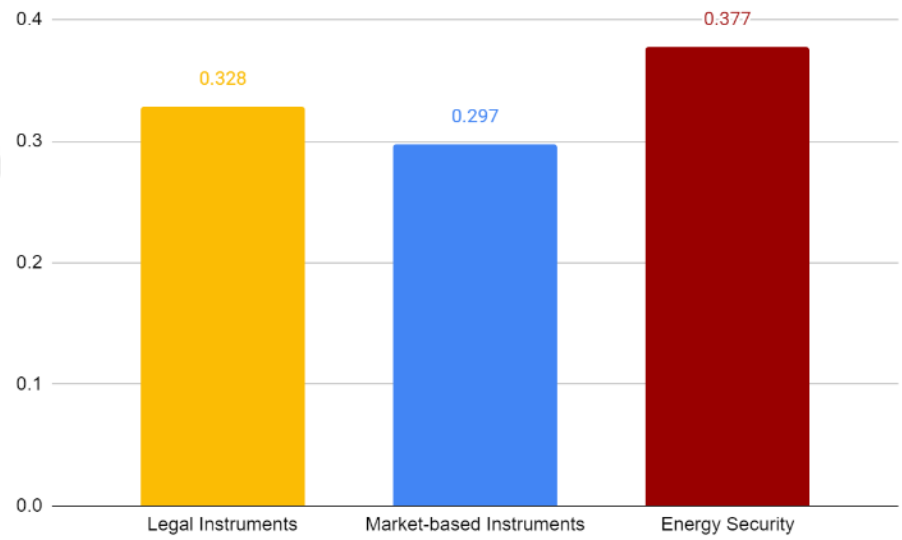

Figure 4.40. The importance weights of political criteria in the model.

The criterion of energy security is the most critical with a weight of 0.377 since it emphasizes the stable and uninterrupted energy supply which is primary for both economic stability and national security. Legal and regulatory instruments follow the criterion of energy security with a weight of 0.328. This criterion proves that the significance of regulatory frameworks and legal mechanisms has great pressure on shaping energy policies, and sustainable energy systems. Market-based policy instruments (MBIs) were ranked in third place with a weight of 0.297. MBIs emphasize the importance of economic tools and mechanisms such as emission trading, and carbon tax.

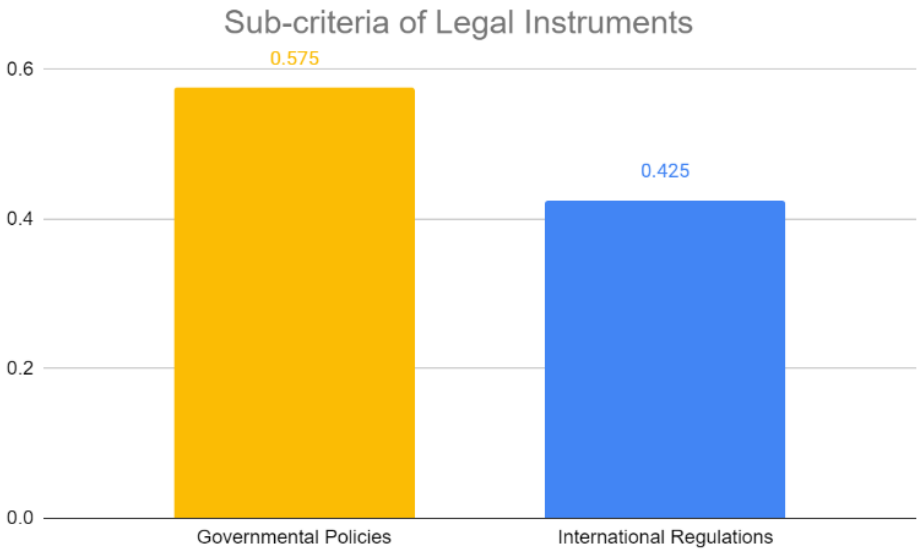

Figure 4.41. The importance weights of legal instruments sub-criteria in the model.

The pairwise comparison assessment of two sets of sub-criteria; legal instruments and market-based policy instruments was also performed in Expert Panel 12. Legal and regulatory instruments have two sub-criteria: governmental policies and international regulations which are two primary drivers of energy and environmental strategies. According to the results, governmental policies were selected as the most important sub-criterion over international regulations with a weight of 0.575. International regulations sub-criterion with a weight of 0.425 is also critical but it is slightly less emphasized than governmental policies as seen in Figure 4.41. The market-based policy instruments have also 3 sub-criterions: these are ETS, carbon tax, and subsidies. Due to experts' results, ETS was the most important sub-criterion with a weight of 0.392, as seen in Figure 4.42. Experts indicated that ETS is a prominent tool for regulating GHG emissions by allowing entities to buy or sell allowances. Then, the carbon tax is ranked as the second most critical sub-criterion with a weight of 0.338. Taxation is the power of fiscal policies in influencing energy consumption patterns and it promotes cleaner energy alternatives. Lastly, the criterion of subsidies is ranked in third place with a weight of 0.268. The role of subsidies is evident since the governments put financial incentives to preferred energy sources or technologies and they try to ensure their competitiveness and viability in the market.

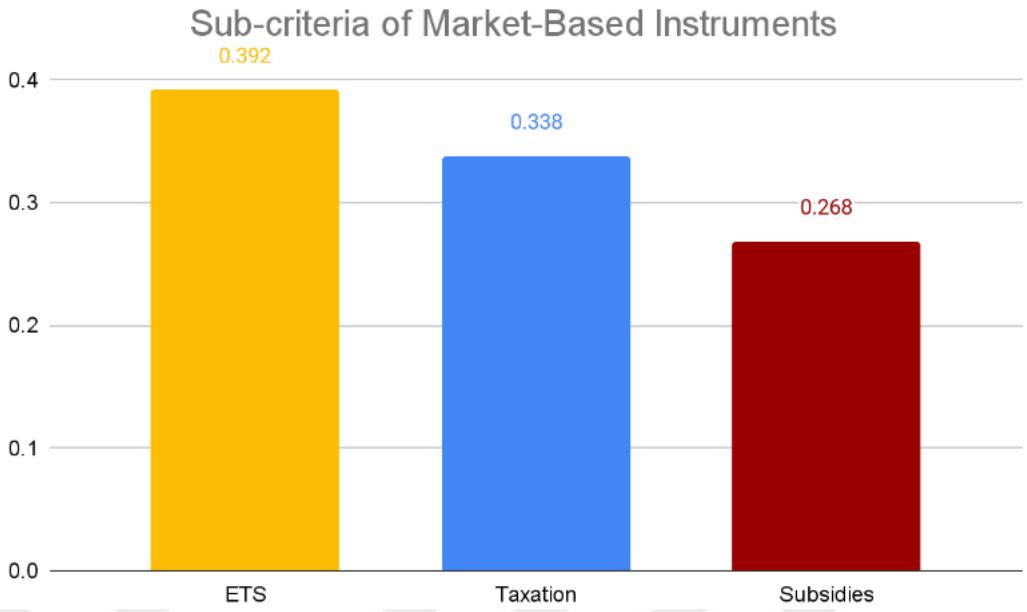

Figure 4.42. The importance weights of MBIs sub-criteria in the model.

25 experts participated in Expert Panel 12 for the assessment of political criteria that affect the implementation of low carbon energy technologies in the oil and gas industry. Pairwise comparison questions were responded to by the experts, and then the data were consolidated by calculating the importance weights of the criteria and sub-criteria. Among the 25 experts, three experts had inconsistent quantification responses. Expert 139, Expert 140, and Expert 142 had high inconsistency values of 0.30, 0.13 and 0.10, respectively. RSV calculations were performed to examine further whether the inconsistency values were at an acceptable level or not. According to Abbas (2016), the RSV value for three variables should not exceed 0.0129 for an 85 % confidence level. The RSV calculations of Expert 139, Expert 140, and Expert 142 were 0.66, 0.35 and 0.28, respectively. Since the RSV results exceeded the threshold value of 0.0129, these experts were removed from the data repository to maintain treated results.

After the data refinement, the data of 22 experts were used for determining the relative importance weights of political criteria and sub-criteria. The criteria and sub-criteria level results of each expert and the group disagreement value of 22 experts are shown in Table 4.28 to Table 4.30.

Table 4.28. Quantification results of political criteria.

Expert No.	CRITERIA LEVEL			
	Legal Instruments	**Market-based Instruments**	**Energy Security**	**Inconsistency**
Expert 141	0.14	0.11	0.75	0.01
Expert 144	0.42	0.21	0.37	0.01
Expert 138	0.29	0.17	0.54	0.03
Expert 146	0.45	0.37	0.18	0.01
Expert 147	0.25	0.38	0.38	0.00
Expert 149	0.25	0.33	0.43	0.00
Expert 150	0.41	0.18	0.41	0.00
Expert 151	0.32	0.22	0.46	0.03
Expert 152	0.44	0.44	0.11	0.00
Expert 66	0.21	0.30	0.49	0.00
Expert 121	0.30	0.09	0.61	0.03
Expert 148	0.43	0.43	0.14	0.00
Expert 143	0.20	0.54	0.26	0.00
Expert 145	0.50	0.50	0.01	0.00
Expert 153	0.55	0.22	0.23	0.00
Expert 154	0.51	0.27	0.22	0.01
Expert 156	0.19	0.23	0.58	0.05
Expert 17	0.36	0.18	0.47	0.00
Expert 166	0.16	0.30	0.54	0.00
Expert 177	0.33	0.25	0.43	0.00
Expert 181	0.31	0.27	0.43	0.00
Expert 182	0.20	0.54	0.26	0.00
Mean	**0.328**	**0.297**	**0.377**	
Minimum	0.14	0.09	0.01	
Maximum	0.55	0.54	0.75	
Std. Deviation	0.12	0.13	0.18	
Disagreement				0.130

Table 4.29. Quantification results of legal and regulatory instruments sub-criteria.

Expert No.	SUB-CRITERIA of LEGAL INSTRUMENTS		
	Governmental Policies	International Regulations	Inconsistency
Expert 141	0.60	0.40	0.00
Expert 144	0.50	0.50	0.00
Expert 138	0.73	0.27	0.00
Expert 146	0.60	0.40	0.00
Expert 147	0.90	0.10	0.00
Expert 149	0.50	0.50	0.00
Expert 150	0.50	0.50	0.00
Expert 151	0.21	0.79	0.00
Expert 152	0.60	0.40	0.00
Expert 66	0.60	0.40	0.00
Expert 121	0.60	0.40	0.00
Expert 148	0.75	0.25	0.00
Expert 143	0.60	0.40	0.00
Expert 145	0.50	0.50	0.00
Expert 153	0.81	0.19	0.00
Expert 154	0.50	0.50	0.00
Expert 156	0.45	0.55	0.00
Expert 17	0.60	0.40	0.00
Expert 166	0.70	0.30	0.00
Expert 177	0.60	0.40	0.00
Expert 181	0.40	0.60	0.00
Expert 182	0.40	0.60	0.00
Mean	0.575	0.425	
Minimum	0.21	0.10	
Maximum	0.90	0.79	
Std. Deviation	0.15	0.15	
Disagreement			0.110

Table 4.30. Quantification results of market-based instruments sub-criteria.

Expert No.	SUB-CRITERIA of MARKET-BASED INSTRUMENTS			
	ETS	**Taxation**	**Subsidies**	**Inconsistency**
Expert 141	0.33	0.33	0.33	0.00
Expert 144	0.41	0.41	0.18	0.00
Expert 138	0.59	0.13	0.27	0.00
Expert 146	0.22	0.47	0.31	0.03
Expert 147	0.39	0.39	0.21	0.00
Expert 149	0.38	0.38	0.25	0.00
Expert 150	0.38	0.33	0.29	0.02
Expert 151	0.60	0.25	0.16	0.05
Expert 152	0.41	0.47	0.12	0.00
Expert 66	0.39	0.31	0.30	0.00
Expert 121	0.62	0.11	0.26	0.00
Expert 148	0.05	0.41	0.54	0.00
Expert 143	0.67	0.21	0.12	0.02
Expert 145	0.51	0.24	0.25	0.00
Expert 153	0.14	0.23	0.63	0.00
Expert 154	0.33	0.33	0.33	0.00
Expert 156	0.31	0.62	0.07	0.00
Expert 17	0.44	0.44	0.11	0.00
Expert 166	0.27	0.24	0.48	0.02
Expert 177	0.47	0.36	0.18	0.00
Expert 181	0.38	0.44	0.18	0.00
Expert 182	0.33	0.33	0.33	0.00
Mean	**0.392**	**0.338**	**0.268**	
Minimum	0.05	0.11	0.07	
Maximum	0.67	0.62	0.63	
Std. Deviation	0.15	0.12	0.14	
Disagreement				0.113

The group disagreement values of political criteria, legal instruments sub-criteria, and MBIs sub-criteria are 0.130, 0.110 and 0.113, respectively. Since the disagreement values are above the threshold limit, the statistical F-test was performed for the whole sub-part of expert panel 12. Table

4.31 shows the F-test results at a significance level of 0.1, 0.05, 0.025, and 0.01. Since the F-test values of political criteria and MBIs sub-criteria are lower than the critical F value at 0.05 significance level, it can be stated that there is a statistically significant disagreement among the experts and further disagreement analysis should be done to identify the subgroups.

Table 4.31. F-test results of Expert Panel 12.

Panel Description	Disagreement	F-test Value	F-Critical (0.1)	F-Critical (0.05)	F-Critical (0.025)	F-Critical (0.01)
Political Perspectives	**0.130**	1.13	2.43	3.22	4.03	5.15
Legal & Regulatory Instruments (LRIs)	**0.110**	5.48	2.96	4.32	5.83	8.02
Market-Based Policy Instruments (MBIs)	**0.113**	3.03	2.43	3.22	4.03	5.15

HAC analysis was performed by R to identify subgroups within the Expert Panel 12. Euclidean method is used for computing the pairwise distances and several trials were conducted in order to find the subgroups that had low disagreement values. The trials were performed by changing the linkage method and number of clusters. The average linkage method was used for identifying the subgroups. The outcome of this analysis showed the formation of three distinct subgroups and clustering results in the form of the dendrogram is shown in Figure 4.43. These subgroups show low disagreement values, indicating a higher degree of consensus within each subgroup. Table 4.32 to Table 4.34 exhibit the relative priorities of experts, inconsistency values, and disagreement values of Subgroup A, Subgroup B, and Subgroup C, respectively. Each subgroup shows varied preferences towards the criteria of legal instruments, MBIs, and energy security. Subgroup A predominantly emphasized the importance of energy security. Subgroup B leaned towards the legal instruments with a more consistent set of values. On the other hand, Subgroup C exhibited a balanced perspective across all criteria, the criterion of energy security was slightly leading, but it indicated from more uniform viewpoint. The range of values for each criterion is narrower compared to Subgroup A, but it indicated a more consistent opinion among the experts.

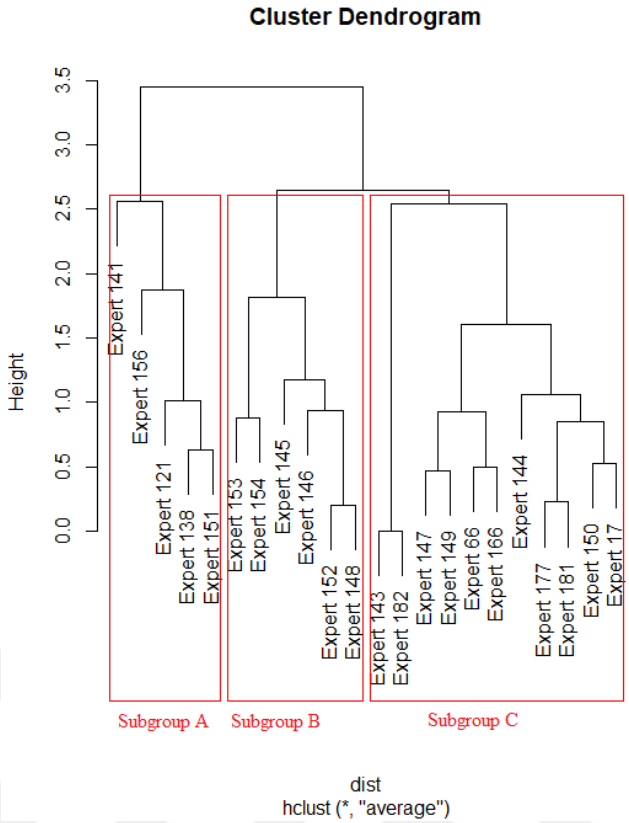

Figure 4.43. Dendrogram of subgroups of Expert Panel 12 for the assessment of political perspective.

Table 4.32. Analysis of the results of Subgroup A in Expert Panel 12 for the assessment of political perspective.

Expert No.	**CRITERIA LEVEL**			
	Legal Instruments	**Market-based Instruments**	**Energy Security**	**Inconsistency**
Expert 141	0.14	0.11	0.75	0.01
Expert 138	0.29	0.17	0.54	0.03
Expert 151	0.32	0.22	0.46	0.03
Expert 152	0.44	0.44	0.11	0.00
Expert 121	0.30	0.09	0.61	0.03
Expert 156	0.19	0.23	0.58	0.05
Mean	**0.280**	**0.210**	**0.508**	
Minimum	0.14	0.09	0.11	
Maximum	0.44	0.44	0.75	
Std. Deviation	0.11	0.13	0.22	
Disagreement				0.070

Table 4.33. Analysis of the results of Subgroup B in Expert Panel 12 for the assessment of political perspective.

Expert No.	**CRITERIA LEVEL**			
	Legal Instruments	**Market-based Instruments**	**Energy Security**	**Inconsistency**
Expert 146	0.45	0.37	0.18	0.01
Expert 152	0.44	0.44	0.11	0.00
Expert 148	0.43	0.43	0.14	0.00
Expert 145	0.50	0.50	0.01	0.00
Expert 153	0.55	0.22	0.23	0.00
Expert 154	0.51	0.27	0.22	0.01
Mean	**0.480**	**0.372**	**0.148**	
Minimum	0.43	0.22	0.01	
Maximum	0.55	0.50	0.23	
Std. Deviation	0.05	0.11	0.08	
Disagreement				0.069

In the assessment of market-based policy instruments conducted by Expert Panel 12, disagreements were also observed. These disagreements emerge from varied perspectives, backgrounds, and interpretations of experts regarding the importance and implications of these instruments. It is essential to categorize these different viewpoints to understand the model outcomes better. By segmenting the panel into subgroups based on their responses, provides clarity on the experts' judgments. HAC analysis was also applied again to identify the subgroups for MBIs' preferences within the Expert Panel 12. The Euclidean method for pairwise distances and the complete method for the linkage were used to identify the subgroups. Two subgroups were formed as shown in Figure 4.44. These two subgroups had low disagreement values. Table 4.35 and Table 4.36 show the relative priorities of experts, inconsistency values, and disagreement values of Subgroup A and Subgroup B, respectively.

Table 4.34. Analysis of the results of Subgroup C in Expert Panel 12 for the assessment of political perspective.

Expert No.	CRITERIA LEVEL			
	Legal Instruments	**Market-based Instruments**	**Energy Security**	**Inconsistency**
Expert 144	0.42	0.21	0.37	0.01
Expert 147	0.25	0.38	0.38	0.00
Expert 149	0.25	0.33	0.43	0.00
Expert 150	0.41	0.18	0.41	0.00
Expert 66	0.21	0.30	0.49	0.00
Expert 143	0.20	0.54	0.26	0.00
Expert 17	0.36	0.18	0.47	0.00
Expert 166	0.16	0.30	0.54	0.00
Expert 177	0.33	0.25	0.43	0.00
Expert 181	0.31	0.27	0.43	0.00
Expert 182	0.20	0.54	0.26	0.00
Mean	**0.282**	**0.316**	**0.406**	
Minimum	0.16	0.18	0.26	
Maximum	0.42	0.54	0.54	
Std. Deviation	0.09	0.13	0.09	
Disagreement				0.087

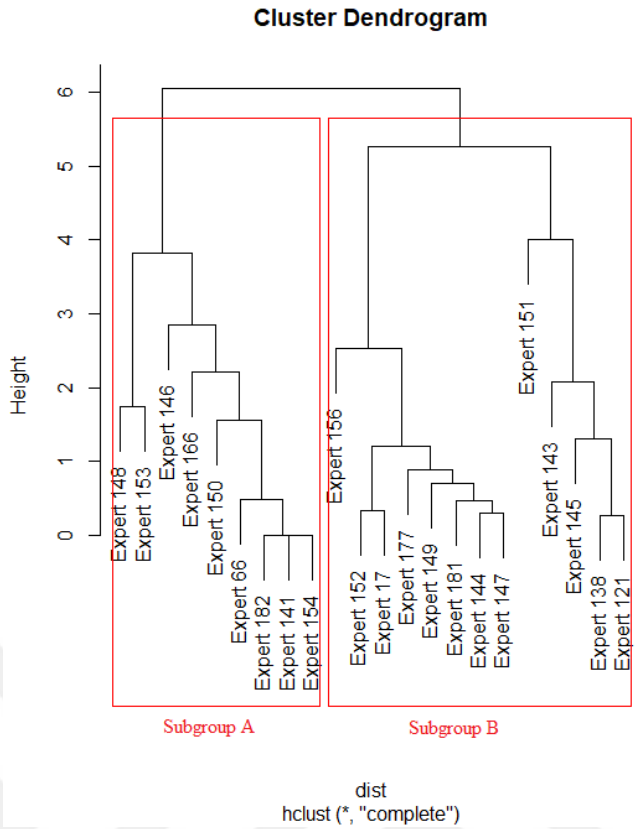

Figure 4.44. Dendrogram of subgroups of Expert Panel 12 for the assessment of MBIs.

Table 4.35. Analysis of the results of Subgroup A in Expert Panel 12 for the assessment of MBIs.

Expert No.	**SUB-CRITERIA of MARKET BASED INSTRUMENTS**			
	ETS	**Taxation**	**Subsidies**	**Inconsistency**
Expert 141	0.33	0.33	0.33	0.00
Expert 146	0.22	0.47	0.31	0.03
Expert 150	0.38	0.33	0.29	0.02
Expert 66	0.39	0.31	0.30	0.00
Expert 148	0.05	0.41	0.54	0.00
Expert 153	0.14	0.23	0.63	0.00
Expert 154	0.33	0.33	0.33	0.00
Expert 166	0.27	0.24	0.48	0.02
Expert 182	0.33	0.33	0.33	0.00
Mean	**0.271**	**0.331**	**0.393**	
Minimum	0.05	0.23	0.29	
Maximum	0.39	0.47	0.63	
Std. Deviation	0.11	0.07	0.12	
Disagreement				0.091

Table 4.36. Analysis of the results of Subgroup B in Expert Panel 12 for the assessment of MBIs.

Expert No.	**SUB-CRITERIA of MARKET BASED INSTRUMENTS**			
	ETS	**Taxation**	**Subsidies**	**Inconsistency**
Expert 144	0.41	0.41	0.18	0.00
Expert 138	0.59	0.13	0.27	0.00
Expert 147	0.39	0.39	0.21	0.00
Expert 149	0.38	0.38	0.25	0.00
Expert 151	0.60	0.25	0.16	0.05
Expert 152	0.41	0.47	0.12	0.00
Expert 121	0.62	0.11	0.26	0.00
Expert 143	0.67	0.21	0.12	0.02
Expert 145	0.51	0.24	0.25	0.00
Expert 156	0.31	0.62	0.07	0.00
Expert 17	0.44	0.44	0.11	0.00
Expert 177	0.47	0.36	0.18	0.00
Expert 181	0.38	0.44	0.18	0.00
Mean	**0.475**	**0.342**	**0.182**	
Minimum	0.31	0.11	0.07	
Maximum	0.67	0.62	0.27	
Std. Deviation	0.11	0.15	0.06	
Disagreement				0.096

The composition of Expert 12 is presented in Table 4.37.

Table 4.37. Composition of Expert Panel 12.

Expert No.	Title/Position	Organization Type	Country
Expert 141	Assoc. Professor in Industrial Ecology & Sustainability	Research Institution	China
Expert 144	Senior Researcher in Energy, Climate and Environment Program	Research Institution	Austria
Expert 138	Professor in Faculty of Technology, Policy, and Management	Research Institution	Netherlands
Expert 146	Professor	Research Institution	Spain
Expert 147	Senior Scientist	Research Institution	USA
Expert 149	Research Fellow	Research Institution	France
Expert 150	Co-Head of Research Unit Sectors and Technologies	Research Institution	Germany
Expert 151	Professor in Integrated Assessment of Global Environmental Change	Research Institution	Netherlands
Expert 152	Professor, President and Scientific Managing Director	Research Institution	Germany
Expert 66	Associate Lecturer	Research Institution	UK
Expert 121	Climate and Sustainability Coordinator	Oil & Gas	Turkey
Expert 148	Energy Analyst	Association	France
Expert 143	Professor in Law Department	Research Institution	Norway
Expert 145	Policy Officer in DG Climate	Governmental Organization	Belgium
Expert 153	Associate Professor in Environmental Energy System Studies	Research Institution	Sweden
Expert 154	Environment, Health, and Safety Manager	Oil & Gas	Turkey
Expert 156	Regional CFO - Tax Manager	Oil & Gas	Spain
Expert 17	Strategy & Business Development Manager	Oil & Gas	Turkey
Expert 166	Climate Change Analyst	Oil & Gas	Italy
Expert 177	International Relations Analyst	Oil & Gas	Italy
Expert 181	Knowledge Owner Sustainability Studies and Scenarios	Oil & Gas	Italy
Expert 182	Sustainability Manager	Oil & Gas	Italy

4.5. Final Weights of Model

The expert evaluations have been methodically quantified; the relative importance of perspectives, various criteria and sub-criteria weighted based on local and global values as shown in Table 4.38, Table 4.39. According to the results, the environmental perspective holds the highest weight with a score of 0.234, underlined by significant factors such as air emissions and pollution. Following closely is the economic perspective, weighted at 0.223, driven by elements like market adoption and R&D investments. The technical perspective is also pivotal, with a weight of 0.211, where system efficiency and process safety are key factors. The political perspective, with a weight

of 0.189, emphasizes the importance of legal and regulatory instruments and energy security. Lastly, the social perspective, while comparatively lower in weight at 0.144, still plays a crucial role, highlighted by criteria such as public acceptance and employment. This comprehensive weighting system effectively represents the aggregate judgments of experts, capturing the nuanced contributions of each criterion across the different perspective.

Table 4.38. Importance Weights of Perspectives and Criteria.

Perspective	Value	Criteria	Local Value of Criteria	Global Value of Criteria
Social	0.144	Public Acceptance	0.186	0.027
		Employment	0.176	0.025
		Working Conditions	0.210	0.030
		Stakeholder Pressure	0.157	0.023
		Public Health and Safety	0.269	0.039
Economic	0.223	Market Adoption	0.249	0.056
		R&D Investments	0.143	0.032
		Cost of Plant	0.228	0.051
		Land Usage and Location	0.136	0.030
		Final Product Type	0.242	0.054
Technical	0.211	System Efficiency	0.189	0.040
		Technology Readiness Level	0.156	0.033
		Process Safety	0.443	0.093
		Integration Capability	0.210	0.044
Environmental	0.234	Air Emissions	0.283	0.066
		Pollution	0.255	0.060
		Co-benefitting	0.200	0.047
		Usage of Resources	0.264	0.062
Political	0.189	Legal & Regulatory Instruments	0.328	0.062
		Market Based Policy Instruments	0.297	0.056
		Energy Security	0.377	0.071

Table 4.39. Importance Weights of Sub-criteria.

Criteria	Sub-criteria	Local Value of Sub-criteria	Global Value of Sub-criteria
Public Acceptance	Public Awareness	0.537	0.014383
	Public Concern	0.463	0.012401
Employment	New Job Opportunities	0.394	0.009986
	Training of employee	0.354	0.008972
	Gender Equity	0.251	0.006361
Working Conditions	Hours of work	0.397	0.012005
	Health & safety of workers	0.603	0.018235
R&D Investments	Private R&D Investments	0.534	0.017029
	Governmental R&D Investments	0.466	0.014860
Cost of Plant	Capital Cost	0.227	0.011542
	Operational Cost	0.155	0.007881
	Feedstock Cost	0.245	0.012457
	Transportation Cost	0.121	0.006152
	Cost Competitiveness	0.256	0.013016
Land Usage and Location	Reliability of Resources	0.469	0.014224
	Feedstock Deliverable	0.272	0.008249
	Required area for resources	0.258	0.007825
System Efficiency	Utility consumption	0.402	0.016031
	Energy Efficiency	0.598	0.023848
Process Safety	Operational Stability	0.630	0.058888
	Easy maintenance	0.370	0.034585
Air Emissions	GHG Emissions	0.678	0.044899
	Other Air Emissions	0.323	0.021390
Pollution	Water Pollution	0.298	0.017782
	Solid Waste Generation	0.138	0.008234
	Hazardous Waste Generation	0.213	0.012710
	Soil & Groundwater Pollution	0.352	0.021004
Usage of Resources	Fresh water	0.457	0.028232
	Critical minerals	0.282	0.017421
	Feedstock	0.262	0.016185
Legal & Regulatory Instruments	Governmental Policies	0.575	0.035645
	International Regulations	0.425	0.026347
Market Based Policy Instruments	ETS	0.392	0.022004
	Taxation	0.338	0.018973
	Subsidies	0.268	0.015044

4.6. Desirability Profiles

The development of desirability metrics for the model started with a literature-based approach. Initially, the metrics were designed by conducting an extensive review of relevant literature on determining the measurement units. Once the measurement units were formulated, these metrics were then presented to the expert panel 13. The last expert panel was formed of 29 selected experts for the refinement and quantification of desirability metrics. Each expert, drawing on their specialized knowledge and experience, assigned a value between 0 and 100 to each metric, indicating its relative desirability. These values, representative of expert opinion and judgment, are instrumental in constructing the desirability curves graph. These graphs are not just a visual tool but a pivotal element in this research, as it translates expert assessments into a quantifiable format. By amalgamating the diverse viewpoints of the experts, the desirability curves provide a robust and nuanced understanding of the metrics, facilitating a more informed and precise decision-making process. This approach exemplifies a collaborative and data-driven methodology, ensuring that the final decision is underpinned by a comprehensive and varied spectrum of expert insights (Estep and Daim, 2018; Giadedi and Daim, 2021). Additionally, these desirability curves serve a crucial tool in evaluating different technologies aimed at reducing CO_2 emissions in the oil and gas sector. This aspect is particularly valuable for experts in the oil and gas industry, as it provides them with a tangible tool to assess the suitability and efficacy of various emission reduction technologies for their specific industry context. By utilizing these curves, industry professionals can make informed decisions about which technologies align best with their operational needs and environmental goals. This approach not only aids in optimizing technology adoption strategies but also contributes significantly to efforts in mitigating environmental impacts within this industry (Giadedi and Daim, 2021).

4.6.1. Desirability Profiles of Social Criteria

The social desirability profiles were composed by oil and gas industry professionals and reflect the mean desirability scores for each sub-criterion and criterion (if the model element does not have any sub-criterion). Participant list for the determination of social desirability profiles is shown in Table 4.40. The quantification results of social desirability profiles are presented in the following tables from Table 4.41 to Table 4.49. The desirability profiles of social criteria are presented in the following figures from Figure 4.45 to Figure 4.53.

Table 4.40. Participant list for the determination of social desirability profiles.

Determination of Desirability Profiles for Social Perspective			
Expert No.	**Title/Position**	**Organization Type**	**Country**
Expert 77	Operating Superintendent	Oil & Gas	Turkey
Expert 120	LCA Expert	Oil & Gas	Turkey
Expert 174	Industrial Hygiene Manager	Oil & Gas	Italy
Expert 185	Safety Specialist	Oil & Gas	Italy
Expert 186	Head of Impact Assessment, Monitoring & Reporting	Oil & Gas	Italy

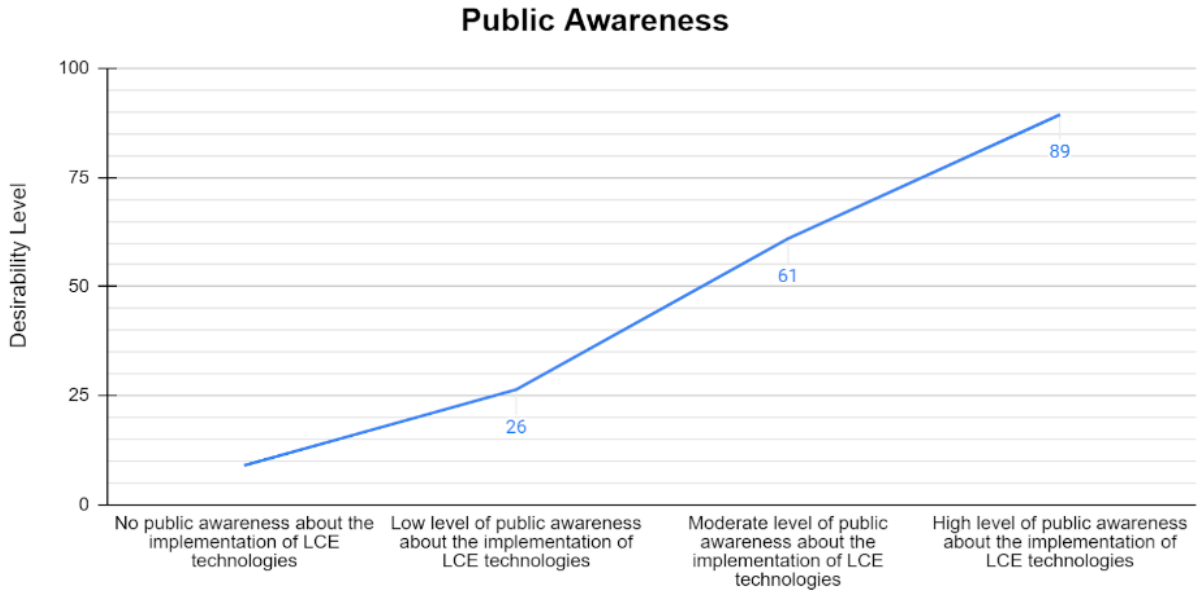

Figure 4.45. Desirability profile for public awareness.

Table 4.41. Desirability units and results for public awareness.

Public Awareness						
Description of Desirability Units	**Expert 77**	**Expert 120**	**Expert 174**	**Expert 185**	**Expert 186**	**Mean**
No public awareness about the implementation of LCE technologies	0	5	40	0	0	9
Low level of public awareness about the implementation of LCE technologies	5	50	28	30	19	26
Moderate level of public awareness about the implementation of LCE technologies	85	75	26	90	29	61
High level of public awareness about the implementation of LCE technologies	100	90	57	100	100	89
This sub-criterion measures public awareness about implementing low-carbon energy (LCE) technologies in the oil and gas industry.						

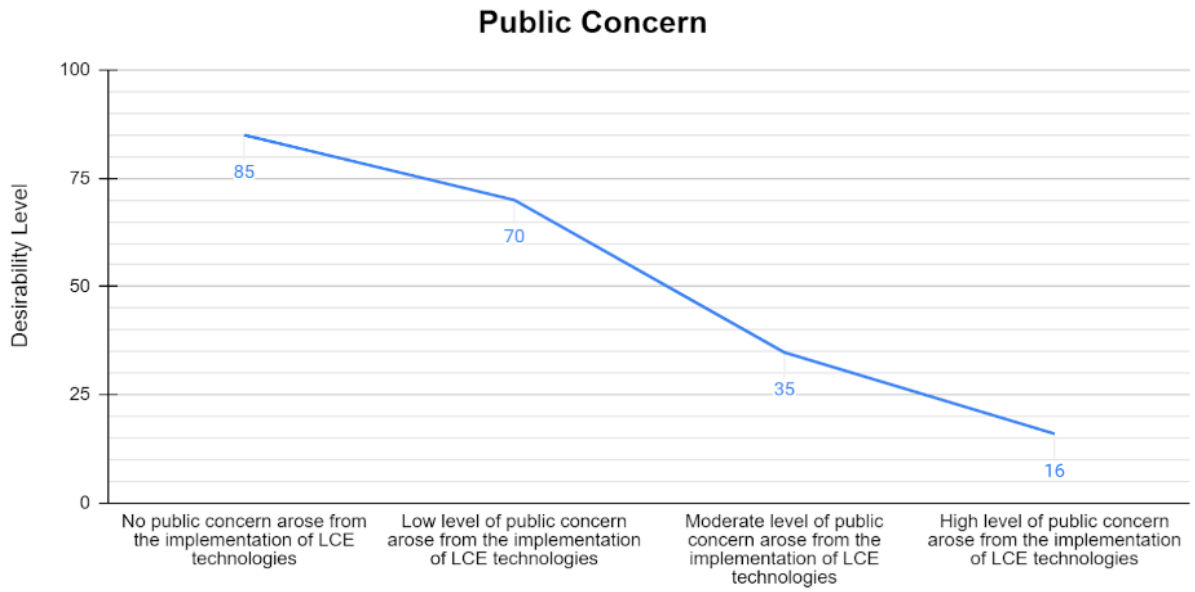

Figure 4.46. Desirability profile for public concern.

Table 4.42. Desirability units and results for public concern.

Public Concern						
Description	**Expert 77**	**Expert 120**	**Expert 174**	**Expert 185**	**Expert 186**	**Mean**
No public concern arose from the implementation of LCE technologies	100	92	51	100	82	85
Low level of public concern arose from the implementation of LCE technologies	85	75	39	90	61	70
Moderate level of public concern arose from the implementation of LCE technologies	5	50	50	30	39	35
High level of public concern arose from the implementation of LCE technologies	0	15	49	0	16	16
This sub-criterion measures public concern about implementing low-carbon energy (LCE) technologies in the oil and gas industry.						

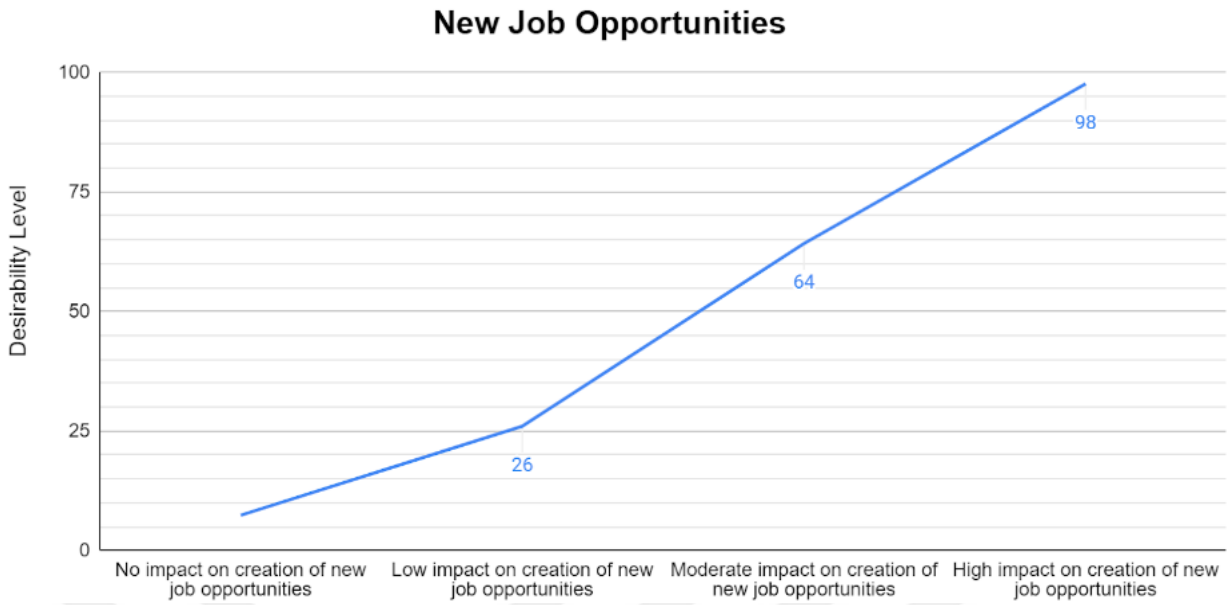

Figure 4.47. Desirability profile for new job opportunities.

Table 4.43. Desirability units and results for new job opportunities.

New Job Opportunities						
Description	**Expert 77**	**Expert 120**	**Expert 174**	**Expert 185**	**Expert 186**	**Mean**
No impact on creation of new job opportunities	5	5	27	0	0	7
Low impact on creation of new job opportunities	10	20	51	40	9	26
Moderate impact on creation of new job opportunities	85	75	76	60	25	64
High impact on creation of new job opportunities	100	96	92	100	100	98
This sub-criterion measures the impact level of low carbon energy technology implementation on new job opportunities in the oil and gas industry.						

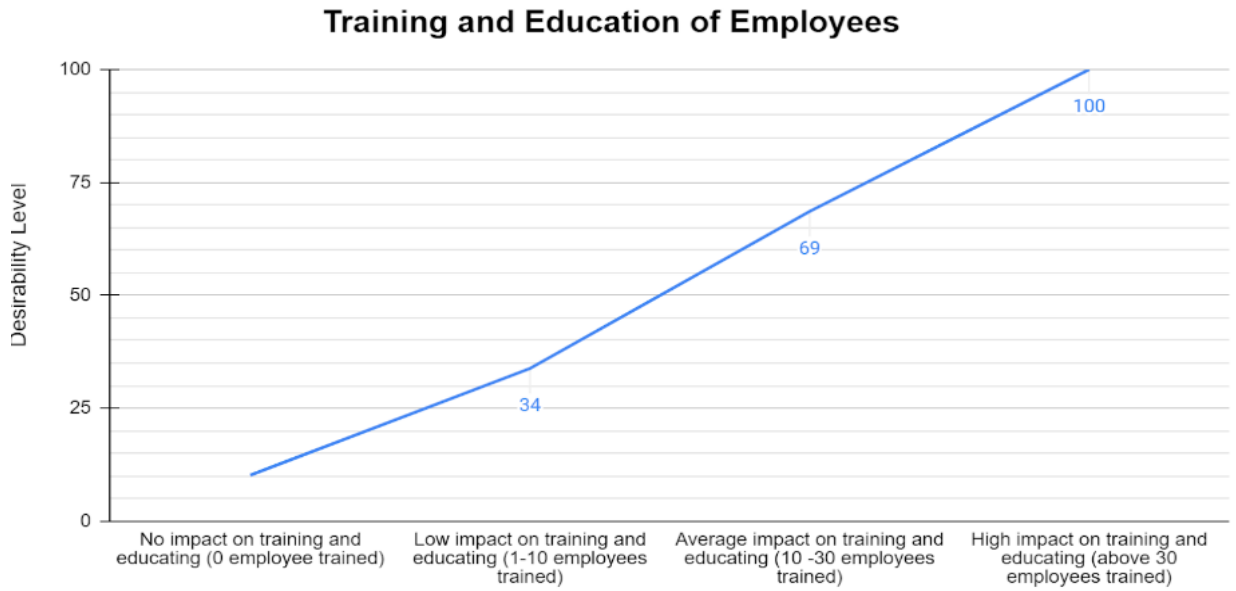

Figure 4.48. Desirability profile for training and education of employees.

Table 4.44. Desirability units and results for training and education of employees.

Training and Education of Employee						
Description	**Expert 77**	**Expert 120**	**Expert 174**	**Expert 185**	**Expert 186**	**Mean**
No impact on training and educating (0 employee trained)	0	0	51	0	0	10
Low impact on training and educating (1-10 employees trained)	5	20	84	50	10	34
Average impact on training and educating (10 -30 employees trained)	80	55	100	90	18	69
High impact on training and educating (above 30 employees trained)	100	100	100	100	100	100
This sub-criterion measures the impact level of low carbon energy technology implementation on the training and education of employees in the oil and gas industry.						

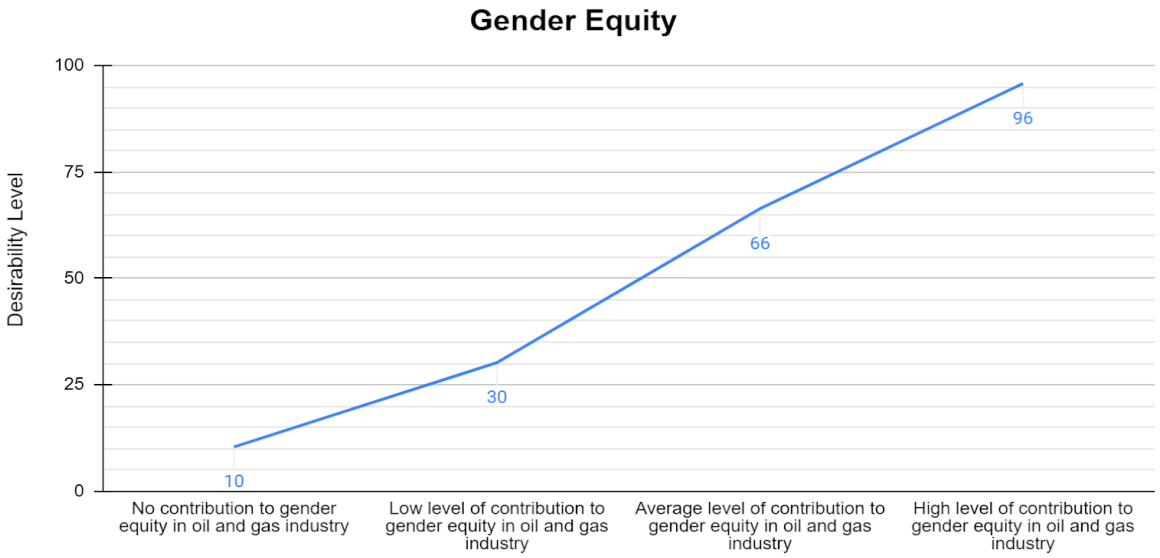

Figure 4.49. Desirability profile for gender equity.

Table 4.45. Desirability units and results for gender equity.

Gender Equity						
Description	**Expert 77**	**Expert 120**	**Expert 174**	**Expert 185**	**Expert 186**	**Mean**
No contribution to gender equity in oil and gas industry	10	0	42	0	0	10
Low level of contribution to gender equity in oil and gas industry	20	20	71	30	10	30
Average level of contribution to gender equity in oil and gas industry	70	42	90	80	50	66
High level of contribution to gender equity in oil and gas industry	80	100	100	100	99	96
This sub-criterion measures the impact level of low carbon energy technology implementation on gender equity in oil and gas industry.						

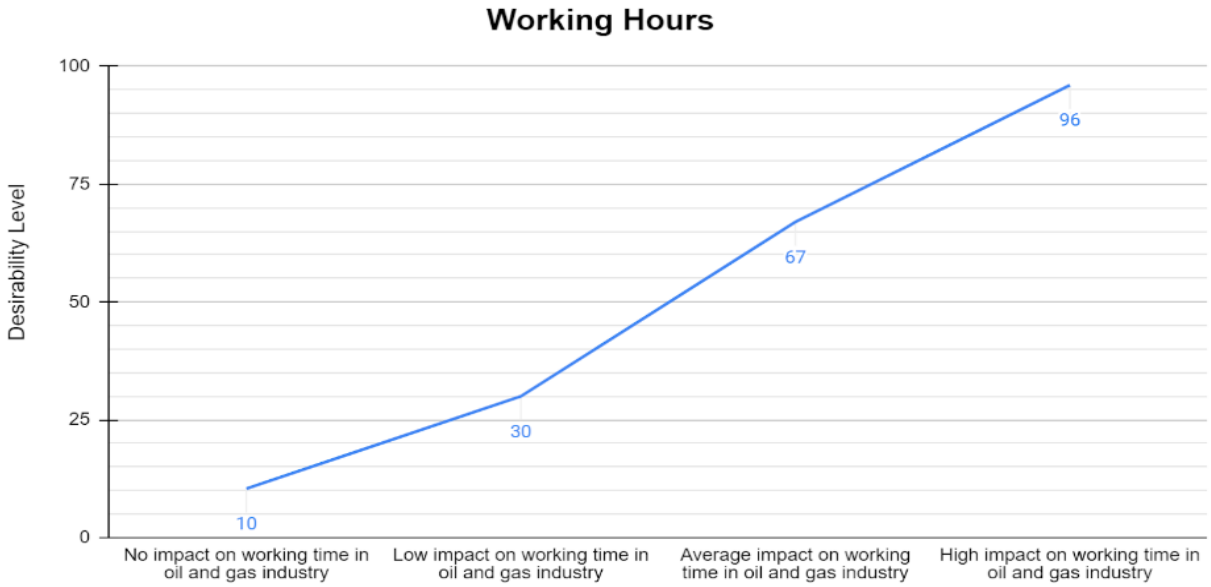

Figure 4.50. Desirability profile for working hours.

Table 4.46. Desirability units and results for working hours.

Working Hours						
Description	**Expert 77**	**Expert 120**	**Expert 174**	**Expert 185**	**Expert 186**	**Mean**
No impact on working time in oil and gas industry	10	5	37	0	0	10
Low impact on working time in oil and gas industry	15	25	60	40	10	30
Average impact on working time in oil and gas industry	75	70	83	80	27	67
High impact on working time in oil and gas industry	90	90	100	100	100	96
This sub-criterion measures the impact level of low carbon energy technology implementation on working hours in oil and gas industry.						

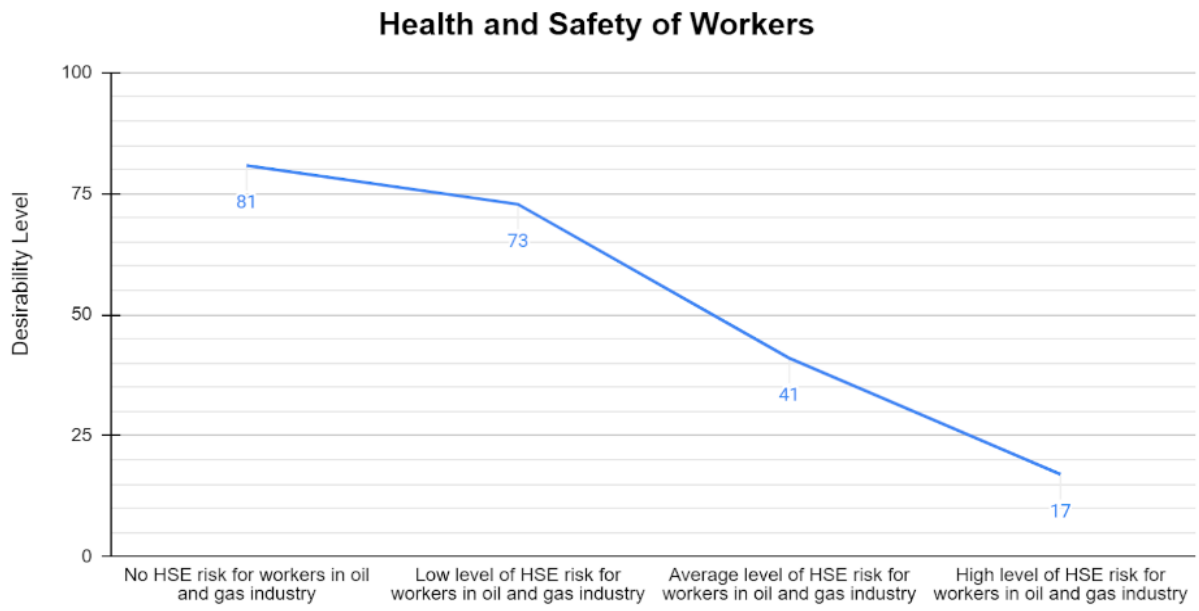

Figure 4.51. Desirability profile for health and safety of workers.

Table 4.47. Desirability units and results for health and safety of workers.

Health and Safety (HSE) of Workers						
Description	**Expert 77**	**Expert 120**	**Expert 174**	**Expert 185**	**Expert 186**	**Mean**
No HSE risk for workers in oil and gas industry	80	100	24	100	100	81
Low level of HSE risk for workers in oil and gas industry	80	80	42	80	82	73
Average level of HSE risk for workers in oil and gas industry	45	15	63	30	52	41
High level of HSE risk for workers in oil and gas industry	10	0	74	0	1	17
This sub-criterion measures the level of HSE risk for workers when the low carbon energy technology will be implemented in oil and gas industry.						

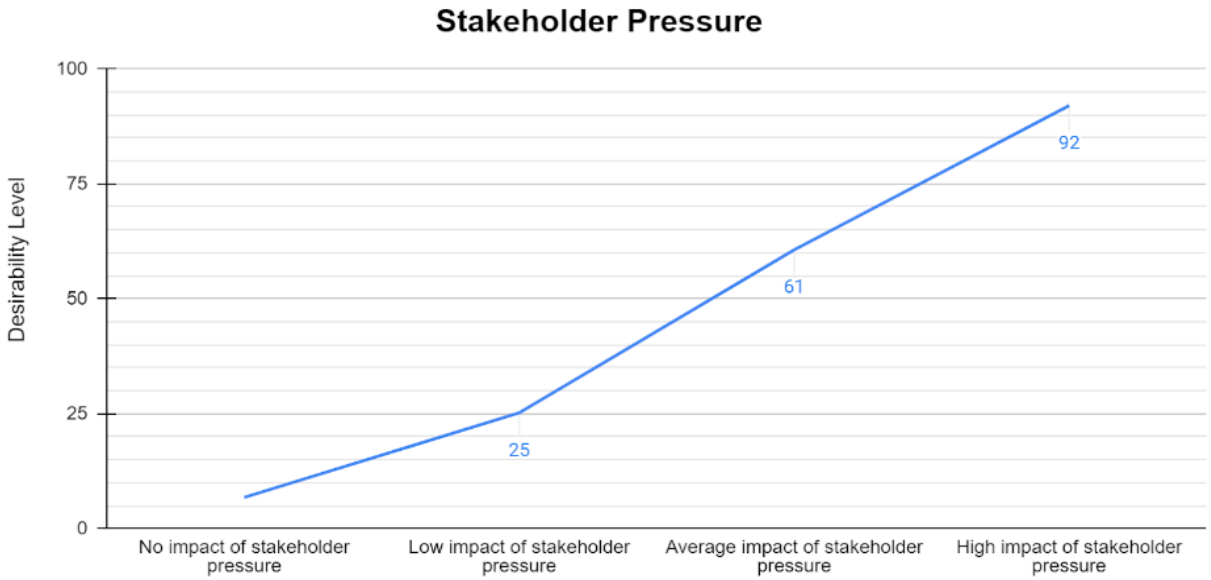

Figure 4.52. Desirability profile for stakeholder pressure.

Table 4.48. Desirability units and results for stakeholder pressure.

Stakeholder Pressure						
Description	**Expert 77**	**Expert 120**	**Expert 174**	**Expert 185**	**Expert 186**	**Mean**
No impact of stakeholder pressure	10	10	9	0	5	7
Low impact of stakeholder pressure	10	30	27	40	19	25
Average impact of stakeholder pressure	50	50	74	80	49	61
High impact of stakeholder pressure	70	90	100	100	100	92
This sub-criterion measures the impact level of stakeholder pressure on the implementation of low carbon energy technology in oil and gas industry.						

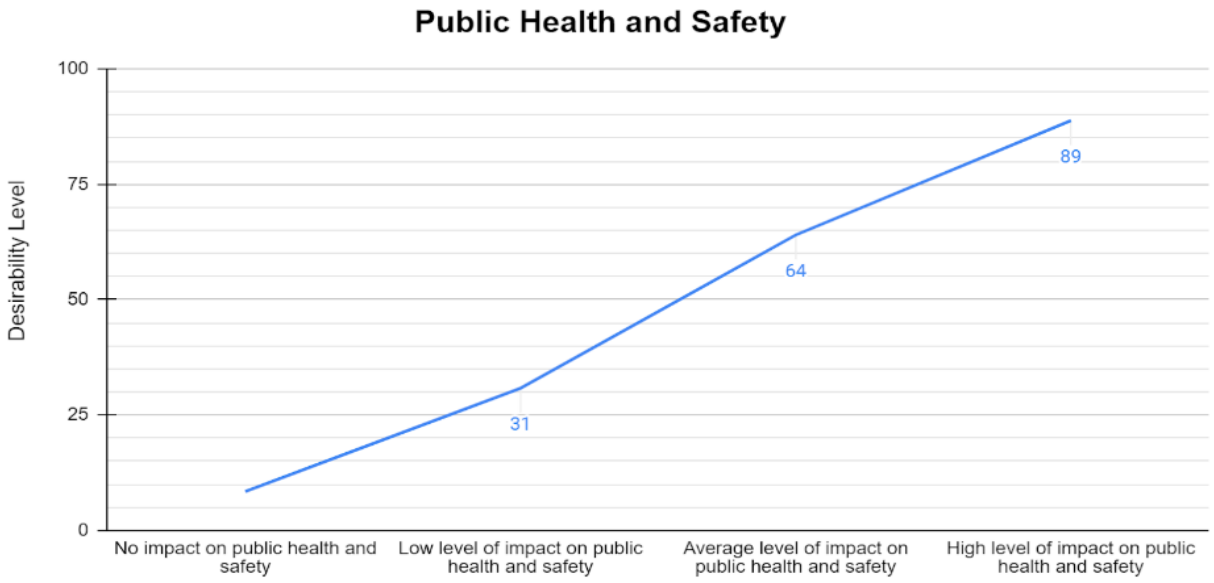

Figure 4.53. Desirability profile for public health and safety.

Table 4.49. Desirability units and results for public health and safety.

Public Health and Safety						
Description	**Expert 77**	**Expert 120**	**Expert 174**	**Expert 185**	**Expert 186**	**Mean**
No impact on public health and safety	10	15	17	0	0	8
Low level of impact on public health and safety	45	35	39	20	15	31
Average level of impact on public health and safety	80	60	62	70	48	64
High level of impact on public health and safety	80	74	90	100	100	89
This sub-criterion measures the impact level of implementing low carbon energy technologies on public health and safety in oil and gas industry.						

4.6.2. Desirability Profiles of Economic Criteria

The economic desirability profiles were generated by oil and gas industry experts and reflect the mean desirability scores for each sub-criterion and criterion (if the model element does not have any sub-criterion). Participant list for the determination of economic desirability profiles is shown in Table 4.50. The quantification results of economic desirability profiles are presented in the following tables from Table 4.51 to Table 4.62. The desirability profiles of economic criteria are presented in the following figures from Figure 4.54 to Figure 4.65.

Table 4.50. Participant list for the determination of economic desirability profiles.

Determination of Desirability Profiles for Economic Perspective			
Expert No.	**Title/Position**	**Organization Type**	**Country**
Expert 04	R&D Manager	Oil & Gas	Turkey
Expert 81	R&D Experimental Chapter Lead	Oil & Gas	Turkey
Expert 160	R&D Renewable Energies Senior Scientist	Oil & Gas	Italy
Expert 56	Technology Portfolio & R&D Services Manager	Oil & Gas	Italy
Expert 172	Environmental Engineer	Oil & Gas	Italy

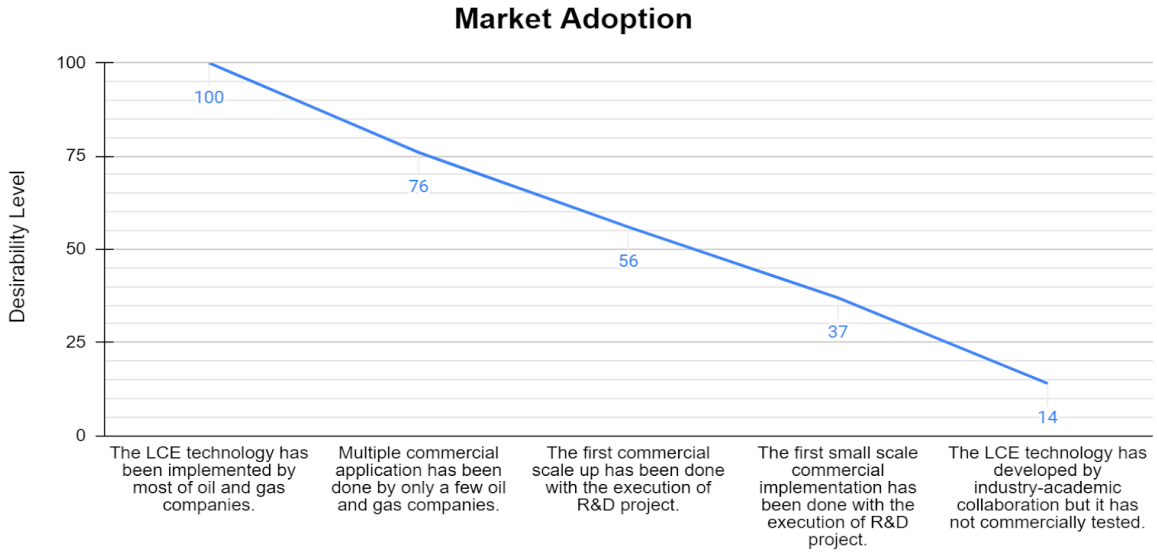

Figure 4.54. Desirability profile for market adoption.

Table 4.51. Desirability units and results for market adoption.

Market Adoption						
Description	**Expert 04**	**Expert 81**	**Expert 160**	**Expert 56**	**Expert 172**	**Mean**
The LCE technology has been implemented by most of oil and gas companies.	100	100	100	100	100	100
Multiple commercial application has been done by only a few oil and gas companies.	80	100	40	80	80	76
The first commercial scale up has been done with the execution of R&D project.	60	90	15	65	50	56
The first small scale commercial implementation has been done with the execution of R&D project.	50	90	10	20	15	37
The LCE technology has developed by industry-academic collaboration, but it has not commercially tested.	20	30	0	15	5	14
This sub-criterion measures the market adoption level of the low carbon energy (LCE) technology when it is implemented by an R&D project in the oil & gas industry.						

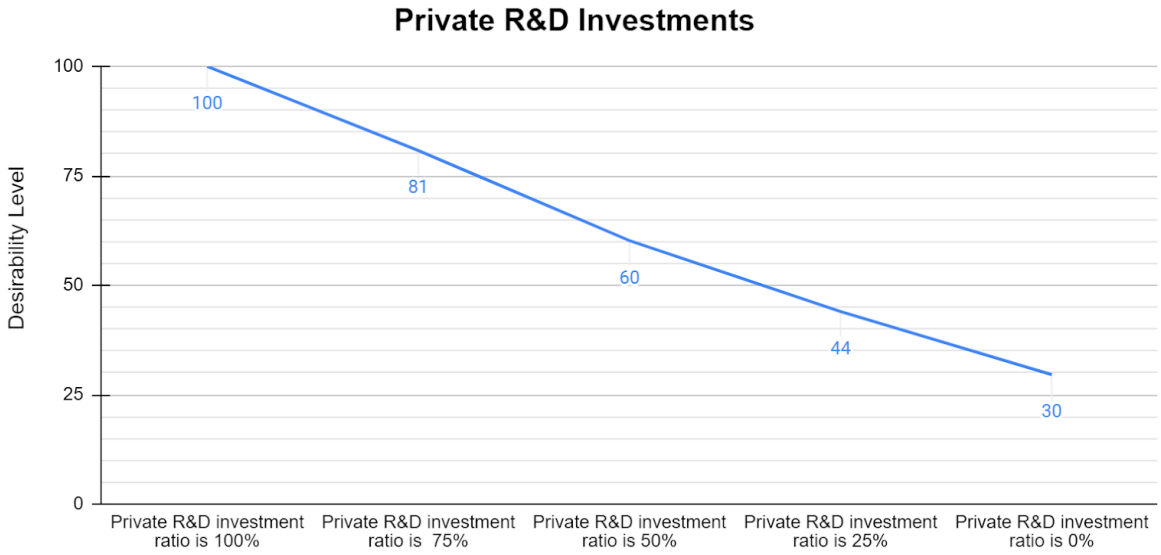

Figure 4.55. Desirability profile for private R&D Investments.

Table 4.52. Desirability units and results for private R&D Investments.

Private R&D Investments							
Description	**Unit**	**Expert 04**	**Expert 81**	**Expert 160**	**Expert 56**	**Expert 172**	**Mean**
Private R&D investment ratio is 100%	%	100	100	100	100	100	100
Private R&D investment ratio is 75%	%	84	90	60	100	70	81
Private R&D investment ratio is 50%	%	61	80	50	60	50	60
Private R&D investment ratio is 25%	%	30	70	30	50	40	44
Private R&D investment ratio is 0%	%	18	60	0	50	20	30
This sub-criterion measures the expected percentage of private R&D investments for the low carbon energy technology when it will be implemented by an R&D project in the oil and gas industry.							

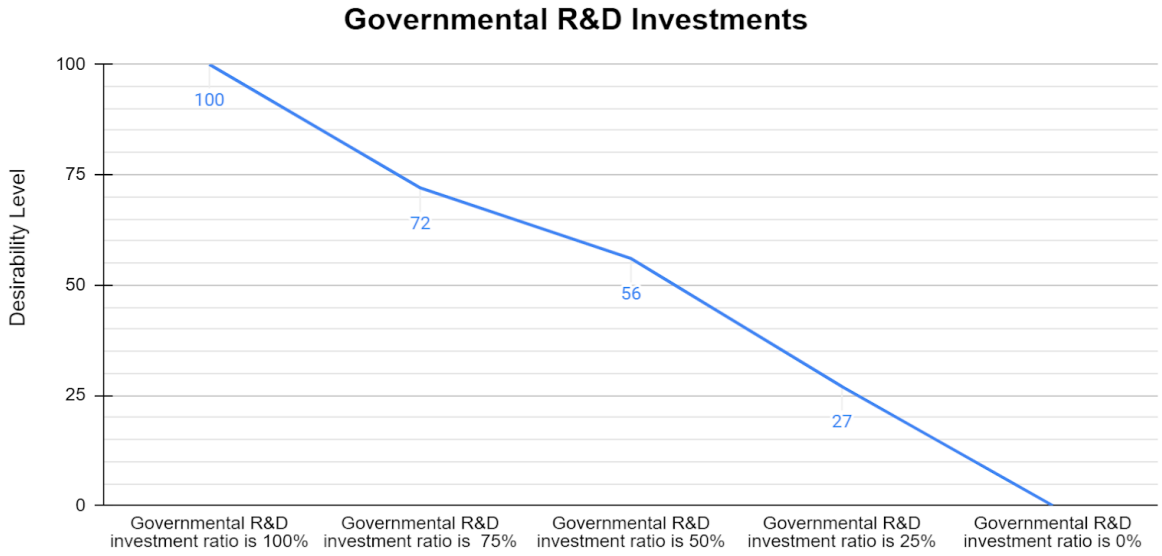

Figure 4.56. Desirability profile for governmental R&D investments.

Table 4.53. Desirability units and results for governmental R&D investments.

Governmental R&D Investments							
Description	**Unit**	**Expert 04**	**Expert 81**	**Expert 160**	**Expert 56**	**Expert 172**	**Mean**
Governmental R&D investment ratio is 100%	%	100	100	100	100	100	100
Governmental R&D investment ratio is 75%	%	75	100	50	75	60	72
Governmental R&D investment ratio is 50%	%	50	80	40	60	50	56
Governmental R&D investment ratio is 25%	%	25	50	20	20	20	27
Governmental R&D investment ratio is 0%	%	0	0	0	0	0	0
This sub-criterion measures the expected percentage of governmental R&D investments for the low carbon energy technology when it will be implemented by an R&D project in the oil and gas industry.							

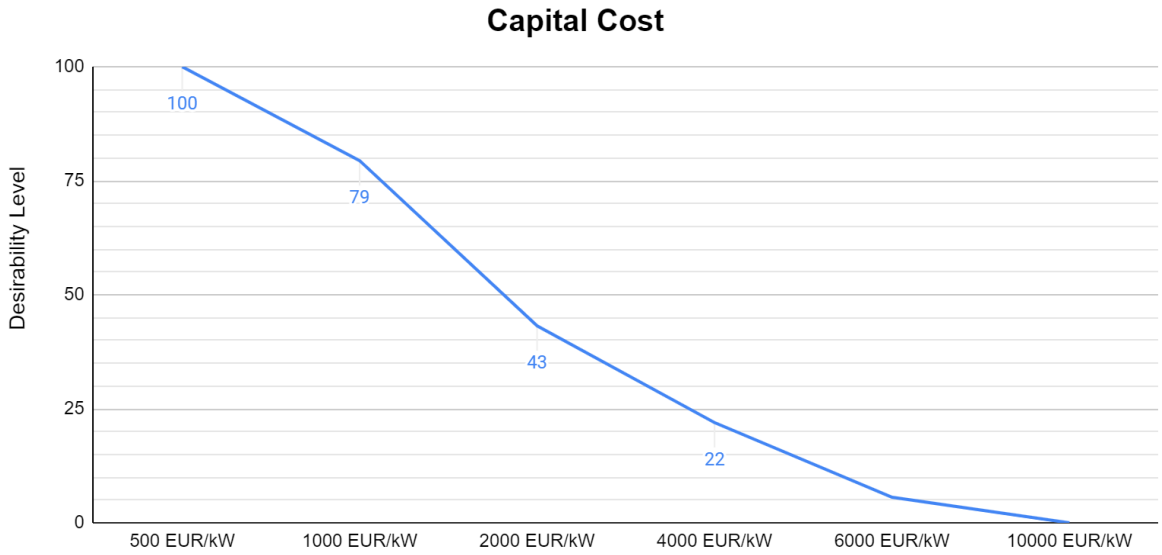

Figure 4.57. Desirability profile for capital cost.

Table 4.54. Desirability units and results for capital cost.

Capital Cost							
Description	**Unit**	**Expert 04**	**Expert 81**	**Expert 160**	**Expert 56**	**Expert 172**	**Mean**
500 EUR/kW	EUR/kW	100	100	100	100	100	100
1000 EUR/kW	EUR/kW	72	100	50	100	75	79
2000 EUR/kW	EUR/kW	45	80	10	51	30	43
4000 EUR/kW	EUR/kW	28	20	0	42	20	22
6000 EUR/kW	EUR/kW	18	0	0	0	10	6
10000 EUR/kW	EUR/kW	0	0	0	0	0	0
This sub-criterion measures the required amount of money in terms of EUR/kW for project start-up when the low carbon energy technology will be implemented by an R&D project in the oil and gas industry.							

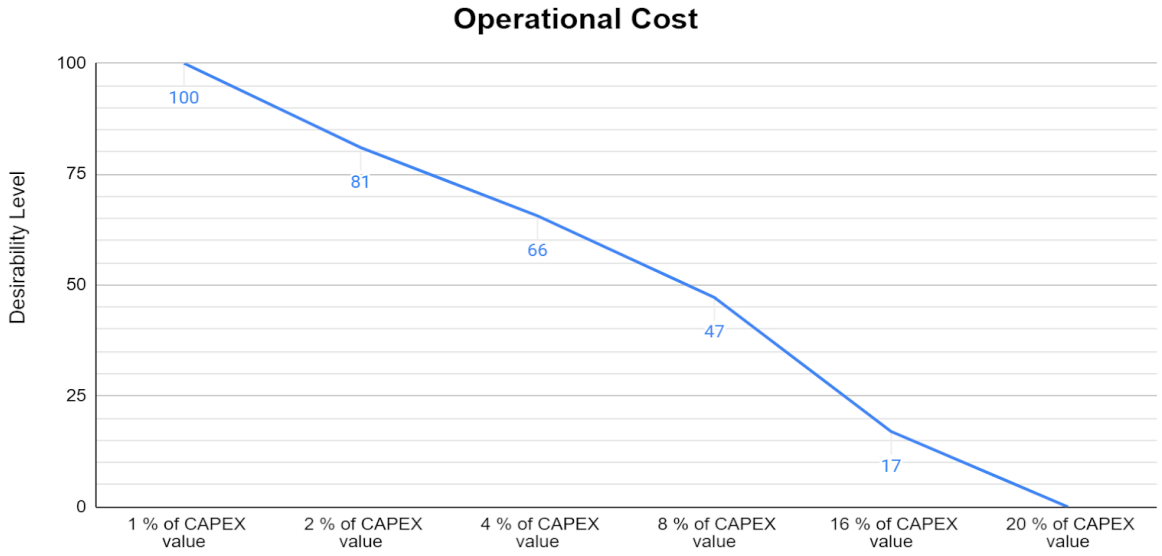

Figure 4.58. Desirability profile for operational cost.

Table 4.55. Desirability units and results for operational cost.

Operational Cost							
Description	**Unit**	**Expert 04**	**Expert 81**	**Expert 160**	**Expert 56**	**Expert 172**	**Mean**
1 % of CAPEX value	%	100	100	100	100	100	100
2 % of CAPEX value	%	80	100	50	100	75	81
4 % of CAPEX value	%	58	90	30	90	60	66
8 % of CAPEX value	%	41	90	15	60	30	47
16 % of CAPEX value	%	25	30	10	10	10	17
20 % of CAPEX value	%	0	0	0	0	0	0
This sub-criterion measures the required operating cost of the project when the low carbon energy technology will be implemented by an R&D project in the oil and gas industry.							

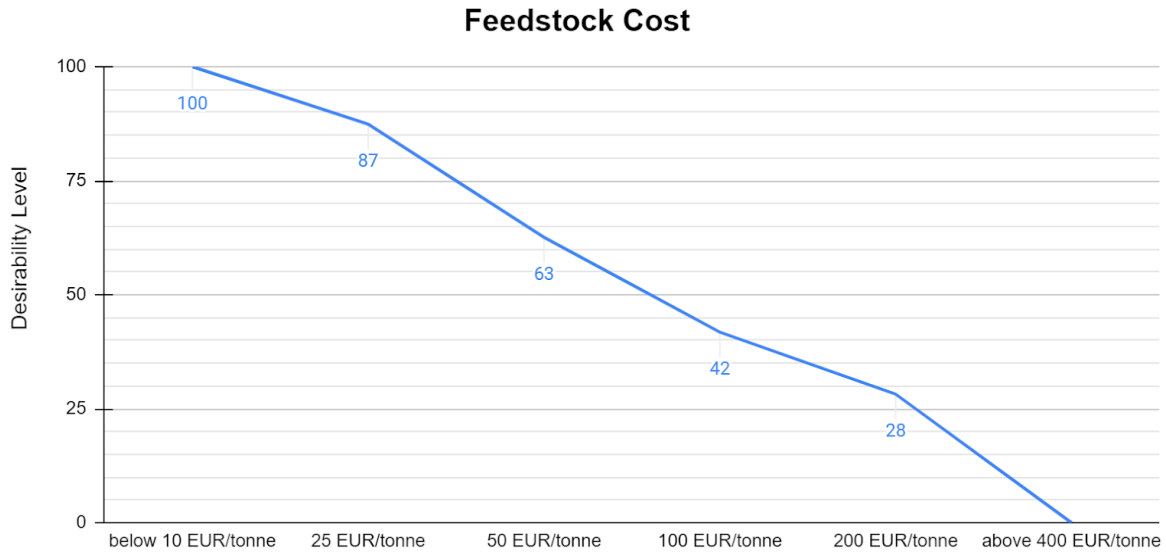

Figure 4.59. Desirability profile for feedstock cost.

Table 4.56. Desirability units and results for feedstock cost.

Feedstock Cost							
Description	**Unit**	**Expert 04**	**Expert 81**	**Expert 160**	**Expert 56**	**Expert 172**	**Mean**
below 10 EUR/tonne	EUR/tonne	100	100	100	100	100	100
25 EUR/tonne	EUR/tonne	77	100	80	100	80	87
50 EUR/tonne	EUR/tonne	53	100	30	80	50	63
100 EUR/tonne	EUR/tonne	19	100	0	60	30	42
200 EUR/tonne	EUR/tonne	12	100	0	19	10	28
above 400 EUR/tonne	EUR/tonne	0	0	0	0	0	0
This sub-criterion measures the expected level of feedstock cost in terms of EUR/tonne when the low carbon energy technology will be implemented by an R&D project in the oil and gas industry.							

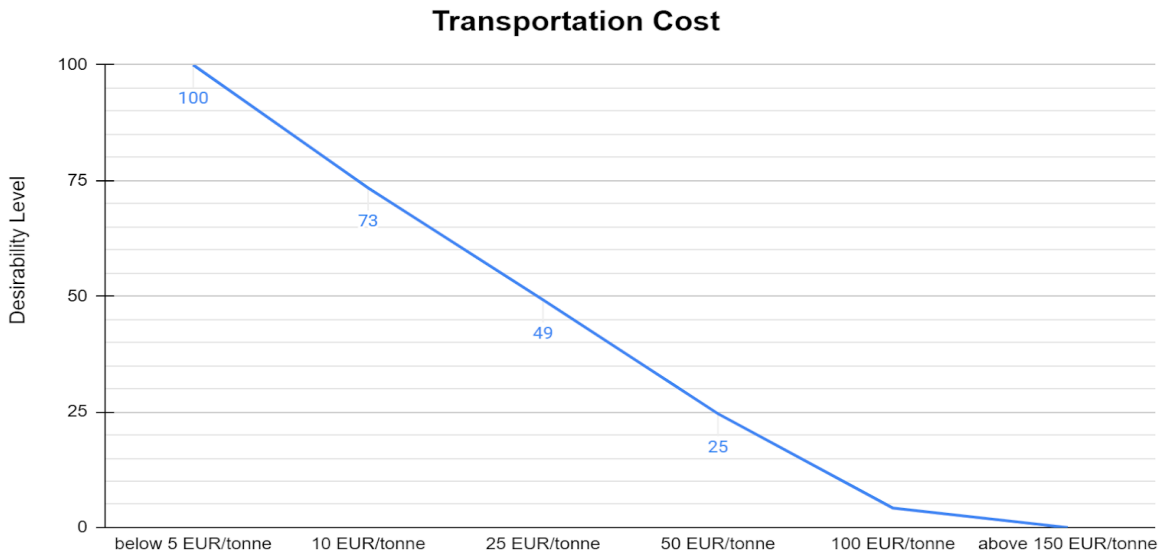

Figure 4.60. Desirability profile for transportation cost.

Table 4.57. Desirability units and results for transportation cost.

Transportation Cost							
Description	**Unit**	**Expert 04**	**Expert 81**	**Expert 160**	**Expert 56**	**Expert 172**	**Mean**
below 5 EUR/tonne	EUR/tonne	100	100	100	100	100	100
10 EUR/tonne	EUR/tonne	77	100	30	100	60	73
25 EUR/tonne	EUR/tonne	55	61	20	70	40	49
50 EUR/tonne	EUR/tonne	33	20	10	40	20	25
100 EUR/tonne	EUR/tonne	11	0	5	0	5	4
above 150 EUR/tonne	EUR/tonne	0	0	0	0	0	0
This sub-criterion measures the expected transportation cost of feedstocks/final products in terms of EUR/tonne when the low carbon energy technology will be implemented by an R&D project in the oil and gas industry.							

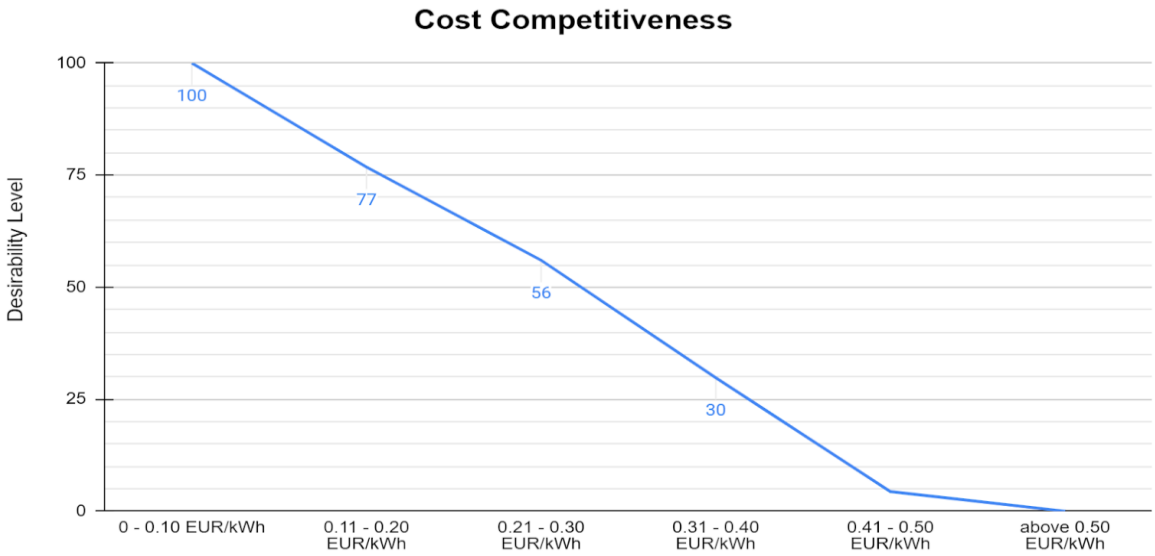

Figure 4.61. Desirability profile for cost competitiveness.

Table 4.58. Desirability units and results for cost competitiveness.

Cost Competitiveness (in terms of LCOE)							
Description	**Unit**	**Expert 04**	**Expert 81**	**Expert 160**	**Expert 56**	**Expert 172**	**Mean**
0 - 0.10 EUR/kWh	EUR/kWh	100	100	100	100	100	100
0.11 - 0.20 EUR/kWh	EUR/kWh	69	90	50	100	75	77
0.21 - 0.30 EUR/kWh	EUR/kWh	50	80	30	70	50	56
0.31 - 0.40 EUR/kWh	EUR/kWh	39	40	15	30	25	30
0.41 - 0.50 EUR/kWh	EUR/kWh	12	0	5	0	5	4
above 0.50 EUR/kWh	EUR/kWh	0	0	0	0	0	0
This sub-criterion measures the expected relative value of application cost in terms of Levelized cost of energy (LCOE) (EUR/kWh) when the low carbon energy technology will be implemented by an R&D project in the oil and gas industry.							

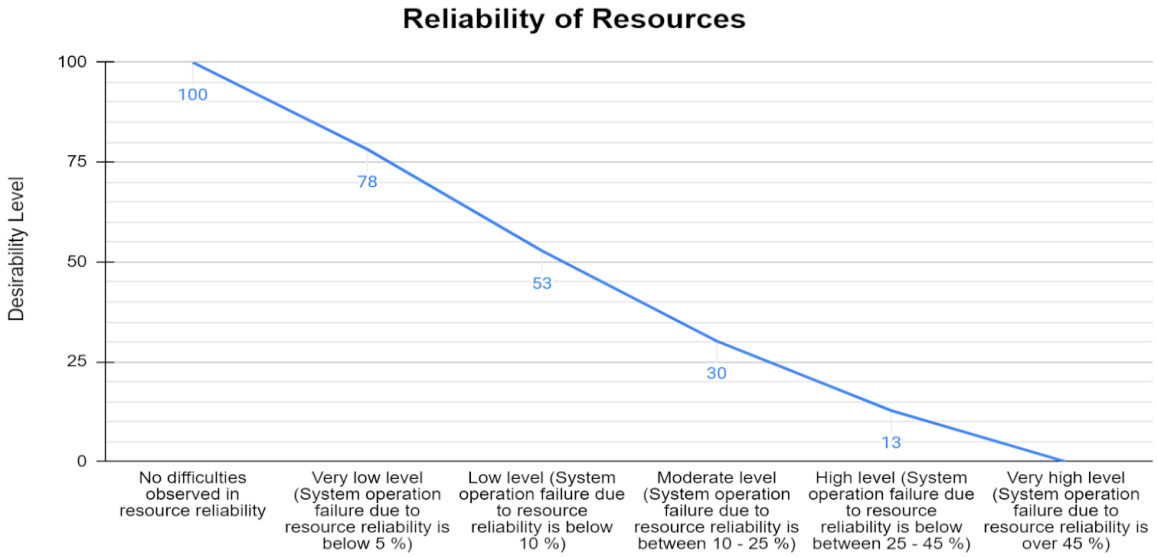

Figure 4.62. Desirability profile for reliability of resources.

Table 4.59. Desirability units and results for reliability of resources.

Reliability of Resources						
Description	**Expert 04**	**Expert 81**	**Expert 160**	**Expert 56**	**Expert 172**	**Mean**
No difficulties observed in resource reliability	100	100	100	100	100	100
Very low level (System operation failure due to resource reliability is below 5 %)	76	90	60	90	75	78
Low level (System operation failure due to resource reliability is below 10 %)	59	75	10	80	40	53
Moderate level (System operation failure due to resource reliability is between 10 - 25 %)	51	20	5	50	25	30
High level (System operation failure due to resource reliability is below between 25 - 45 %)	49	0	0	10	5	13
Very high level (System operation failure due to resource reliability is over 45 %)	0	0	0	0	0	0
This sub-criterion measures the expected difficulties in resource reliability for the project when the low carbon energy technology will be implemented by an R&D project in the oil and gas industry.						

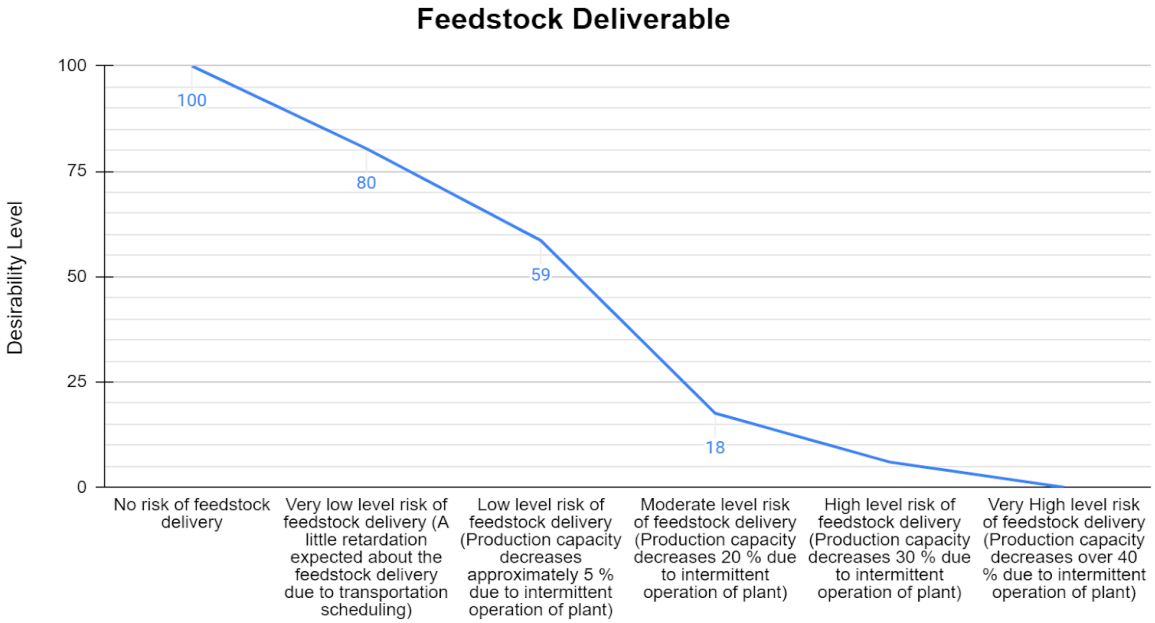

Figure 4.63. Desirability profile for feedstock delivery.

Table 4.60. Desirability units and results for feedstock delivery.

Feedstock Deliverable						
Description	**Expert 04**	**Expert 81**	**Expert 160**	**Expert 56**	**Expert 172**	**Mean**
No risk of feedstock delivery	100	100	100	100	100	100
Very low-level risk of feedstock delivery (A little retardation expected about the feedstock delivery due to transportation scheduling)	42	90	80	100	90	80
Low level risk of feedstock delivery (Production capacity decreases approximately 5 % due to intermittent operation of plant)	28	80	40	85	60	59
Moderate level risk of feedstock delivery (Production capacity decreases 20 % due to intermittent operation of plant)	23	20	20	10	15	18
High level risk of feedstock delivery (Production capacity decreases 30 % due to intermittent operation of plant)	15	0	10	0	5	6
Very High-level risk of feedstock delivery (Production capacity decreases over 40 % due to intermittent operation of plant)	0	0	0	0	0	0
This sub-criterion measures the expected risk of feedstock delivery when the low carbon energy technology will be implemented by an R&D project in the oil and gas industry.						

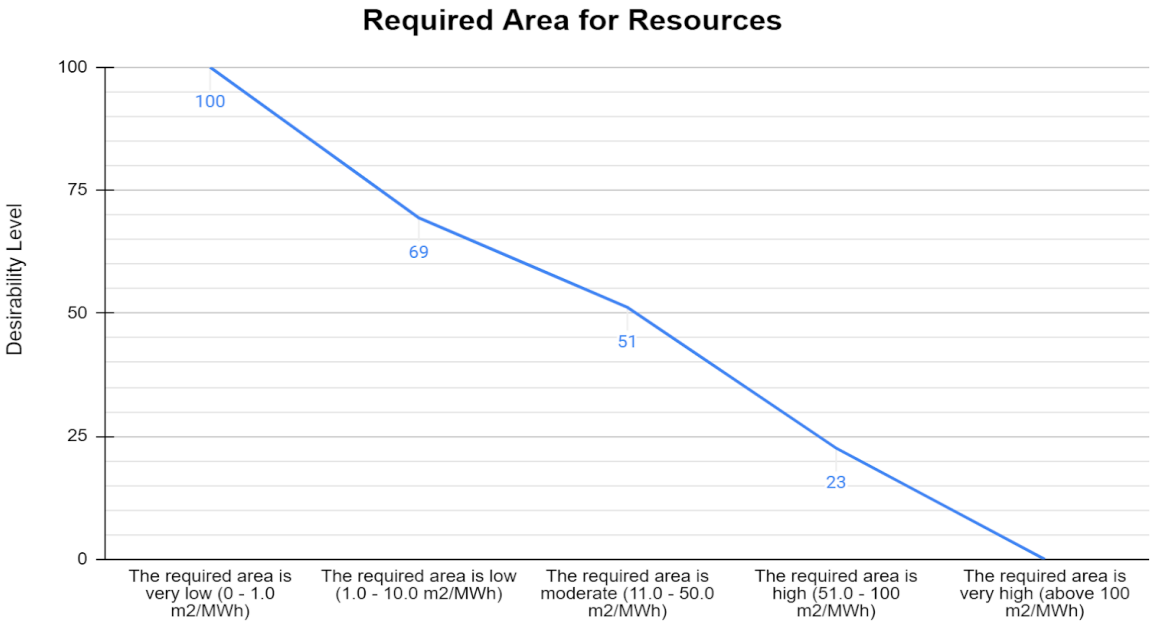

Figure 4.64. Desirability profile for required area for resources.

Table 4.61. Desirability units and results for required area for resources.

Required area for resources							
Description	**Unit**	**Expert 04**	**Expert 81**	**Expert 160**	**Expert 56**	**Expert 172**	**Mean**
The required area is very low (0 - 1.0 m2/MWh)	m2/MWh	100	100	100	100	100	100
The required area is low (1.0 - 10.0 m2/MWh)	m2/MWh	27	95	50	100	75	69
The required area is moderate (11.0 - 50.0 m2/MWh)	m2/MWh	16	90	20	80	50	51
The required area is high (51.0 - 100 m2/MWh)	m2/MWh	8	20	0	60	25	23
The required area is very high (above 100 m2/MWh)	m2/MWh	0	0	0	0	0	0
This sub-criterion measures the estimated required area for resources in terms of m2/MWh when the low carbon energy technology will be implemented by an R&D project in the oil and gas industry.							

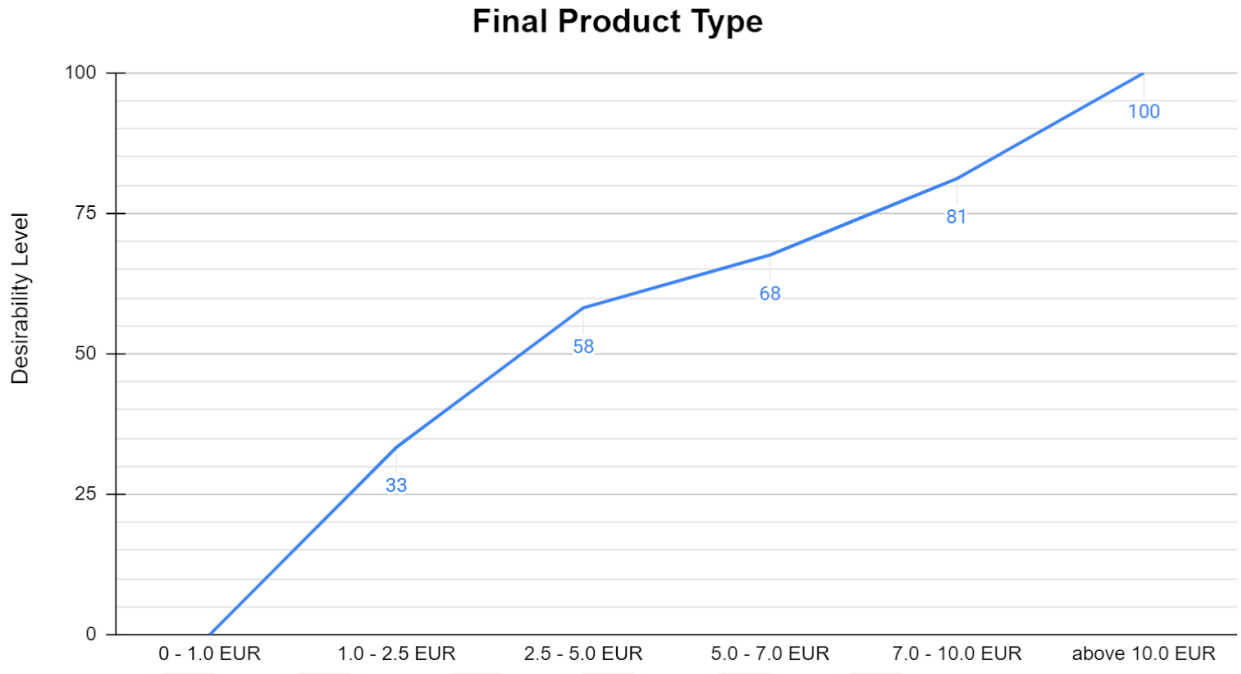

Figure 4.65. Desirability profile for final product type.

Table 4.62. Desirability units and results for final product type.

Final Product Type							
Description	**Unit**	**Expert 04**	**Expert 81**	**Expert 160**	**Expert 56**	**Expert 172**	**Mean**
0 - 1.0 EUR	EUR/L or EUR/kg	0	0	0	0	0	0
1.0 - 2.5 EUR	EUR/L or EUR/kg	67	20	5	50	25	33
2.5 - 5.0 EUR	EUR/L or EUR/kg	81	70	10	80	50	58
5.0 - 7.0 EUR	EUR/L or EUR/kg	83	80	25	90	60	68
7.0 - 10.0 EUR	EUR/L or EUR/kg	91	90	50	100	75	81
above 10.0 EUR	EUR/L or EUR/kg	100	100	100	100	100	100
This sub-criterion measures the estimated monetary value of the final product in terms of EUR/L or EUR/kg when the low carbon energy technology will be implemented by an R&D project in the oil and gas industry.							

4.6.3. Desirability Profiles of Technical Criteria

The technical desirability profiles were composed by oil and gas industry experts and reflect the mean desirability scores for each sub-criterion and criterion (if the model element does not have any sub-criterion). Participant list for the determination of technical desirability profiles is shown in Table 4.63.

Table 4.63. Participant list for the determination of Technical Desirability Profiles.

Determination of Desirability Profiles for Technical Perspective			
Expert No.	**Title/Position**	**Organization Type**	**Country**
Expert 81	R&D Experimental Chapter Lead	Oil & Gas	Turkey
Expert 99	Investment & Project Development Chief	Oil & Gas	Turkey
Expert 171	Operations & Production Engineer	Oil & Gas	Italy
Expert 162	Process & Technologies Vice President	Oil & Gas	Italy
Expert 117	Senior Vice President Environmental R&D	Oil & Gas	Italy
Expert 176	GHG Technical Advisor	Oil & Gas	Spain

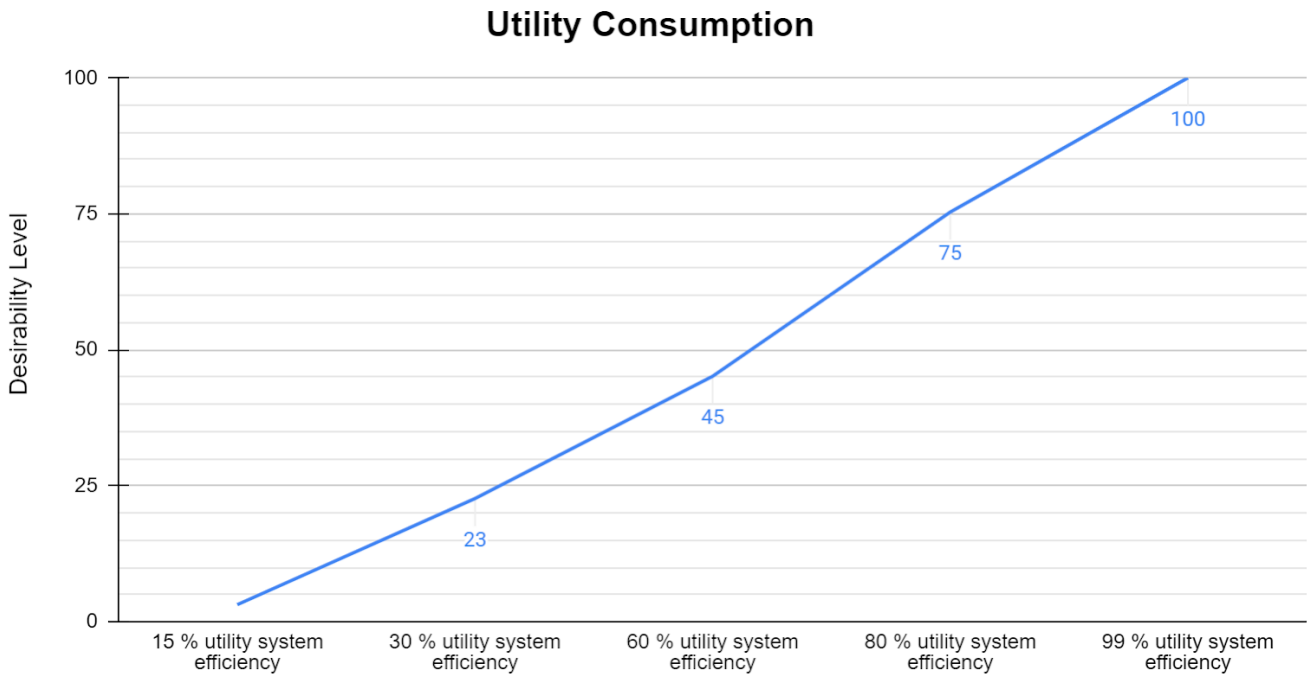

Figure 4.66. Desirability profile for utility consumption.

Table 4.64. Desirability units and results for utility consumption.

Utility Consumption								
Description	**Unit**	**Expert 81**	**Expert 99**	**Expert 171**	**Expert 162**	**Expert 117**	**Expert 176**	**Mean**
15 % utility system efficiency	%	0	0	0	10	9	0	3
30 % utility system efficiency	%	40	20	20	19	14	23	23
60 % utility system efficiency	%	60	65	40	31	35	40	45
80 % utility system efficiency	%	80	85	60	61	85	81	75
99 % utility system efficiency	%	100	100	100	100	100	100	100
This sub-criterion measures the efficiency level of utility system during the operation of implemented low carbon energy technology in the oil and gas industry.								

The quantification results of technical desirability profiles are presented in the following tables from Table 4.64 to Table 4.69. The desirability profiles of technical criteria are presented in the following figures from Figure 4.66 to Figure 4.71.

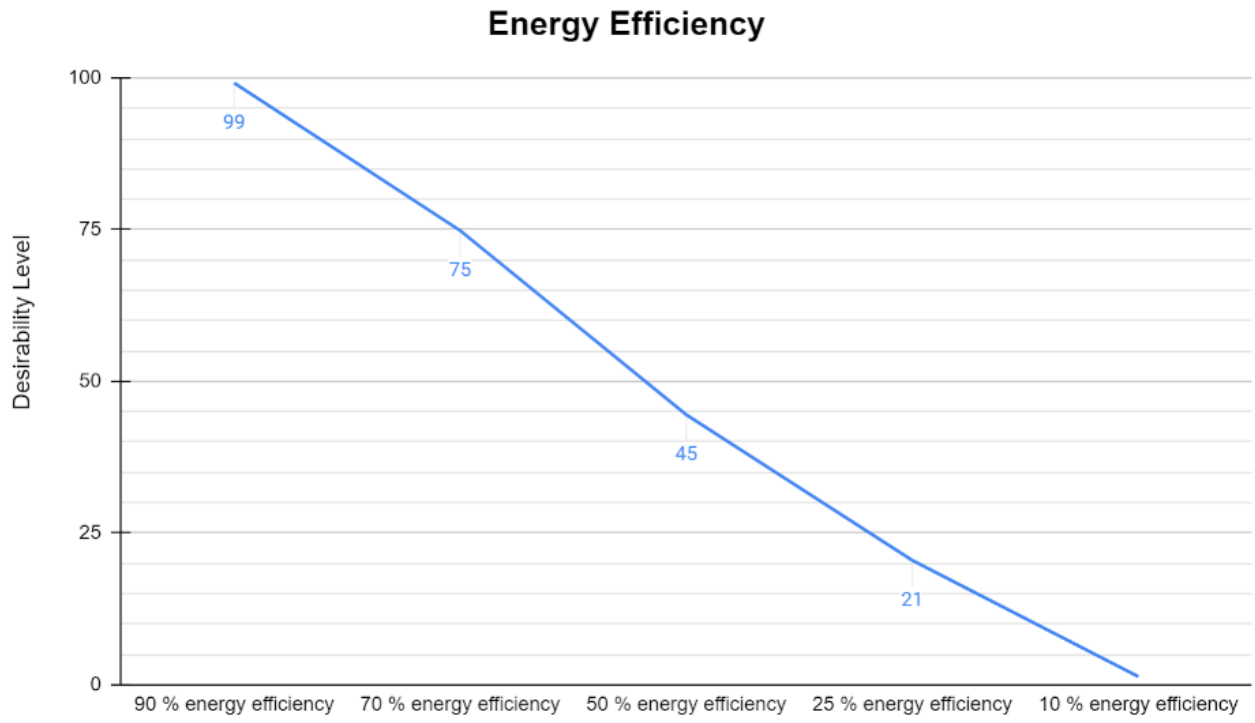

Figure 4.67. Desirability profile for energy efficiency.

Table 4.65. Desirability units and results for energy efficiency.

Energy Efficiency								
Description	**Unit**	**Expert 81**	**Expert 99**	**Expert 171**	**Expert 162**	**Expert 117**	**Expert 176**	**Mean**
90 % energy efficiency	%	100	100	100	100	95	100	99
70 % energy efficiency	%	87	80	80	60	71	71	75
50 % energy efficiency	%	56	55	30	47	34	45	45
25 % energy efficiency	%	21	30	10	28	9	25	21
10 % energy efficiency	%	0	0	0	8	0	0	1
This sub-criterion measures the energy efficiency level of low carbon energy technology during the operation in the oil and gas industry.								

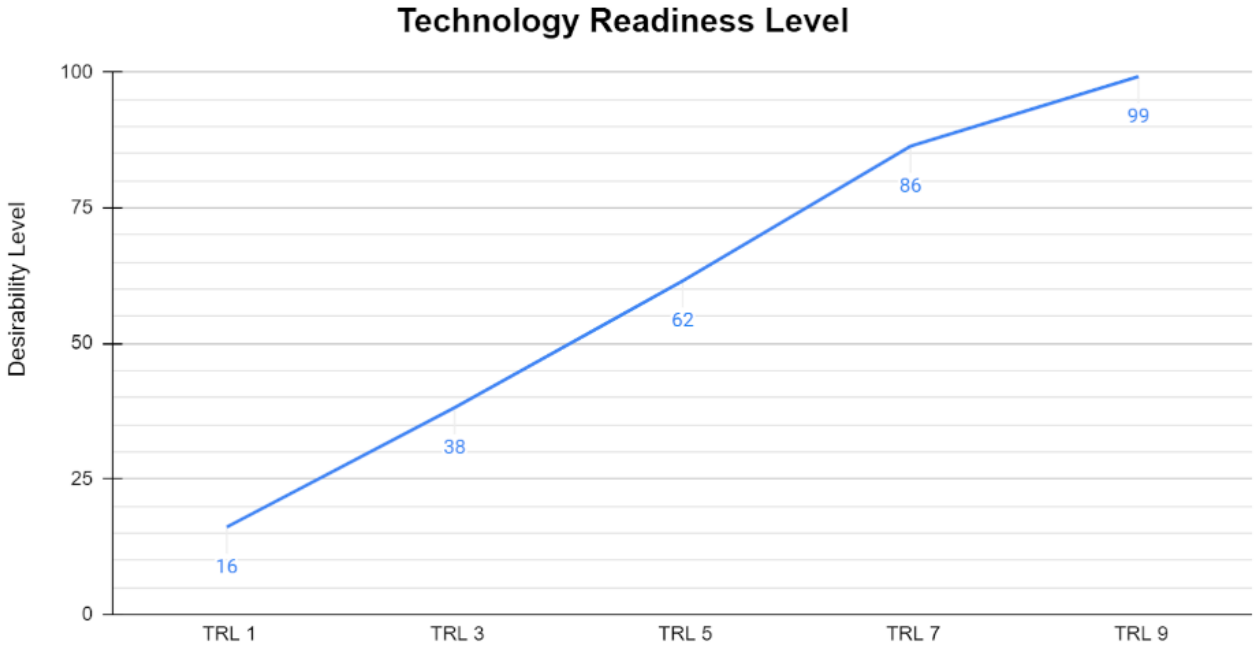

Figure 4.68. Desirability profile for technology readiness level.

Table 4.66. Desirability units and results for technology readiness level.

Technology Readiness Level								
Description	**Unit**	**Expert 81**	**Expert 99**	**Expert 171**	**Expert 162**	**Expert 117**	**Expert 176**	**Mean**
TRL 1	TRL	64	0	0	18	15	0	16
TRL 3	TRL	74	30	20	40	35	30	38
TRL 5	TRL	83	60	60	60	50	56	62
TRL 7	TRL	92	85	95	80	85	81	86
TRL 9	TRL	100	100	100	100	95	100	99
This sub-criterion measures the expected technology readiness level at the end of the project when the low carbon energy technology is implemented by an R&D project in the oil and gas industry.								

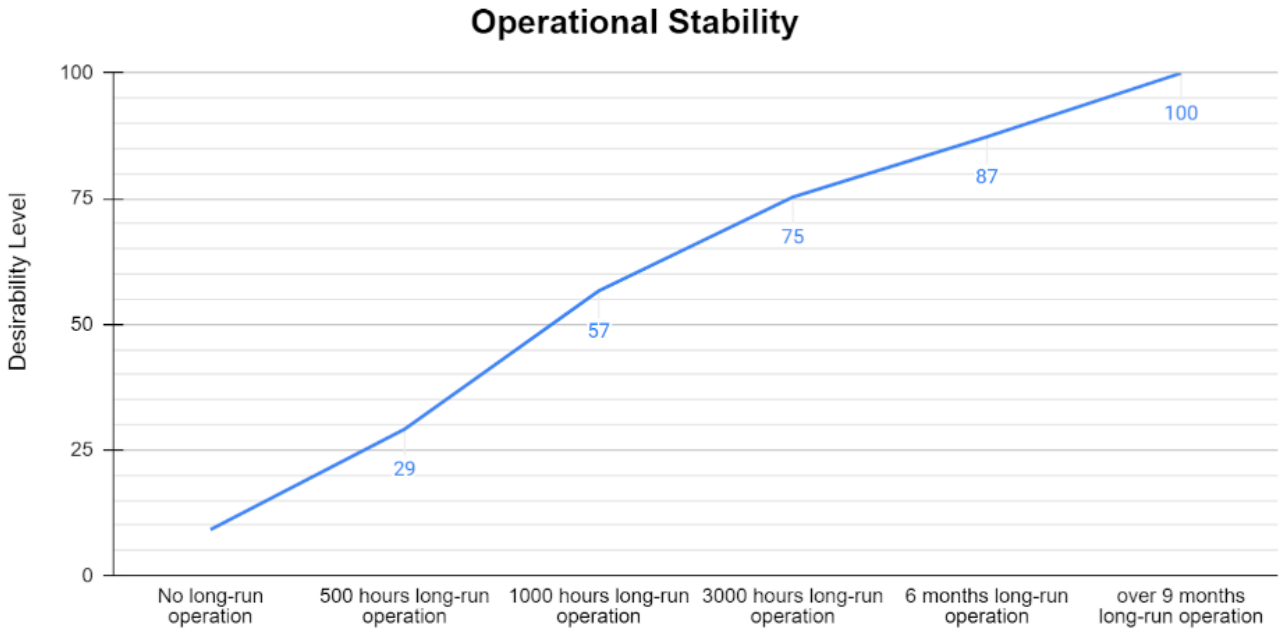

Figure 4.69. Desirability profile for operational stability.

Table 4.67. Desirability units and results for operational stability.

Operational Stability								
Description	**Unit**	**Expert 81**	**Expert 99**	**Expert 171**	**Expert 162**	**Expert 117**	**Expert 176**	**Mean**
No long-run operation	time	40	0	0	10	5	0	9
500 hours long-run operation	time	75	35	0	24	15	26	29
1000 hours long-run operation	time	90	60	30	63	50	47	57
3000 hours long-run operation	time	90	75	70	84	75	58	75
6 months long-run operation	time	100	90	90	90	90	64	87
over 9 months long-run operation	time	100	100	100	100	100	100	100
This sub-criterion measures the operational stability level of the low carbon energy technology for project execution when it is implemented by an R&D project in the oil and gas industry.								



Figure 4.70. Desirability profile for easy maintenance.

Table 4.68. Desirability units and results for easy maintenance.

Easy Maintenance								
Description	**Unit**	**Expert 81**	**Expert 99**	**Expert 171**	**Expert 162**	**Expert 117**	**Expert 176**	**Mean**
Daily maintenance required	time	0	0	0	9	10	0	3
Weekly maintenance required	time	0	5	0	15	20	23	11
Monthly maintenance required	time	10	15	20	32	40	45	27
Yearly maintenance required	time	100	90	90	91	85	68	87
No maintenance required	time	100	100	100	100	95	100	99
This sub-criterion measures the required maintenance frequency of the low carbon energy technology when it is implemented by an R&D project in the oil and gas industry.								

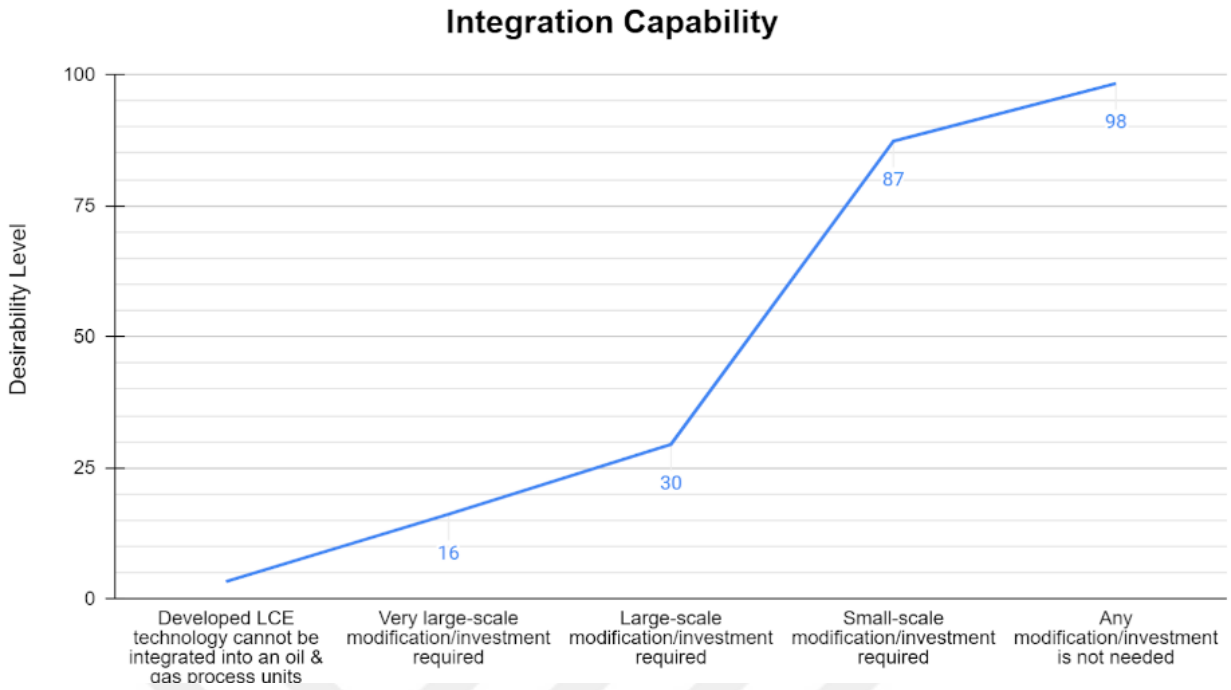

Figure 4.71. Desirability profile for integration capability.

Table 4.69. Desirability units and results for integration capability.

Integration Capability							
Description	**Expert 81**	**Expert 99**	**Expert 171**	**Expert 162**	**Expert 117**	**Expert 176**	**Mean**
Developed LCE technology cannot be integrated into an oil & gas process unit	0	0	0	10	10	0	3
Very large-scale modification/investment required	0	15	10	28	25	19	16
Large-scale modification/investment required	10	45	30	36	30	26	30
Small-scale modification/investment required	100	95	90	100	80	59	87
Any modification/investment is not needed	100	100	100	100	90	100	98
This sub-criterion measures the expected integration capability of the low carbon energy technology when it is implemented by an R&D project in the oil and gas industry.							

4.6.4. Desirability Profiles of Environmental Criteria

The environmental desirability profiles were composed by oil and gas industry experts and reflect the mean desirability scores for each sub-criterion and criterion (if the model element does not have any sub-criterion). Participant list for the determination of environmental desirability profiles is shown in Table 4.70. The quantification results of environmental desirability profiles are presented in the following tables from Table 4.71 to Table 4.80. The desirability profiles of environmental criteria are presented in the following figures from Figure 4.72 to Figure 4.81.

Table 4.70. Participant list for the determination of Environmental Desirability Profiles.

Determination of Desirability Profiles for Environmental Perspective			
Expert No.	**Title/Position**	**Organization Type**	**Country**
Expert 77	Operating Superintendent	Oil & Gas	Turkey
Expert 121	Climate Change Coordinator	Oil & Gas	Turkey
Expert 172	Environmental Engineer	Oil & Gas	Italy
Expert 175	R&D Project Engineer	Oil & Gas	Italy
Expert 183	Researcher	Oil & Gas	Italy
Expert 119	Sustainability Group Manager	Oil & Gas	Turkey

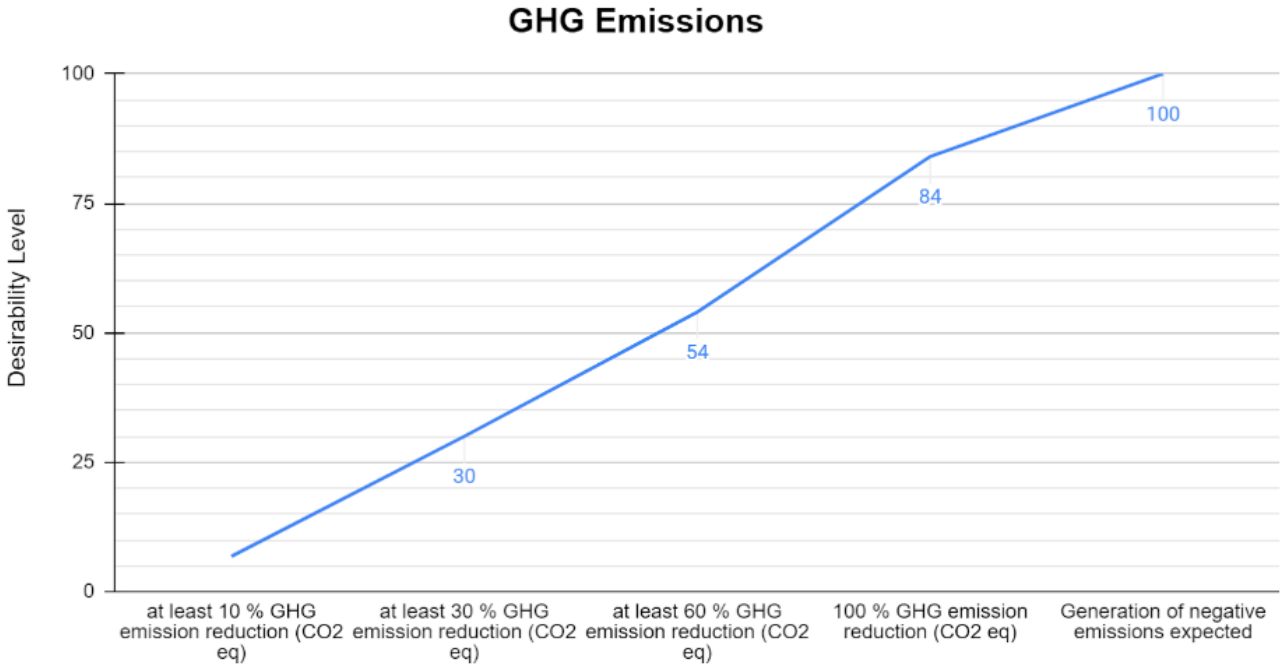

Figure 4.72. Desirability profile for GHG emissions.

Table 4.71. Desirability units and results for GHG emissions.

GHG Emissions								
Description	**Unit**	**Expert 77**	**Expert 121**	**Expert 172**	**Expert 175**	**Expert 183**	**Expert 119**	**Mean**
at least 10 % GHG emission reduction (CO_2 eq)	%	10	5	0	0	10	16	7
at least 30 % GHG emission reduction (CO_2 eq)	%	35	20	30	30	30	35	30
at least 60 % GHG emission reduction (CO_2 eq)	%	40	80	50	47	60	47	54
100 % GHG emission reduction (CO_2 eq)	%	90	100	95	69	90	60	84
Generation of negative emissions expected	%	100	100	100	100	100	100	100
This sub-criterion measures the expected GHG emission reduction capability of the low carbon energy technology when it will be implemented by an R&D project in the oil and gas industry.								

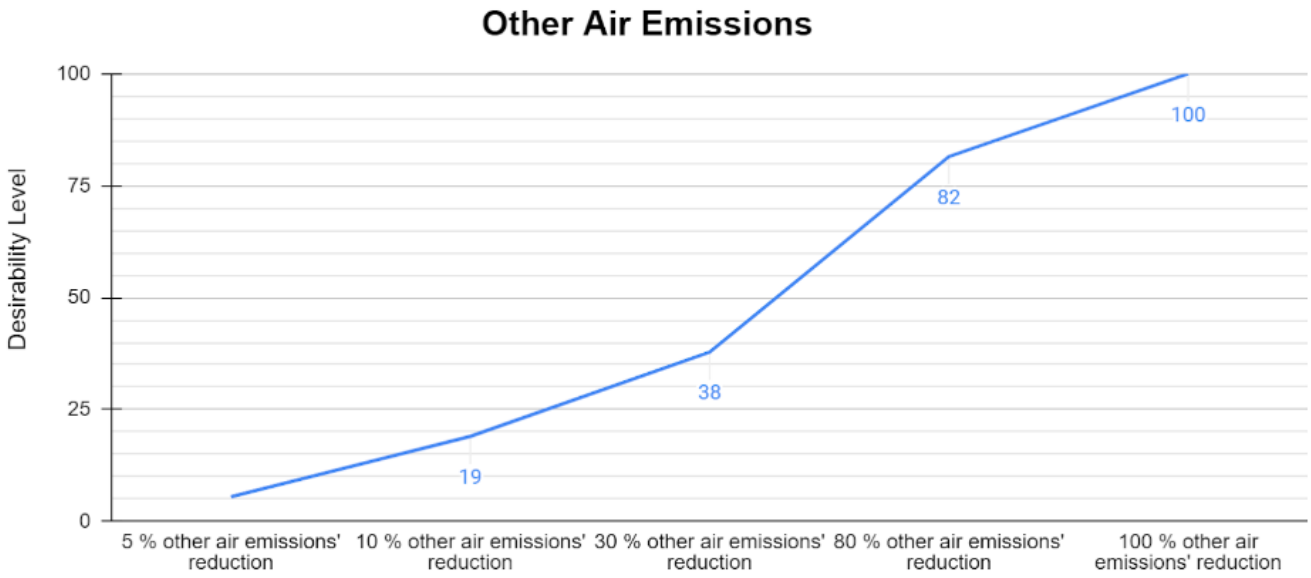

Figure 4.73. Desirability profile for other air emissions.

Table 4.72. Desirability units and results for other air emissions.

Other Air Emissions								
Description	**Unit**	**Expert 77**	**Expert 121**	**Expert 172**	**Expert 175**	**Expert 183**	**Expert 119**	**Mean**
5 % other air emissions' reduction	%	11	5	0	0	5	12	6
10 % other air emissions' reduction	%	19	10	20	33	10	22	19
30 % other air emissions' reduction	%	35	20	40	57	30	45	38
80 % other air emissions' reduction	%	80	90	85	81	80	73	82
100 % other air emissions' reduction	%	100	100	100	100	100	100	100
This sub-criterion measures the other air emissions reduction capability of the low carbon energy technology when it will be implemented by an R&D project in the oil and gas industry.								

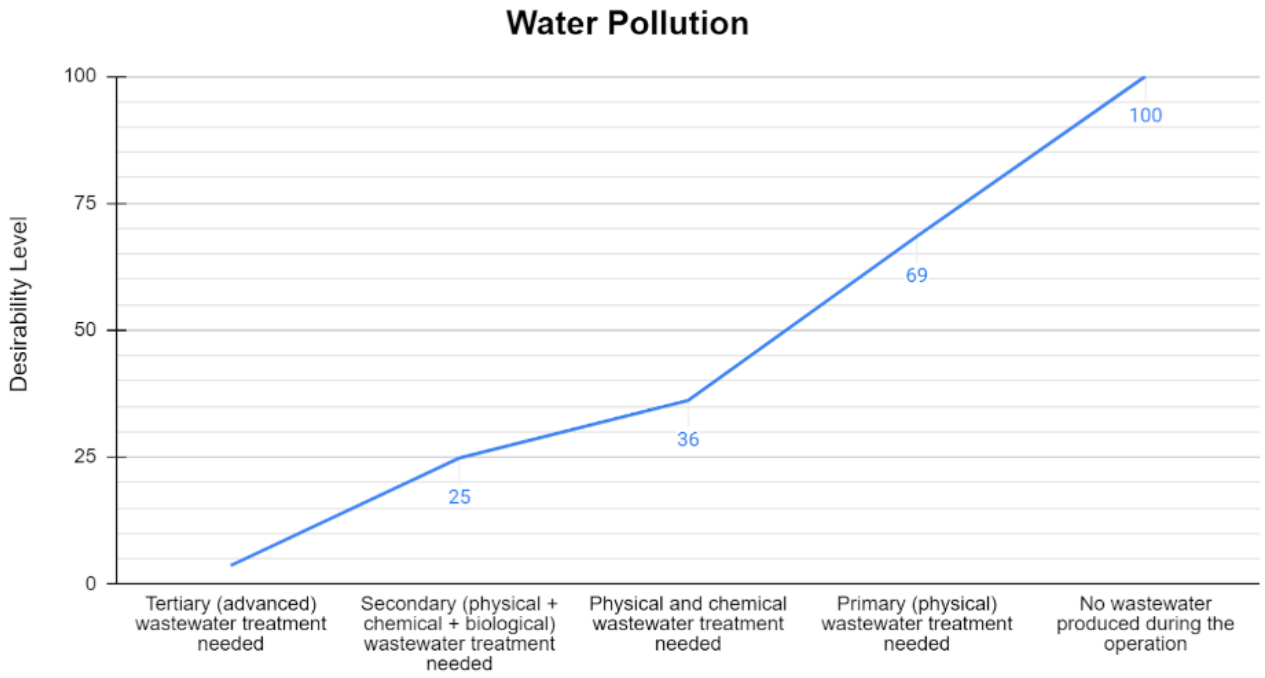

Figure 4.74. Desirability profile for water pollution.

Table 4.73. Desirability units and results for water pollution.

Water Pollution								
Description	**Unit**	**Expert 77**	**Expert 121**	**Expert 172**	**Expert 175**	**Expert 183**	**Expert 119**	**Mean**
Tertiary (advanced) wastewater treatment needed	-	0	5	0	0	10	7	4
Secondary (physical + chemical + biological) wastewater treatment needed	-	10	20	25	7	60	27	25
Physical and chemical wastewater treatment needed	-	10	35	50	35	40	47	36
Primary (physical) wastewater treatment needed	-	80	90	90	62	20	69	69
No wastewater produced during the operation	-	100	100	100	100	100	100	100
This sub-criterion measures the estimated required wastewater treatment alternatives when the low carbon energy technology will be implemented by an R&D project in the oil and gas industry.								

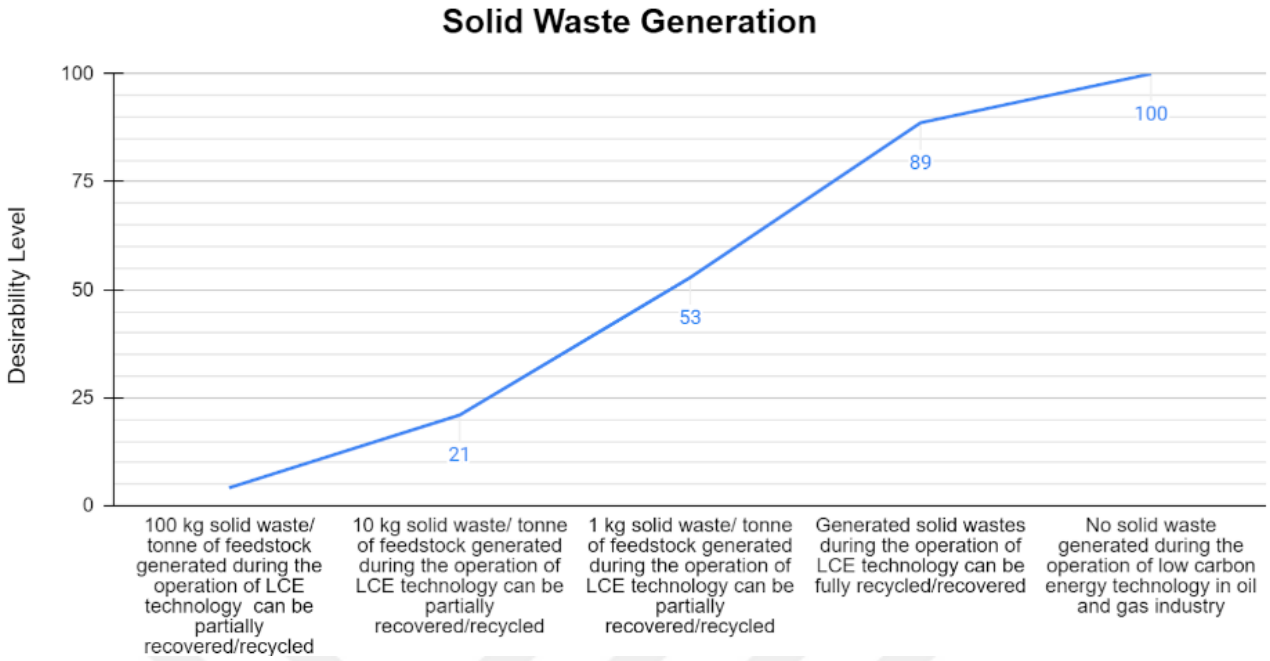

Figure 4.75. Desirability profile for solid waste generation

Table 4.74. Desirability units and results for solid waste generation

Solid Waste Generation								
Description	**Unit**	**Expert 77**	**Expert 121**	**Expert 172**	**Expert 175**	**Expert 183**	**Expert 119**	**Mean**
100 kg solid waste/ tonne of feedstock generated during the operation of LCE technology can be partially recovered/recycled	kg solid waste/tonne of feedstock	9	5	0	0	5	6	4
10 kg solid waste/ tonne of feedstock generated during the operation of LCE technology can be partially recovered/recycled	kg solid waste/tonne of feedstock	10	10	30	44	10	22	21
1 kg solid waste/ tonne of feedstock generated during the operation of LCE technology can be partially recovered/recycled	kg solid waste/tonne of feedstock	45	60	60	76	30	46	53
Generated solid wastes during the operation of LCE technology can be fully recycled/recovered	kg solid waste/tonne of feedstock	100	100	80	93	90	69	89
No solid waste generated during the operation of low carbon energy technology in oil and gas industry	kg solid waste/tonne of feedstock	100	100	100	100	100	100	100
This sub-criterion measures the expected solid waste generation amount of the low carbon energy technology when it is implemented by an R&D project in the oil and gas industry.								

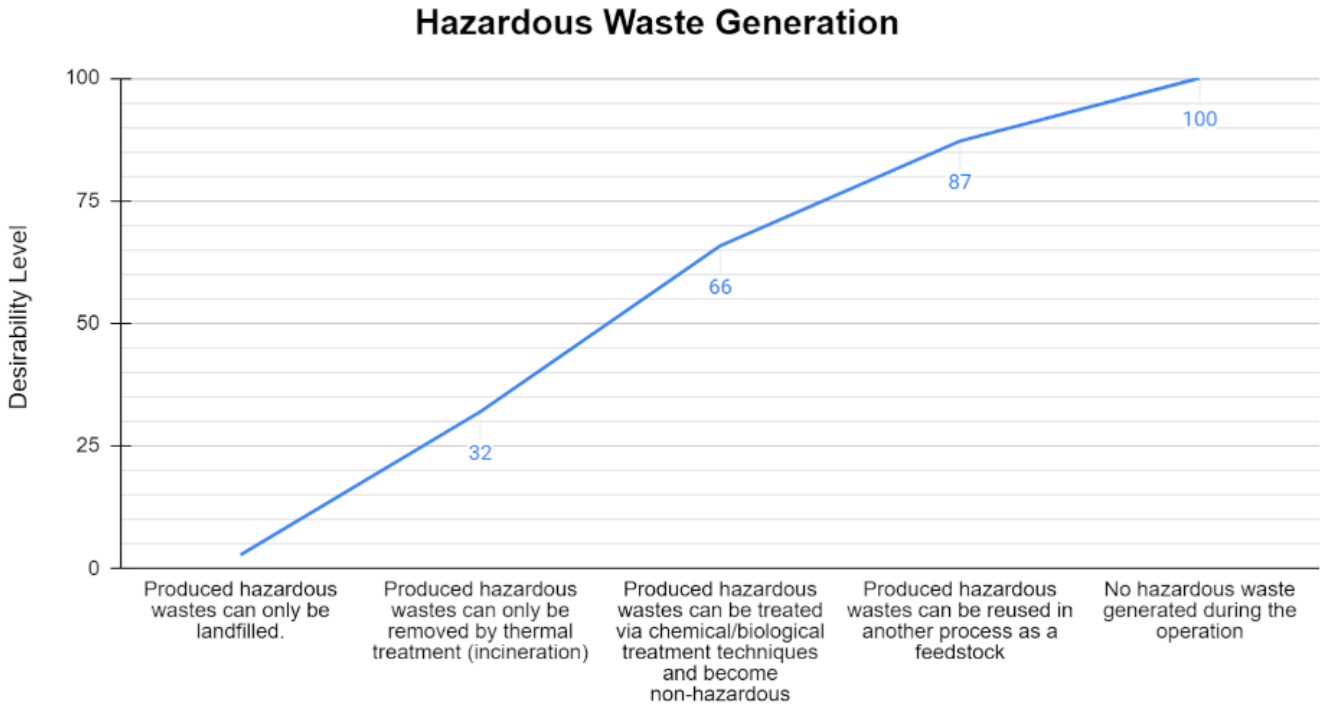

Figure 4.76. Desirability profile for hazardous waste generation.

Table 4.75. Desirability units and results for hazardous waste generation.

Hazardous Waste Generation								
Description	**Unit**	**Expert 77**	**Expert 121**	**Expert 172**	**Expert 175**	**Expert 183**	**Expert 119**	**Mean**
Produced hazardous wastes can only be landfilled.	-	3	3	0	0	5	6	3
Produced hazardous wastes can only be removed by thermal treatment (incineration)	-	7	10	30	68	50	27	32
Produced hazardous wastes can be treated via chemical/biological treatment techniques and become non-hazardous	-	65	80	60	85	60	45	66
Produced hazardous wastes can be reused in another process as a feedstock	-	90	100	80	94	90	69	87
No hazardous waste generated during the operation	-	100	100	100	100	100	100	100
This sub-criterion measures the estimated required hazardous waste treatment alternatives when the low carbon energy technology will be implemented by an R&D project in the oil and gas industry.								

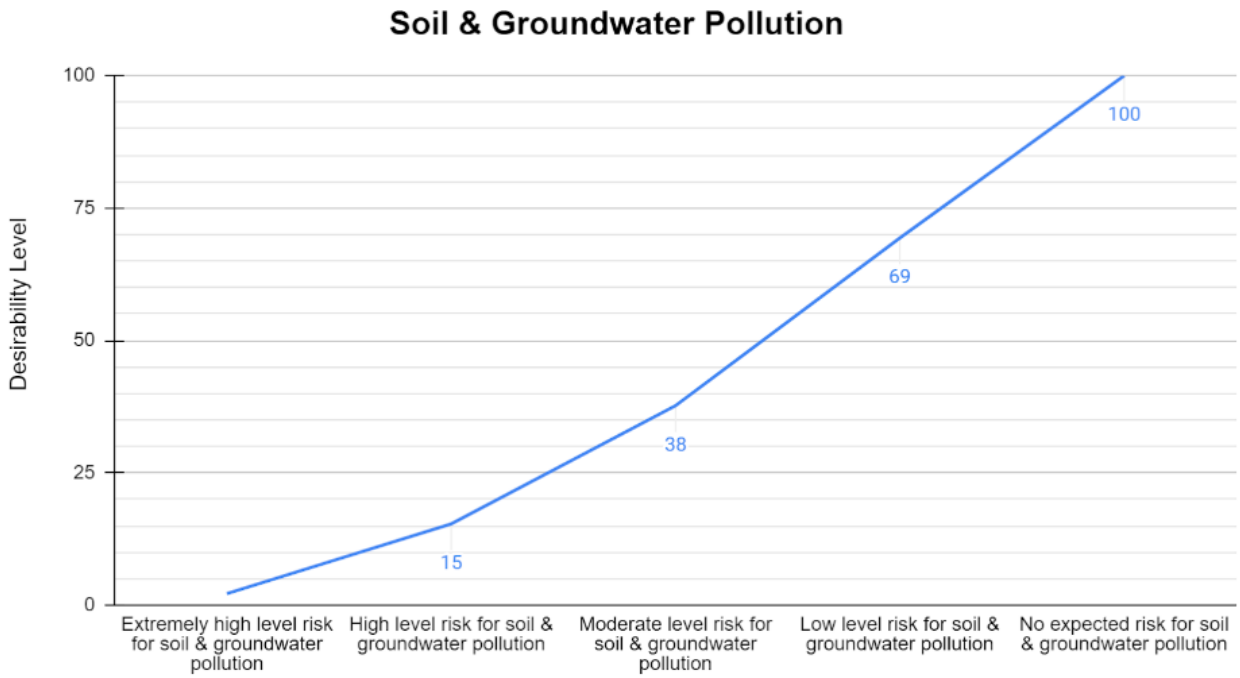

Figure 4.77. Desirability profile for soil and groundwater pollution.

Table 4.76. Desirability units and results for soil and groundwater pollution.

Soil & Groundwater Pollution								
Description	**Unit**	**Expert 77**	**Expert 121**	**Expert 172**	**Expert 175**	**Expert 183**	**Expert 119**	**Mean**
Extremely high-level risk for soil & groundwater pollution	-	5	3	0	0	1	4	2
High level risk for soil & groundwater pollution	-	12	6	30	18	5	21	15
Moderate level risk for soil & groundwater pollution	-	25	30	60	59	15	37	38
Low level risk for soil & groundwater pollution	-	80	80	85	79	30	62	69
No expected risk for soil & groundwater pollution	-	100	100	100	100	100	100	100
This sub-criterion measures the expected soil & groundwater pollution risk when the low carbon energy technology will be implemented by an R&D project in the oil and gas industry.								

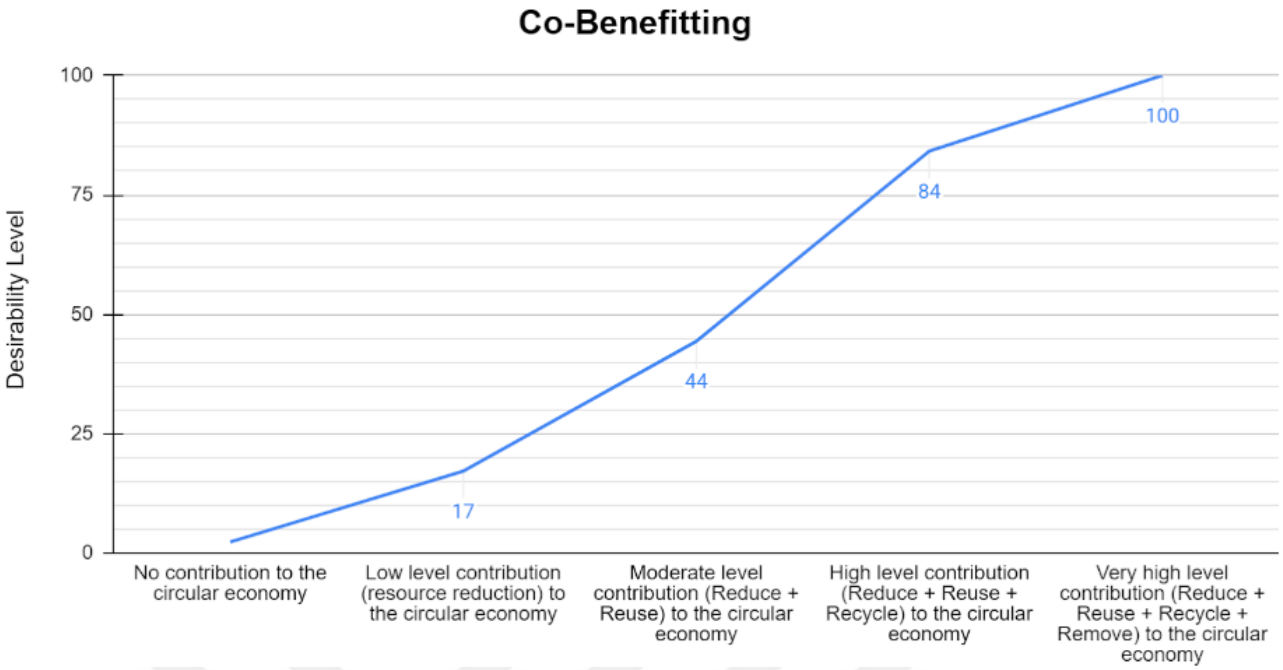

Figure 4.78. Desirability profile for co-benefitting.

Table 4.77. Desirability units and results for co-benefitting.

Co-benefiting								
Description	**Unit**	**Expert 77**	**Expert 121**	**Expert 172**	**Expert 175**	**Expert 183**	**Expert 119**	**Mean**
No contribution to the circular economy	-	4	3	0	0	1	6	2
Low level contribution (resource reduction) to the circular economy	-	10	5	30	10	29	19	17
Moderate level contribution (Reduce + Reuse) to the circular economy	-	40	40	60	39	50	37	44
High level contribution (Reduce + Reuse + Recycle) to the circular economy	-	80	90	90	89	90	66	84
Very high-level contribution (Reduce + Reuse + Recycle + Remove) to the circular economy	-	100	100	100	100	100	100	100
This sub-criterion measures the expected contribution of low carbon energy technology to the circular economy when it is implemented by an R&D project in the oil and gas industry								

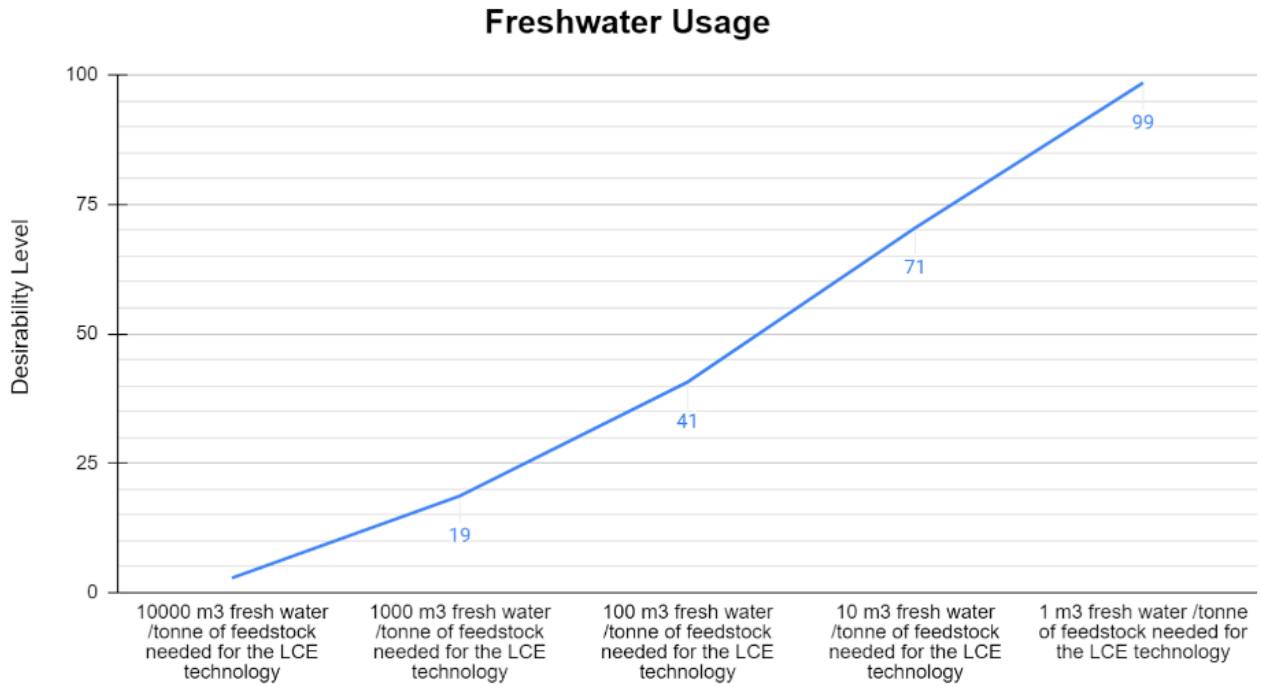

Figure 4.79. Desirability profile for freshwater usage.

Table 4.78. Desirability units and results for freshwater usage.

Freshwater Usage								
Description	**Unit**	**Expert 77**	**Expert 121**	**Expert 172**	**Expert 175**	**Expert 183**	**Expert 119**	**Mean**
10000 m^3 fresh water /tonne of feedstock needed for the LCE technology	m^3 freshwater/tonne of feedstock	3	2	0	0	10	2	3
1000 m^3 fresh water /tonne of feedstock needed for the LCE technology	m^3 freshwater/tonne of feedstock	7	5	40	17	30	13	19
100 m^3 fresh water /tonne of feedstock needed for the LCE technology	m^3 freshwater/tonne of feedstock	14	30	70	42	60	28	41
10 m^3 fresh water /tonne of feedstock needed for the LCE technology	m^3 freshwater/tonne of feedstock	60	70	80	85	80	48	71
1 m^3 fresh water /tonne of feedstock needed for the LCE technology	m^3 freshwater/tonne of feedstock	100	100	100	100	100	91	99
This sub-criterion measures the estimated amount of freshwater usage when the low carbon energy technology will be implemented by an R&D project in the oil and gas industry.								

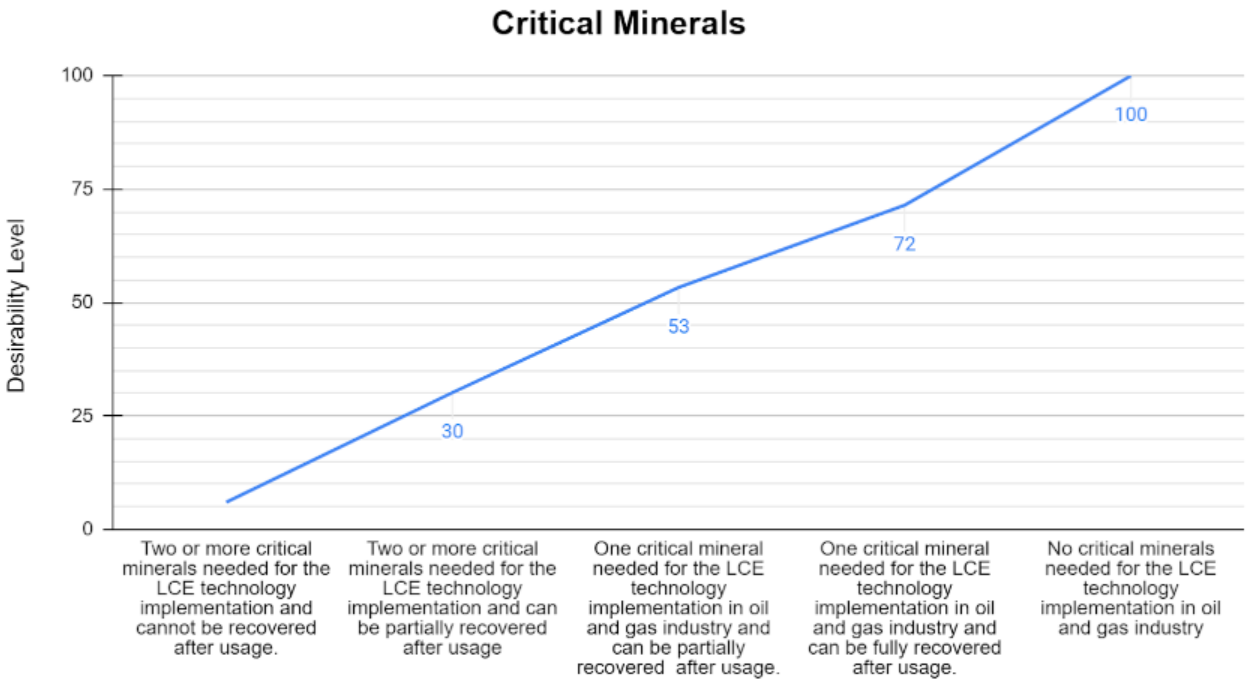

Figure 4.80. Desirability profile for critical minerals.

Table 4.79. Desirability units and results for critical minerals.

Critical minerals							
Description	**Expert 77**	**Expert 121**	**Expert 172**	**Expert 175**	**Expert 183**	**Expert 119**	**Mean**
Two or more critical minerals needed for the LCE technology implementation and cannot be recovered after usage.	4	3	0	0	20	9	6
Two or more critical minerals needed for the LCE technology implementation and can be partially recovered after usage	18	15	30	12	70	36	30
One critical mineral needed for the LCE technology implementation in oil and gas industry and can be partially recovered after usage.	50	65	50	23	80	52	53
One critical mineral needed for the LCE technology implementation in oil and gas industry and can be fully recovered after usage.	85	95	60	31	85	73	72
No critical minerals needed for the LCE technology implementation in oil and gas industry	100	100	100	100	100	100	100
This sub-criterion measures the expected amount of critical mineral usage when the low carbon energy technology will be implemented by an R&D project in the oil and gas industry.							

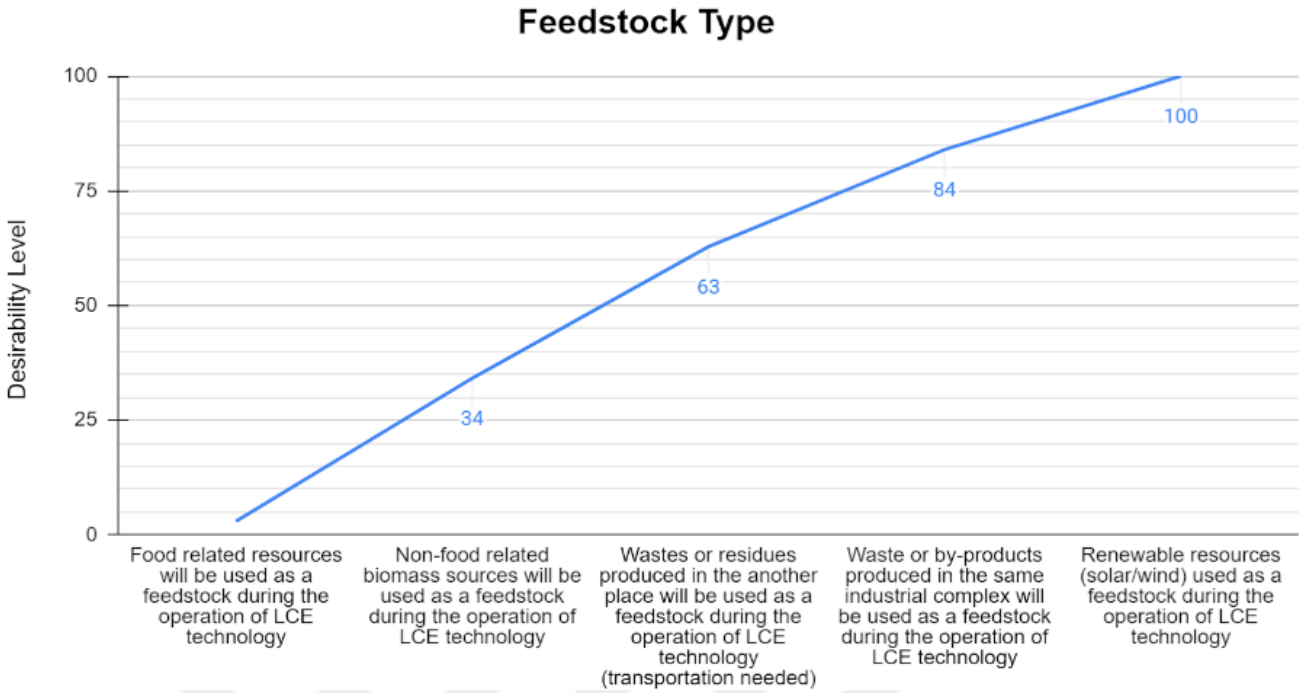

Figure 4.81. Desirability profile for feedstock type.

Table 4.80. Desirability units and results for feedstock type.

Feedstock Type							
Description	**Expert 77**	**Expert 121**	**Expert 172**	**Expert 175**	**Expert 183**	**Expert 119**	**Mean**
Food related resources will be used as a feedstock during the operation of LCE technology	6	3	1	0	5	3	3
Non-food related biomass sources will be used as a feedstock during the operation of LCE technology	12	10	30	56	80	17	34
Wastes or residues produced in another place will be used as a feedstock during the operation of LCE technology (transportation needed)	40	60	65	86	90	36	63
Waste or by-products produced in the same industrial complex will be used as a feedstock during the operation of LCE technology	80	95	85	93	90	61	84
Renewable resources (solar/wind) used as a feedstock during the operation of LCE technology	100	100	100	100	100	100	100
This sub-criterion measures the required feedstock type for the low carbon energy technology when it will be implemented by an R&D project in the oil and gas industry.							

4.6.5. Desirability Profiles of Political Criteria

The political desirability profiles were composed by oil and gas industry experts and reflect the mean desirability scores for each sub-criterion and criterion (if the model element does not have any sub-criterion). The desirability of technologies is influenced politically by their alignment with governmental policies, international regulations, and benefits from emission trading systems and subsidies, advocating for technologies that enhance energy security and receive strong policy support. The consolidated desirability profiles thus provide a nuanced, multi-dimensional framework to guide stakeholders in making informed decisions about implementing low carbon energy technologies. The participant list for the determination of political desirability profiles is shown in Table 4.81. The quantification results of political desirability profiles are presented in the following tables from Table 4.82 to Table 4.87. The desirability profiles of political criteria are presented in the following figures from Figure 4.82 to Figure 4.87.

Table 4.81. Participant list for the determination of political desirability profiles.

Determination of Desirability Profiles for Political Perspective			
Expert No.	**Title/Position**	**Organization Type**	**Country**
Expert 121	Climate Change Coordinator	Oil & Gas	Turkey
Expert 17	Strategy & Business Development Manager	Oil & Gas	Turkey
Expert 181	Knowledge Owner Sustainability Studies	Oil & Gas	Italy
Expert 182	Sustainability Manager	Oil & Gas	Italy
Expert 183	Researcher	Oil & Gas	Italy

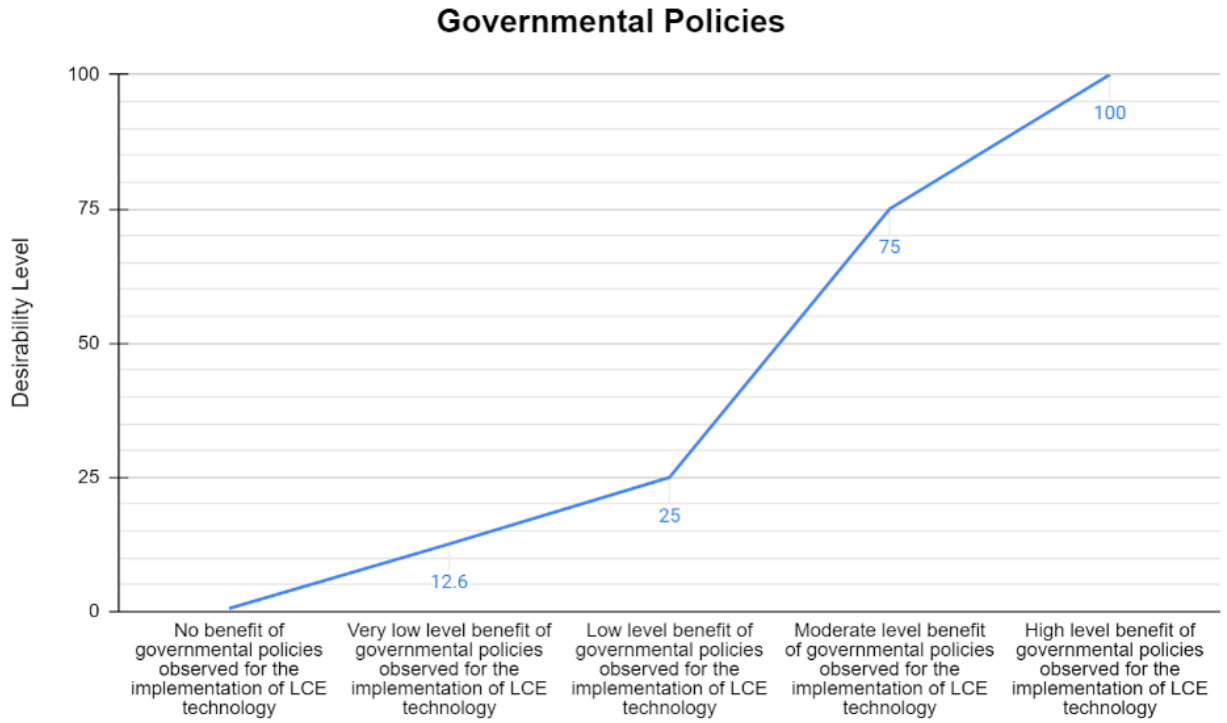

Figure 4.82. Desirability profile for governmental policies.

Table 4.82. Desirability units and results for governmental policies.

Governmental Policies						
Description	**Expert 121**	**Expert 17**	**Expert 181**	**Expert 182**	**Expert 183**	**Mean**
No benefit of governmental policies observed for the implementation of LCE technology	3	0	0	0	0	1
Very low-level benefit of governmental policies observed for the implementation of LCE technology	15	5	10	23	10	13
Low level benefit of governmental policies observed for the implementation of LCE technology	25	10	20	50	20	25
Moderate level benefit of governmental policies observed for the implementation of LCE technology	80	90	70	75	60	75
High level benefit of governmental policies observed for the implementation of LCE technology	100	100	100	100	100	100
This sub-criterion measures the expected benefits of governmental policies for the implementation of low carbon energy technology as an R&D project in the oil and gas industry.						

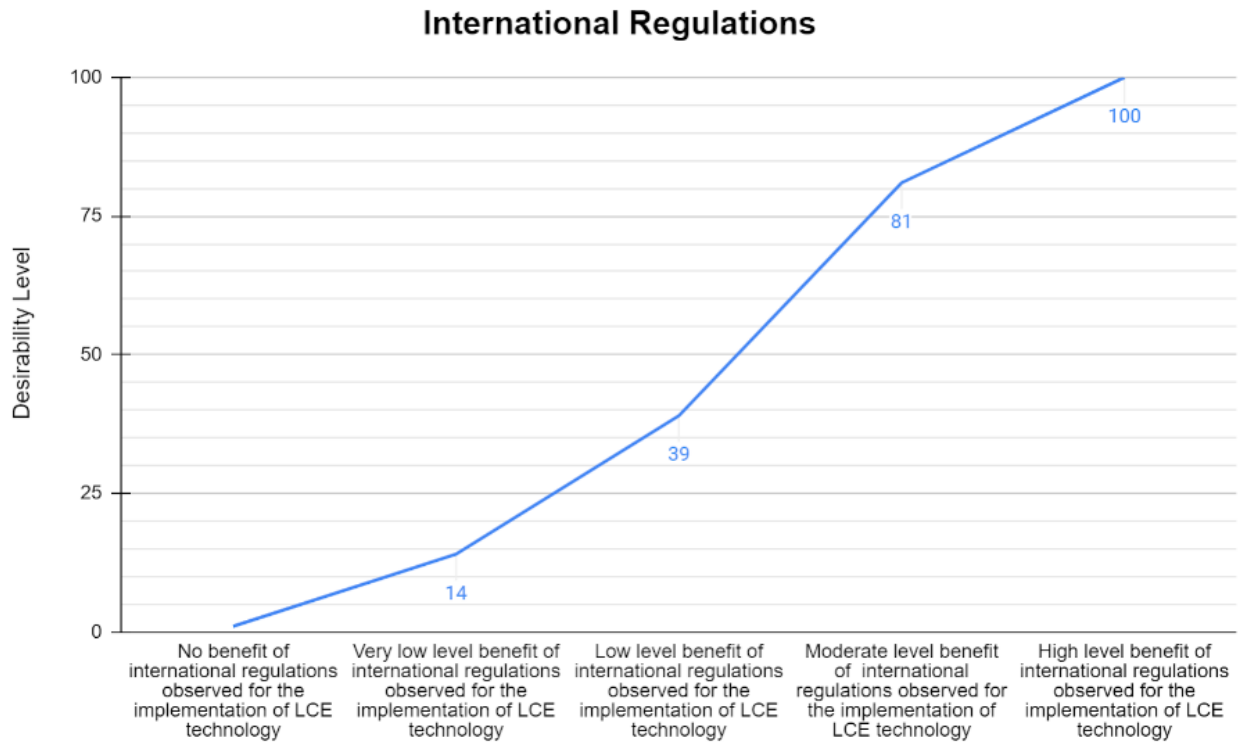

Figure 4.83. Desirability profile for international regulations.

Table 4.83. Desirability units and results for international regulations.

International Regulations						
Description	**Expert 121**	**Expert 17**	**Expert 181**	**Expert 182**	**Expert 183**	**Mean**
No benefit of international regulations observed for the implementation of LCE technology	5	0	0	0	0	1
Very low-level benefit of international regulations observed for the implementation of LCE technology	10	5	10	25	20	14
Low level benefit of international regulations observed for the implementation of LCE technology	55	40	20	50	30	39
Moderate level benefit of international regulations observed for the implementation of LCE technology	90	90	70	75	80	81
High level benefit of international regulations observed for the implementation of LCE technology	100	100	100	100	100	100
This sub-criterion measures the expected benefits of international regulations for the implementation of low carbon energy (LCE) technology as an R&D project in the oil and gas industry.						

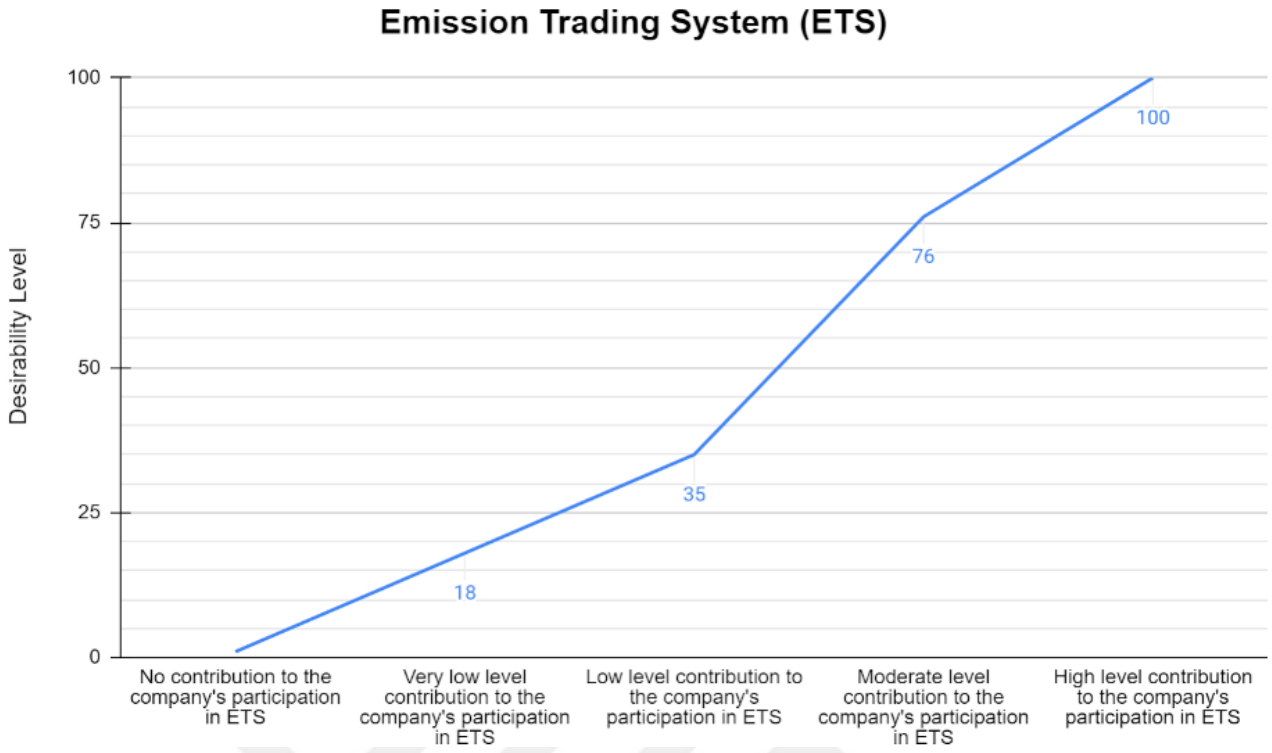

Figure 4.84. Desirability profile for ETS.

Table 4.84. Desirability units and results for ETS.

Emission Trading System (ETS)						
Description	**Expert 121**	**Expert 17**	**Expert 181**	**Expert 182**	**Expert 183**	**Mean**
No contribution to the company's participation in ETS	5	0	0	0	0	1
Very low-level contribution to the company's participation in ETS	20	10	10	30	20	18
Low level contribution to the company's participation in ETS	40	15	20	70	30	35
Moderate level contribution to the company's participation in ETS	90	90	60	80	60	76
High level contribution to the company's participation in ETS	100	100	100	100	100	100
This sub-criterion measures the effect of low carbon energy technology implementation on the company's participation in ETS.						

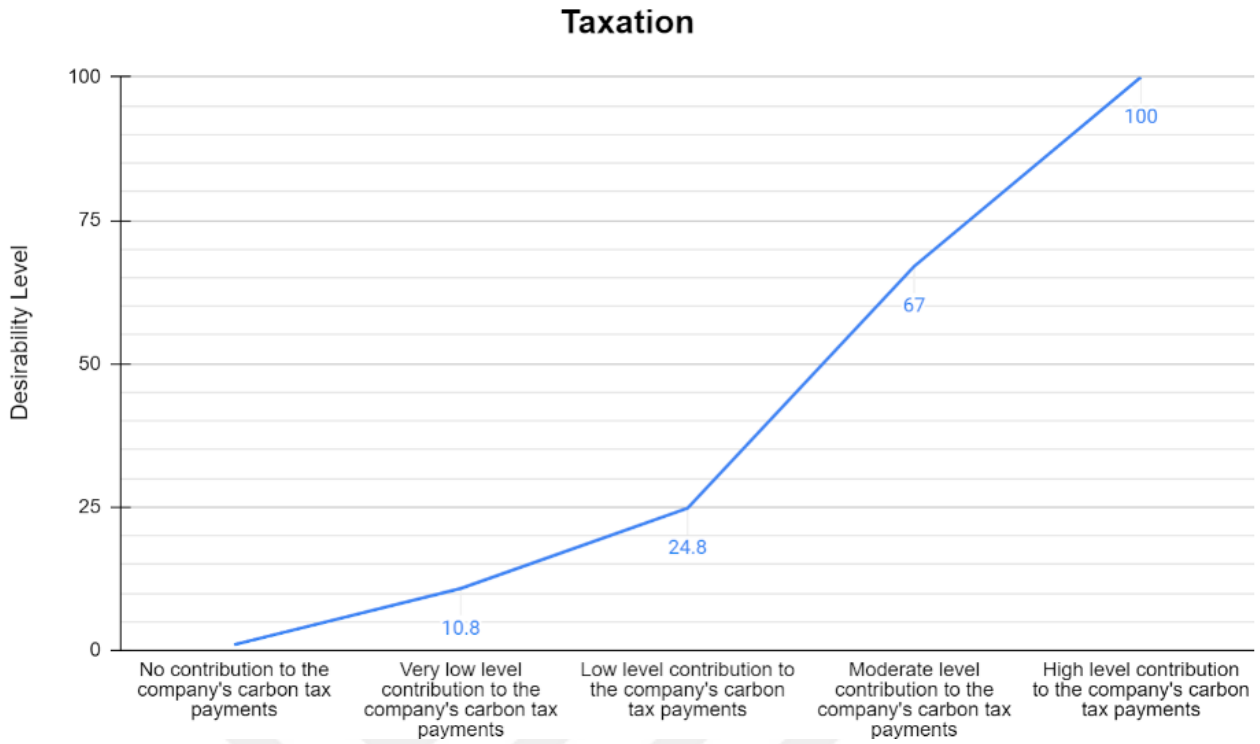

Figure 4.85. Desirability profile for taxation.

Table 4.85. Desirability profile for taxation.

Taxation						
Description	**Expert 121**	**Expert 17**	**Expert 181**	**Expert 182**	**Expert 183**	**Mean**
No contribution to the company's carbon tax payments	5	0	0	0	0	1
Very low-level contribution to the company's carbon tax payments	15	10	10	9	10	11
Low level contribution to the company's carbon tax payments	40	15	20	9	40	25
Moderate level contribution to the company's carbon tax payments	85	90	60	40	60	67
High level contribution to the company's carbon tax payments	100	100	100	100	100	100
This sub-criterion measures the effect of low carbon energy technology implementation to the company's carbon tax payments.						

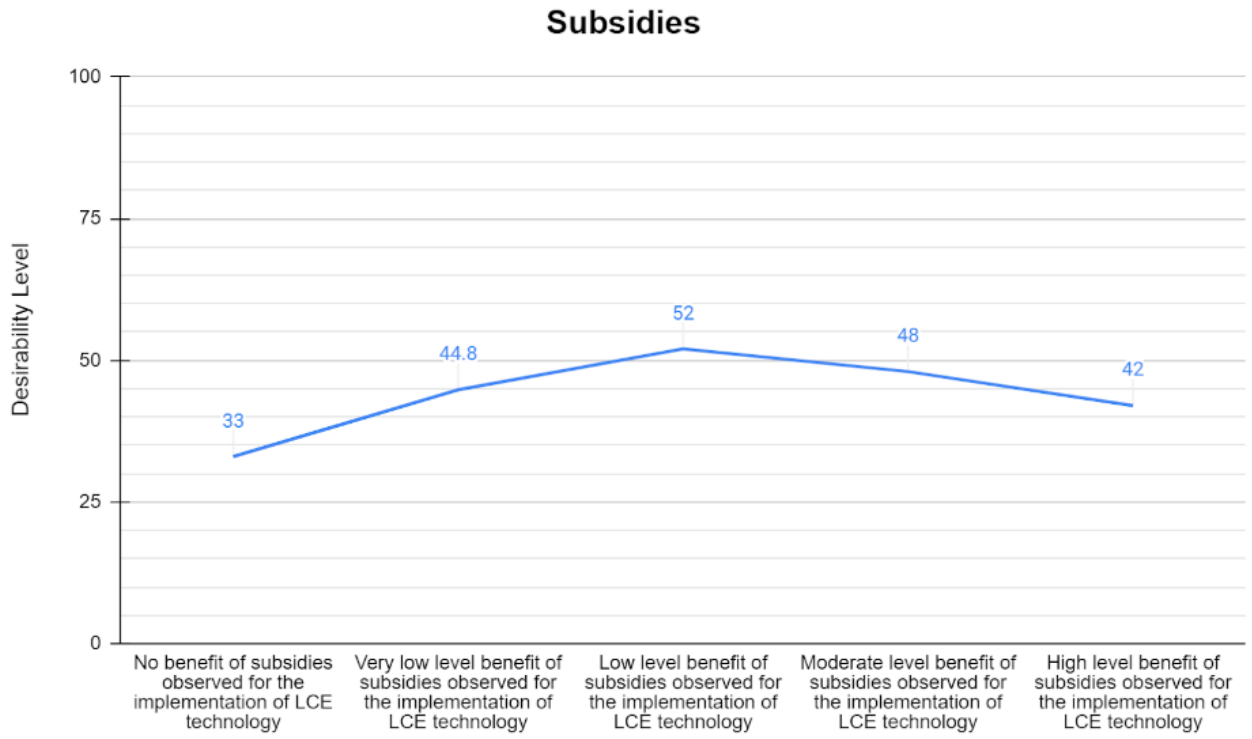

Figure 4.86. Desirability profile for subsidies.

Table 4.86. Desirability units and results for subsidies.

Subsidies						
Description	**Expert 121**	**Expert 17**	**Expert 181**	**Expert 182**	**Expert 183**	**Mean**
No benefit of subsidies observed for the implementation of LCE technology	5	0	30	80	50	33
Very low-level benefit of subsidies observed for the implementation of LCE technology	15	10	80	59	60	45
Low level benefit of subsidies observed for the implementation of LCE technology	35	15	100	40	70	52
Moderate level benefit of subsidies observed for the implementation of LCE technology	80	90	20	20	30	48
High level benefit of subsidies observed for the implementation of LCE technology	100	100	0	0	10	42
This sub-criterion measures the benefit of subsidies for the implementation of low carbon energy technology in oil and gas industry.						

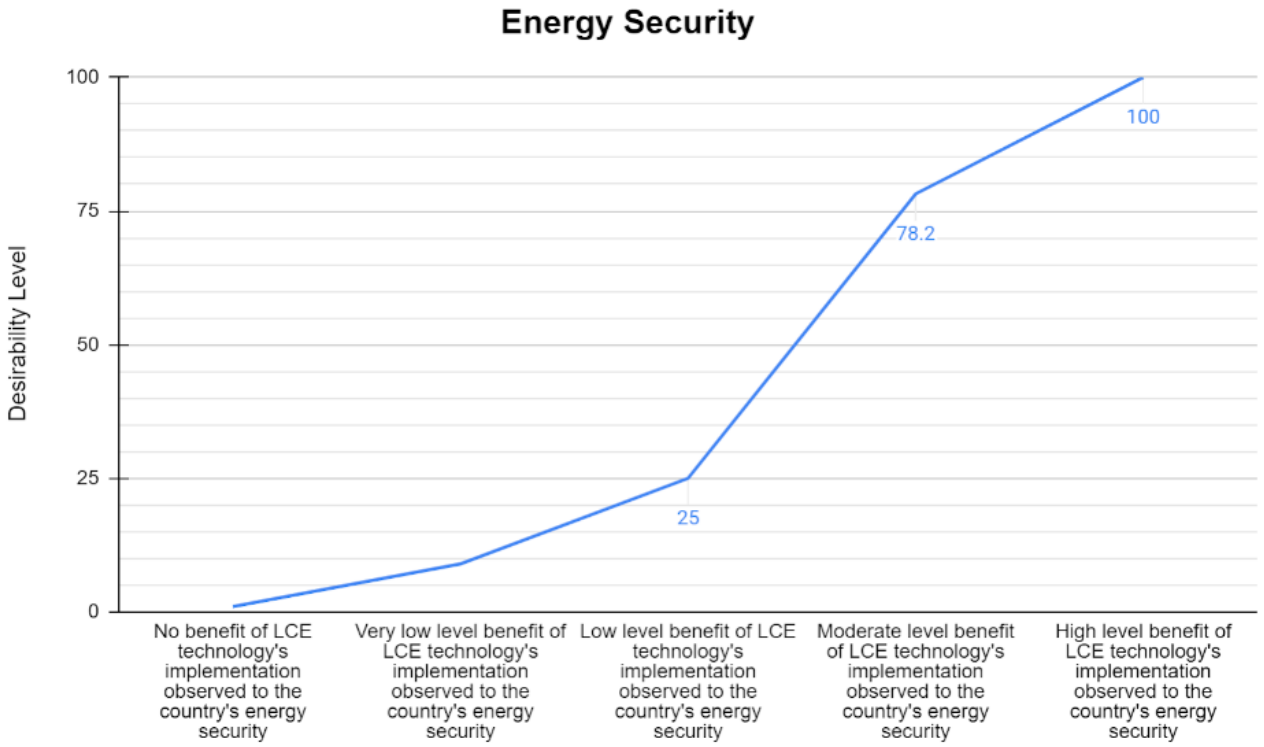

Figure 4.87. Desirability profile for energy security.

Table 4.87. Desirability units and results for energy security.

Energy Security						
Description	**Expert 121**	**Expert 17**	**Expert 181**	**Expert 182**	**Expert 183**	**Mean**
No benefit of LCE technology's implementation observed to the country's energy security	5	0	0	0	0	1
Very low-level benefit of LCE technology's implementation observed to the country's energy security	10	10	10	5	10	9
Low level benefit of LCE technology's implementation observed to the country's energy security	40	30	30	5	20	25
Moderate level benefit of LCE technology's implementation observed to the country's energy security	90	90	80	71	60	78
High level benefit of LCE technology's implementation observed to the country's energy security	100	100	100	100	100	100
This sub-criterion measures the benefit level of low carbon energy technology to energy security when it will be implemented by an R&D project in the oil and gas industry.						

5. RESEARCH MODEL APPLICATION

Integration of a case study is of capital importance for this research, as it enables the exploitation of the model in a tangible organizational setting. This step is crucial for applying the assessment criteria developed for the adoption of low-carbon energy technologies in the oil and gas industry. The model, shaped with inputs from industry experts, moves beyond traditional academic frameworks, offering a pragmatic approach grounded in the realities of the industry. Applying the model in actual organizational scenarios not only confirms its effectiveness and reliability but also enhances the understanding of its practical implementation. This approach is instrumental in providing actionable insights for both end users and technology developers, focusing on improving technology itself and the adoption strategies of technologies. By aligning the model with real-world applications, the study bridges the gap between expert-driven research and industry practices, ensuring that the outcomes are directly relevant and beneficial for the industry. This method emphasizes the significance of incorporating industry expertise in research, highlighting the synergy between expert knowledge and practical application in shaping models that are both robust and directly applicable to industry needs.

This model was specifically applied to a particular oil and gas organization, focusing on hydrogen production technologies as alternatives for low-carbon energy. In this case study, seven distinct hydrogen production technologies were identified and subsequently assessed by industry professionals. The case study presents a unique opportunity to explore how organizations within the oil and gas industry evaluate the technology alternatives with the aid of the parameters of the model. It provides an in-depth look at the decision-making processes in a real-world setting, allowing for a comprehensive understanding of the practical implications of adopting low-carbon technologies. This application not only validates the model's relevance and efficacy but also highlights its adaptability and applicability in addressing industry-specific challenges and opportunities. Through this case study, the model's utility in guiding strategic decisions about technology adoption in the oil and gas sector is thoroughly examined, offering valuable insights into the dynamics of integrating sustainable practices in an energy-intensive industry.

Regarding the clean energy technology alternatives, hydrogen production technologies were determined to meet the unique challenges of the oil and gas industry in transitioning towards sustainable and low-carbon operations. These selected technologies, though varied in their operational mechanisms, share the unified objective of minimizing carbon emissions and

optimizing the use of resources, with a strong focus on integrating renewable energy sources (IEA, 2023a, 2023b).

The technology selection process was thoroughly performed by an in-depth analysis of European R&D programs, specifically FP7, Horizon 2020, and Horizon Europe (EC, 2018; EC, 2022; EC, 2023). These programs have played a pivotal role in fostering innovation and promoting sustainability across various sectors, including oil and gas (IEA, 2023b). Within the scope of these programs, a total of 303 research projects were reviewed, spanning from FP7 to the Horizon Europe Programme. These projects were specifically scrutinized for their relevance and potential in advancing the decarbonization efforts of the oil and gas sector (EC, 2018; EC, 2022; EC, 2023).

From the EU R&D project database, the focus was refined to identify the most advanced and emergent hydrogen production technologies. This attentive approach ensured that the technologies selected were not only at the forefront of innovation but also in alignment with current industry needs and environmental sustainability trends. Each chosen hydrogen production technology was evaluated for its specific potential to address critical issues within the oil and gas industry. This includes considerations such as efficiency in emissions reduction, enhancement of energy efficiency, and the strategic utilization of resources, making them ideal candidates for the study's focus on hydrogen production as a pathway to a more sustainable oil and gas industry. Additionally, a comprehensive technology characterization table was developed to further detail these technology alternatives. The characterization encompassed various aspects of each technology, such as operational efficiency, environmental impact, technological maturity, and potential for scalability within the oil and gas industry as seen in Table 2.1. The technology characterization table was distributed to the experts who participated in the case study application with desirability curves. Their task was to review and discuss the technologies in depth, by using the desirability profiles and the characterization table as a reference point.

The desirability profiles in the case study application allowed for a more nuanced and comprehensive evaluation of each hydrogen production technology. It facilitated a shared understanding among the experts and provided a structured framework for assessing the technologies against the backdrop of the industry’s current challenges and future aspirations. This collaborative approach, underpinned by rigorous research and expert input, further enhanced the robustness and credibility of the HDM.

5.1. Technology Evaluation Scores of Technology Alternatives

In this section, the results of case study application which is performed by an international oil and gas company are assessed. The case study application is composed of the comprehensive evaluation of various hydrogen production technologies, the MCDM approach was employed. This section discusses the implications of the findings, which assessed technologies which are SE-SMR, E-SMR, P-MR, AWE, AEM-WE, PEM-WE, and SOE across diverse criteria including social, economic, technical, environmental, and political perspectives. One organization was selected from the last expert panel (Expert Panel 13) and a series of discussions were conducted with the experts in order to determine the scores of technology alternatives with respect to each desirability curve.

The analysis results show that PEM-WE has the highest evaluation scores than other project alternatives. The total evaluation score of PEM-WE is 79 out of 100 while the evaluation scores of other electrolyser technology alternatives (AWE, SOE and AEM-WE) are 77, 76 and 72, respectively as seen in the figure. When the advanced steam methane reformer technologies (E-SMR, SE-SMR and P-MR) were reviewed, we can see that their total scores are 63, 61, 42, respectively. In the evaluation results, a striking contrast were observed between electrolyser technologies and steam methane reforming technologies. Even electrification of industrial process, carbon capture, renewable energy was integrated into the steam methane reforming process; evaluation scores of these technology alternatives were lower than electrolyser technologies. Electrolyser technologies generally outperform the steam reforming technologies in environmental and political perspectives. Since steam methane reforming technologies are fundamentally relied on fossil fuels, it causes a significant limitation. Even with modifications like electrification or carbon capture, these technologies cannot fully mitigate the inherent carbon emissions associated with fossil fuel usage. This is evidenced by their lower scores in environmental criteria and specific metrics like GHG emissions and air quality impacts. Moreover, P-MR demonstrates the challenges faced by technologies heavily reliant on fossil fuels, as shown in its lower overall and environmental scores. In the context of P-MR technology, it is important to consider the implications of the high-voltage systems used for plasma generation. As indicated in the studies by Miura et al. and Barni et al., Kim et al. such systems can lead to the formation of byproducts, including ozone (O_3), nitrogen oxides (NO_x) because of the Dielectric Barrier Discharge (DBD) process (Barni et al., 2019; Miura et al., 2020; Kim et al., 2023). These findings underscore a critical aspect of P-MR technology: while it offers certain advantages, it does not fully address other emission reduction concerns, as the generation of byproducts like O_3 can pose environmental challenges. This highlights the need for careful consideration of the overall environmental impact of P-MR technology, considering both its advantages and potential drawbacks. While the

modifications to traditional steam methane reforming processes, such as electrification or carbon capture, can yield improvements, but they do not suffice to meet stringent emission reduction targets if the underlying process remains dependent on fossil fuels. The transition to technologies like electrolysers, which can be powered entirely by renewable energy, represents a more viable path toward achieving the ambitious goals of a low-carbon future.

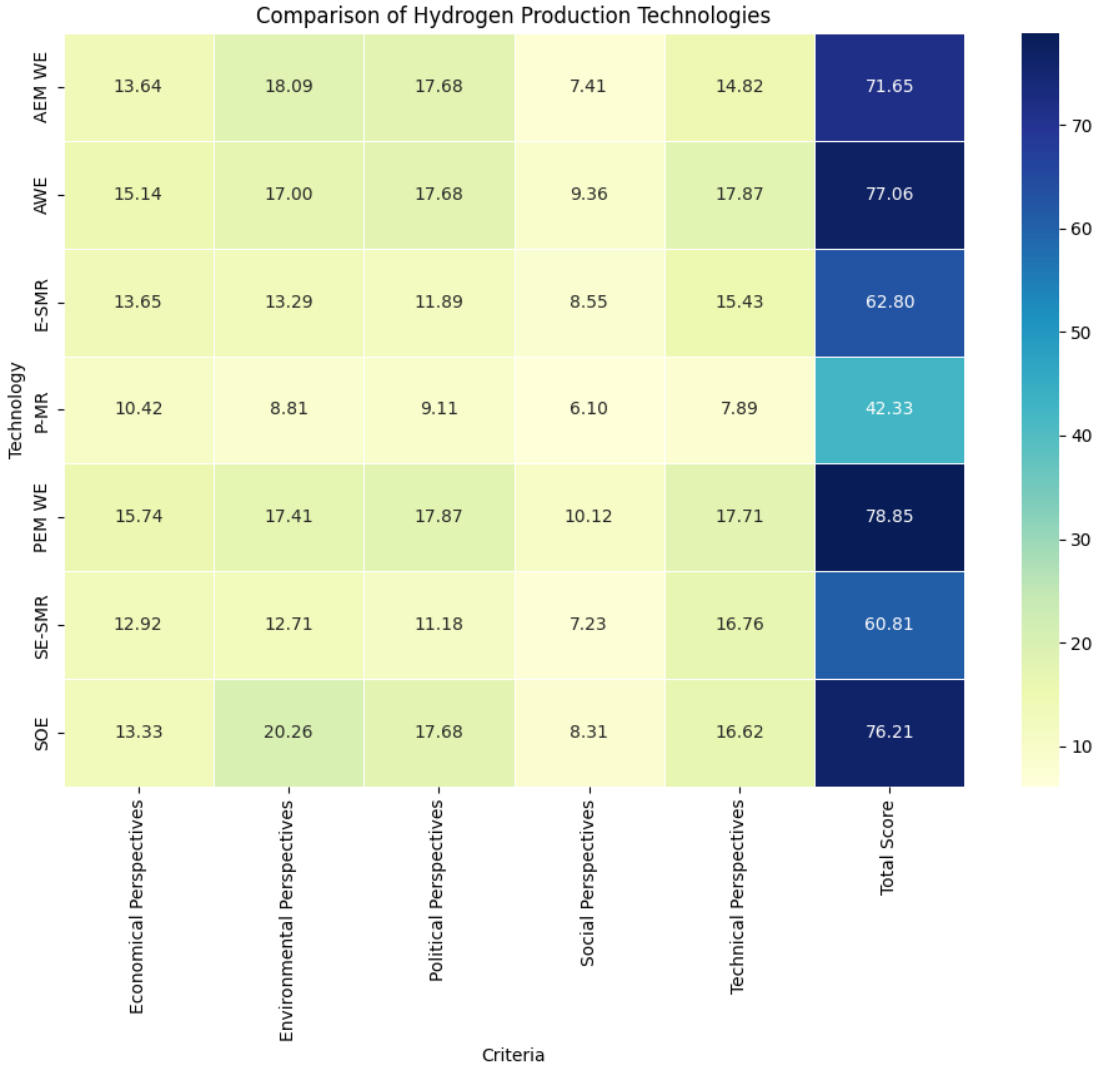

Figure 5.1. Evaluation Results of Technology Alternatives.

While the evaluation results were examined in detail, the areas of development were determined for each technological alternative. The highest and the lowest scores of model elements for each technology alternative were listed in the following tables from Table 5.1 to Table 5.7. The lowest scores of each technology alternative were used for the creation of actions.

Table 5.1. Highest and lowest scores of SE-SMR technology

Sorption Enhanced Steam Methane Reforming (SE-SMR)			
Scores	**Sub-criteria**	**Desirability Value**	**Desirability Value Metrics**
Highest Scores	Governmental R&D Investments	100	Governmental R&D investment ratio is 100%
	Feedstock Deliverable	95	No risk of feedstock delivery
	Easy maintenance	91	Yearly maintenance required
	Integration Capability	98	Any modification/investment is not needed
	GHG Emissions	80	90 % GHG emission reduction (CO_{2eq})
	Governmental Policies	100	High level benefit observed
	ETS	100	High level contribution in ETS
Lowest Scores	Gender Equity	10	No contribution to gender equity in oil and gas industry
	Stakeholder Pressure	25	Low impact of stakeholder pressure
	Market Adoption	37	The first small scale commercial implementation
	Hazardous Waste Generation	30	Produced hazardous wastes can only be removed by thermal treatment
	Feedstock	3	Food related resources or fossil fuel (non-renewable resources) will be used
	Energy Security	9	Very low-level benefit observed to the country's energy security

Table 5.2. Highest and lowest scores of E-SMR technology.

Electrified Steam Methane Reforming (E-SMR)			
Scores	**Sub-criteria**	**Desirability Value**	**Desirability Value Metrics**
Highest Scores	Stakeholder Pressure	92	High impact of stakeholder pressure
	Capital Cost	98	Between 500-1000 EUR/kW
	Feedstock Deliverable	95	No risk of feedstock delivery
	Governmental Policies	100	High level benefit observed
	International Regulations	100	High level benefit observed
Lowest Scores	Public Concern	32	Moderate level of public concern
	Gender Equity	10	No contribution to gender equity in oil and gas industry
	Integration Capability	50	Small to medium scale modification/investment required
	Energy Security	25	Low level benefit observed to the country's energy security

Table 5.3. Highest and lowest scores of P-MR technology.

Plasma Methane Reforming (P-MR)			
Scores	**Sub-criteria**	**Desirability Value**	**Desirability Value Metrics**
Highest Scores	Training of employee	81	High impact on training and educating
	Governmental R&D Investments	100	Governmental R&D investment ratio is 100%
Lowest Scores	Market Adoption	14	The technology has developed by industry-academic collaboration, but it has not commercially tested
	Energy Efficiency	44	50 % energy efficiency
	Technology Readiness Level	30	Below TRL 3
	Operational Stability	11	No long-run operation
	Feedstock	3	Food related resources or fossil fuel (non-renewable resources) will be used
	Energy Security	9	Very low-level benefit observed to the country's energy security

Table 5.4. Highest and lowest scores of AWE technology.

Alkaline Water Electrolyser (AWE)			
Scores	**Sub-criteria**	**Desirability Value**	**Desirability Value Metrics**
Highest Scores	Public Awareness	89	High level of public awareness
	Capital Cost	95	Between 500-1000 EUR/kW
	Transportation Cost	100	below 5 EUR/tonne
	Technology Readiness Level	99	TRL 9
	Operational Stability	100	over 9 months long-run operation
	GHG Emissions	89	100 % GHG emission reduction (CO_{2eq})
	Feedstock	100	Renewable resources (solar/wind) used as a feedstock
	Governmental Policies	100	High level benefit of governmental policies observed
	Energy Security	100	High level benefit observed to the country's energy security
Lowest Scores	Gender Equity	30	Low level of contribution to gender equity in oil and gas industry
	Private R&D Investments	30	Private R&D investment ratio is 0%
	Utility consumption	46	60 % utility system efficiency
	Co-benefitting	46	Moderate level contribution to the circular economy

Table 5.5. Highest and lowest scores of AEM-WE technology.

Anion Exchange Membrane Electrolyser (AEM-WE)			
Scores	**Sub-criteria**	**Desirability Value**	**Desirability Value Metrics**
Highest Scores	New Job Opportunities	72	Moderate impact on creation of new job opportunities
	Governmental R&D Investments	100	Governmental R&D investment ratio is 100%
	Capital Cost	95	Between 500-1000 EUR/kW
	Technology Readiness Level	80	TRL 6
	Integration Capability	90	Small-scale modification/investment required
	GHG Emissions	89	100 % GHG emission reduction (CO_{2eq})
	Water Pollution	100	No wastewater produced during the operation
	Governmental Policies	100	High level benefit of governmental policies observed
	Energy Security	100	High level benefit observed to the country's energy security
Lowest Scores	Stakeholder Pressure	25	Low impact of stakeholder pressure
	Market Adoption	37	The first small scale commercial implementation has been done with an R&D project.
	Private R&D Investments	30	Private R&D investment ratio is 0%

Table 5.6. Highest and lowest scores of PEM-WE technology.

Proton Exchange Membrane Water Electrolyser (PEM-WE)			
Scores	**Sub-criteria**	**Desirability Value**	**Desirability Value Metrics**
Highest Scores	Public Awareness	92	High level of public awareness
	Stakeholder Pressure	92	High impact of stakeholder pressure
	Technology Readiness Level	99	TRL 9
	GHG Emissions	89	100 % GHG emission reduction (CO_{2eq})
	Water Pollution	100	No wastewater produced during the operation
	Governmental Policies	100	High level benefit of governmental policies observed
	Taxation	100	High level contribution to the company's carbon tax payments
	Energy Security	100	High level benefit observed to the country's energy security
Lowest Scores	Training of employee	34	Low impact on training and educating
	Private R&D Investments	30	Private R&D investment ratio is 0%
	Energy Efficiency	44	50 % energy efficiency
	Critical minerals	20	Two or more critical minerals needed and can be partially recovered after usage

Table 5.7. Highest and lowest scores of SOE technology.

Solid Oxide Water Electrolyser (SOE)			
Scores	**Sub-criteria**	**Desirability Value**	**Desirability Value Metrics**
Highest Scores	Public Health and Safety	70	Average to high level of impact on public health and safety
	Energy Efficiency	90	80 % energy efficiency
	GHG Emissions	89	100 % GHG emission reduction (CO_{2eq})
	Water Pollution	100	No wastewater produced during the operation
	Feedstock	100	Renewable resources (solar/wind) used as a feedstock
	Governmental Policies	100	High level benefit of governmental policies observed
	Energy Security	100	High level benefit observed to the country's energy security
Lowest Scores	Health & safety of workers	30	Moderate to high level risk for workers in oil and gas industry
	Capital Cost	30	Above 2000 EUR/kW
	Easy maintenance	65	Semi-annually maintenance required
	Critical minerals	29	Two or more critical minerals needed and can be partially recovered after usage

5.2. Actions for the Improvement of Technology Alternatives

5.2.1. Improvement for SE-SMR

SE-SMR technology is the combination of CCS and steam methane reforming. According to Williams (2019), there is an instability in the oil and gas industry in terms of gender balance. Women in STEM fields within the oil and gas sector face significantly higher attrition rates compared to their male counterparts. Also, another study shows that CCS technologies, by their nature, do not directly influence gender equality or the empowerment of women and girls. The impact, if any, is seen as very indirect and not specific to CCS technologies, suggesting that these technologies, in their current state, do not contribute to or impede the progress of gender equality initiatives (Olfe-Krautlein, 2020, Olabi et al., 2023). Therefore, while sorption enhanced steam methane reforming represents a technological advancement within the oil and gas industry, it has not addressed underlying issues of gender equity comprehensively. The integration of this technology is currently confronting gender biases and a culture of job insecurity, particularly among its STEM professionals underscores the importance of promoting STEM education among women. By encouraging and accepting more women as researchers and professionals in STEM fields, the industry can take a significant step towards enhancing gender equity and diversifying its workforce.

The implementation of carbon capture technology, as utilized in sorption enhanced steam methane reforming, inherently carries a lower stakeholder pressure compared to technology alternatives based on renewable energy sources. This difference is primarily due to the nature of the feedstock selection, which significantly influences the technology’s desirability. Utilizing fossil fuels as a feedstock garners lower ratings in aspects such as feedstock type, stakeholder pressure, and energy security, primarily due to environmental concerns and sustainability issues. In contrast, the adoption of biomass as a methane resource could enhance the technology's appeal, as it aligns more closely with current environmental priorities and could potentially elevate stakeholder engagement due to its renewable nature (Cho et al., 2022; Dang et al., 2022).

To facilitate an increased market uptake of SE-SMR technology, the critical role of governmental R&D programs cannot be overstated. As Udemu and Font-Palma (2023) state that, the technology currently resides at an early stage, with a low TRL that necessitates ramped-up activities in reactor modelling and validation at pilot scales. This is where governmental R&D can play a pivotal role, by not only funding experimental projects but also supporting comprehensive modelling studies, which are integral for understanding and refining the SE-SMR process (Udemu

and Font-Palma, 2023). Furthermore, pilot projects such as the 1.5 MW plant at Cranfield University, which aim to demonstrate SE-SMR under high-pressure conditions, illustrate how initial government-supported projects can serve as crucial steps toward establishing economic feasibility and operational reliability. The successful demonstration and dissemination of results from these projects are critical for building trust and interest among stakeholders and investors, aligning with global efforts to achieve net-zero emissions through the deployment of low-carbon technologies (Udemu and Font-Palma, 2023).

Furthermore, addressing the generation of hazardous waste, specifically through the aspect of sorbent replacement, is imperative in the SE-SMR process. The integration of more environmentally friendly carbon capture technologies could mitigate this issue. According to Soltani et al. (2021), exploring advancements in sorbent materials and processes that minimize environmental impact should be a priority. Efficient sorbents, such as CaO-based materials and other high-temperature sorbents like lithium and sodium zirconates, offer advantages in terms of CO_2 capture capacity and reaction kinetics. However, overcoming challenges like rapid sorbent decay due to sintering is crucial. Innovative approaches like combined sorbent-catalyst materials (CSCM) are proposed to enhance the system's efficiency and sustainability. These materials not only improve mass transfer and reaction kinetics but also offer cost-effective solutions for large-scale applications. This approach aligns with environmental regulations and significantly enhances the technology's overall sustainability profile, contributing to a more environmentally responsible implementation of SE-SMR processes (Soltani et al., 2021).

In summary, the advancement of sorption enhanced steam methane reforming technology necessitates a multifaceted approach, incorporating considerations of feedstock sustainability, stakeholder engagement, and environmental impact mitigation. Through strategic governmental support and continual technological refinement, this technology can achieve greater market penetration and contribute to the broader goals of sustainable energy development. The study by Faheem et al. (2021) provides valuable insights into the performance benefits of sorption enhanced processes over conventional reforming methods. They observed significant advantages in terms of methane conversion, hydrogen purity, and the efficiency of hydrogen energy production per unit of methane consumed. Particularly, SE-SMR demonstrated superior performance in CH_4 conversion, H_2 purity, and CO_2 capture compared to traditional SMR. This emphasizes the potential of SE-SMR to optimize hydrogen production while reducing environmental impacts, showcasing its alignment with sustainable energy goals (Faheem et al., 2021). Additionally, Capa et al. (2020) demonstrates that high-purity and high-yield hydrogen can be efficiently produced from biogas, a renewable

source, using sorption enhanced steam reforming. They found that varying the biogas composition does not negatively impact the process and that higher methane partial pressures favour the production of hydrogen, pointing towards the technology's compatibility with renewable energy sources and its potential in green hydrogen production. These results underscore the promise of sorption enhanced steam methane reforming as a viable technology for sustainable energy development, aligning with global efforts towards a cleaner energy future (Capa et al., 2020).

5.2.2. Improvement for E-SMR

According to Li et al. (2023a), public concern about the decarbonization of the industry are mainly related to environmental benefits, social issues and governance of the projects. Transparency, awareness campaigns and public reporting is crucial for managing the public concern (Upham et al., 2022; From et al., 2024). Public awareness campaigns to inform the public about the environmental benefits of e-SMR, highlighting that electrification projects balance the power demand with the integration of renewable electricity can provide positive engagements with public (Jannasch et al., 2020).

E-SMR technology, a critical innovation for integrating renewable energy into the oil and gas industry, presents significant opportunities for environmental advancements. However, achieving gender balance remains a challenge within the renewable energy sector. To address this, firms can broaden their recruitment strategies to include associated STEM subjects with higher female graduation rates, provide targeted work experience opportunities, set explicit gender diversity goals, and ensure transparent salary scales, thereby fostering a more inclusive and gender-balanced workforce in this evolving field (Clancy and Feenstra, 2019).

E-SMR technology not only allows for agile operation and precise process control due to its technological advancements, but it also significantly contributes to energy security beyond just integrating renewable electricity. The inclusion of renewable carbon sources like biogas in E-SMR systems further enhances energy security. This technology demonstrates remarkable efficiency in converting biogas to syngas, enabling sustainable and renewable production of chemicals and fuels. Moreover, the ability to operate at higher temperatures with E-SMR leads to improved methane conversion and feedstock utilization, thereby optimizing the entire process and making it a robust solution for future energy needs (From et al., 2024).

5.2.3. Improvement for P-MR

The development of P-MR technology presents a unique opportunity to revolutionize the energy sector, yet it faces several critical challenges. To enhance its market uptake, two approaches are beneficial. Firstly, conducting a detailed market analysis will identify potential commercial applications and industries that stand to benefit from this innovation. Secondly, establishing partnerships with key industry players to pilot the technology in real-world settings provides to increase TRL level. These partnerships not only provide a platform for practical testing but also offer valuable insights into commercial viability, paving the way for broader market acceptance.

Energy efficiency is another vital area needing attention for the advancement of P-MR technology. According to Barni et al., (2019) P-MR process has approximately 45-60 % methane conversion rate and the current of this technology calls for significant improvements (Feng et al., 2021). Investing in research and development to enhance energy efficiency is imperative. This could involve exploring advanced materials or design modifications, which can substantially increase efficiency. Such advancements not only make the technology more attractive from an economic standpoint but also contribute to environmental sustainability.

Addressing the TRL of P-MR, which is below TRL 3, is essential for its advancement. This involves conducting a series of phased research and development projects aimed at progressively advancing the technology to higher TRL levels. Seeking funding and partnerships for dedicated R&D projects that focus on overcoming specific technical challenges identified at the current TRL is also vital. These actions will help bridge the gap between the conceptual and practical applications of the technology, moving it closer to commercial readiness.

Operational stability of P-MR technology indicates a need for significant research. To address this, initiating long-term operational tests to evaluate the technology under continuous use is critical. Currently, only eight hour-operations were tested in laboratory conditions (Kim et al., 2020). Additionally, developing and integrating advanced monitoring and control systems will enhance operational stability. These actions will not only prove the technology's robustness over time but also build confidence among potential users and investors.

Lastly, the technology's low scores in feedstock type and energy security highlight the need for sustainable and secure energy solutions. Researching alternative, renewable feedstocks to replace or supplement non-renewable resources is essential. For instance, H_2S commonly regarded as a waste

product and hazardous emission in oil refineries, holds untapped potential as a valuable feedstock for P-MR. The utilization of H_2S does not only mitigates environmental hazards but also contributes to circular economy. Such collaborations are pivotal in transforming these emissions into sustainable feedstock sources, fostering a more environmentally responsible and economically viable industry landscape (Chan et al., 2023). Furthermore, conducting a comprehensive analysis of how this technology can contribute to the country's energy mix and advocating for policy support and incentives will demonstrate its potential benefits to national energy security. In conclusion, developing P-MR technology requires a multi-faceted approach addressing each identified weakness. These efforts will not only enhance the technology's feasibility but also position it as a viable, efficient, and sustainable solution in the energy sector.

5.2.4. Improvement for AWE

In the renewable energy sector, including technologies like alkaline electrolysers, gender equality and equity are crucial aspects to consider. Gender equality is achieved when men and women have equal rights, freedoms, conditions, and access to opportunities for realizing their capabilities and contributing to development. Gender equity, closely related to equality, is about being fair to both genders, taking measures to compensate for historical and social disadvantages preventing equitable operations. The renewable energy sector, being young and dynamic, offers remarkable opportunities and is more open to change compared to the mature fossil fuel sector. This openness provides a valuable chance for women to garner a growing share of employment, particularly in emerging technological fields like electrolyser technologies (IRENA, 2019). However, women are currently underrepresented in the renewable energy sector, comprising only 32% of the full-time workforce, though this is notably higher than their representation in the oil and gas sector. Studies have shown that women tend to act collaboratively in the workplace, contributing to greater fairness and improving working conditions for both genders. Thus, integrating more women into the renewable energy workforce, particularly in roles related to alkaline electrolysers, is a strategic move to minimize skills shortages and maximize sectoral growth. To enhance gender equity in the context of the alkaline electrolyser technology within the renewable energy sector, a comprehensive action plan is needed. This plan should include initiatives to enhance gender diversity and inclusion in the workforce, especially in technical and leadership roles. Targeted recruitment strategies, career development opportunities, and training programs to address unconscious bias and promote equality are key components of achieving gender balance for this technology (IRENA, 2019).

The technological development of alkaline electrolysers is significantly dependent on increasing private R&D investments. A strategic approach to supporting these investments includes a targeted communications strategy for potential investors. This strategy should highlight the promising market returns and notable environmental impacts of alkaline electrolysers and portray them as a viable and sustainable investment recommendation. In addition, demonstrating the return on investment (ROI) through successful case studies and pilot projects plays an important role in increasing the investment potential in this technology. These examples should highlight the efficiency of the technology and provide concrete evidence of its economic viability. Another important issue is establishing partnerships for innovation. Collaborating with research institutions and companies to jointly develop new technologies and applications for alkaline electrolysers can lead to groundbreaking advances, attract more investment, and increase the market attractiveness of the technology (IEA, 2023b).

Alkaline water electrolysers (AWEs) are the most commercialized electrolyser types, however their operational performance is low with respect to other electrolyser technologies because of corrosive environment, operating temperature, and less efficient electrolytes (Gul et al., 2023). Advancing the energy and utility efficiency of AWEs involves innovative approaches to both operational and systemic challenges. Currently, AWEs operate within a temperature range of 80-100°C, primarily due to limitations in separator materials like Zirfon PERL, which are susceptible to damage at higher temperatures (Ehlers et al., 2023). However, technological advancements are making it feasible to operate AWEs at elevated temperatures, which can significantly enhance their energy efficiency. By increasing the system's temperature, the electrolysis process becomes more efficient, and the waste heat generated can be usable in district heating networks. This not only contributes to circular economy benefits by utilizing waste heat but also potentially reduces costs associated with cooling, thereby improving the overall economics of the system. Furthermore, addressing the efficiency gap between membranes and diaphragms in AWEs is crucial. Thinning the diaphragms used in AWEs to a substantial degree (down to 150 μm) can align their performance more closely with that of membranes, without significant concerns of gas crossover due to the low solubility of hydrogen and oxygen in concentrated lye. This adjustment would enable AWEs to operate with increased efficiency and at higher current densities, thereby boosting their utility efficiency and overall performance. These combined strategies, focusing on operational temperature adjustments and diaphragm modifications, provides more energy-efficient and economically viable alkaline electrolysers (Ehlers et al., 2023).

5.2.5. Improvement for AEM-WE

Anion Exchange Membrane (AEM) electrolysers, as highlighted by Santoro et al. (2022) and Miller (2022), represent a transformative advancement in sustainable energy technologies, specifically in the context of green hydrogen production. These electrolysers, key to achieving the 2050 decarbonization goals, are at the forefront of innovation but face critical challenges that need addressing to unlock their full potential.

According to Santoro et al. (2022), AEM-WEs are more efficient than traditional AWEs and operate effectively in high-pH environments without the need for Critical Raw Materials (CRM) and Platinum Group Metals (PGM). This technological edge leads to a smaller carbon footprint and improved system safety. To enhance market adoption, increasing pilot projects and demonstrations in real environment is crucial. These initiatives provide tangible proof of AEM-WE's effectiveness and reliability, allowing potential customers to experience the benefits firsthand. Moreover, forming strategic partnerships with industry leaders can enhance the credibility of AEM technology and facilitate its adoption and integration into existing systems.

Miller (2022) also elaborates on the recent advancements and the potential for large-scale hydrogen production. The need for significant reduction or elimination of CRMs like rare PGMs for hydrogen production on a massive scale is emphasized. AEM-WE technology has shown remarkable progress in single-cell electrolysis activity, primarily due to the development of PGM-free catalysts and improved anion exchange materials. Miller (2022) also points out the increase in research efforts in AEM electrolysis, driven by the rising interest in green hydrogen production.

Both Santoro et al. (2022) and Miller (2022) identify the development of PGM-free and CRM-free electrocatalysts as critical for making these systems more sustainable and less reliant on scarce resources. These research and development efforts indicate an active pursuit of sustainable and efficient solutions for AEM-WEs. However, as Miller (2022) and Li et. al (2023b) notes, despite these advancements, AEM-WE technology still faces issues in efficiency and durability that must be resolved to fulfil its potential.

In summary, the development of AEM electrolyser technology necessitates a comprehensive and adaptive approach. Regular review and adaptation of strategies, as suggested by Santoro et al. (2022), are vital to align with the evolving landscape of the industry. Miller (2022) calls for a unified effort in research and standardization to fully realize the potential of AEM-WE in achieving

green hydrogen production goals. Addressing developmental challenges, enhancing market adoption, and fostering stakeholder engagement are crucial steps towards realizing the full potential of AEM electrolysers as a cornerstone of sustainable energy solutions.

5.2.6. Improvement of PEM-WE

The development of PEM-WE for hydrogen production is critically dependent on the availability and efficient use of iridium (Ir). According to Riedmayer et al., to meet the hydrogen production targets for 2030 and 2050, significant improvements in average operational current density or iridium loading are essential. Current technology might only be sufficient to meet the lower end of 2050 hydrogen production targets, requiring modest technological advances for higher demand levels (Riedmayer et al., 2023). The scarcity and high cost of iridium are caused mainly due to its status as a secondary mining metal (approximately 90%) and the current global supply is 7-8 tons per year in Southern Africa (Clapp et al., 2023). Moreover, Moschovi et al. emphasize the importance of developing sustainable End-of-Life (EoL) strategies for PEM-WE systems, focusing on the recycling of Membrane Electrode Assemblies (MEAs) and electrocatalysts to optimize the recovery of CRMs like iridium in an environmentally friendly process (Moschovi et al., 2021). To address these challenges, research and development in efficient recycling mechanisms, and diversification of supply chain are required. Developing efficient recycling processes for the recovery of these minerals from used electrolysers is vital, not only addressing the scarcity of such minerals but also contributing to environmental sustainability. MONOLITHOS Ltd. has developed a promising single-step hydrometallurgical process for PGMs recovery, which can be applied to PEM-WE systems for efficient and environmentally friendly recovery of CRMs such as iridium (Moschovi et al., 2021). Diversifying the supply chain will reduce reliance on limited sources of these critical minerals. Additionally, conducting a life cycle analysis will provide a clearer understanding of the environmental impact of using these minerals and help in finding ways to mitigate it.

In light of the mature status of PEM-WE technology, employee training, necessitates a customized approach to enhance operational efficiency and safety. Acknowledging the existing proficiency with this technology, training initiatives should primarily focus on reinforcing and updating the workforce's knowledge. This involves the creation of targeted training modules, designed to be concise and specific, to refresh employees on the maintenance, operation, and safety aspects of PEM-WE. Additionally, periodic workshops, although less frequent due to the technology's maturity, are crucial for keeping staff updated on the latest technological

advancements and best operational practices in the field. Collaborating with industry experts and academic institutions will provide employees with advanced insights and exposure to new developments, thereby enriching their knowledge base. Performance assessments should be tailored to evaluate understanding of new developments and adherence to best practices rather than basic operational knowledge. This approach will help identify specific areas for improvement in a workforce already well-versed in the fundamentals of PEM-WE technology.

Enhancing the energy efficiency of PEM-WE is a critical aspect with a multifaceted strategy integrating technological advancements, process optimization, and operational condition management. As Makhsoos et al. (2023) stated that, the efficiency of PEM-WE is significantly influenced by operational factors like temperature, pressure, flow rate, and current density. Also, Koponen et al. (2017) underscores the importance of controlling hydrogen outlet pressure, as variations from 2.0 MPa to 4.0 MPa significantly impact specific energy consumption, primarily due to changes in Faraday efficiency. This study also shows that the controllability of stack current improves with lower hydrogen outlet pressures. Additionally, integrating PEM-WE with renewable energy sources like solar PV systems requires balancing grid power with variable renewable energy output. Overall, the path to increased efficiency in PEM-WE lies in a combination of targeted technological upgrades, process optimizations, and management of operational conditions to minimize energy wastage and maximize system performance (Koponen et al., 2017).

5.2.7. Improvement of SOE

Technology evaluation of SOE includes several critical points that require attention for the advancement of the technology. The lowest evaluation scores are health as safety issues, capital cost of the system, easy maintenance, and the use of critical minerals.

SOEs operate at high temperatures which increases the efficiency of the system, on the other hand, it causes thermal stresses and higher probability of stack failure (Flis and Wakim, 2023). For that reason, it is essential to prioritize the development of stringent safety protocols and the integration of advanced safety features for this technology. Additionally, research and development for SOE technology should focus on enhancing the durability and operational stability of the system. This can be achieved through the use of more robust materials and the incorporation of innovative features like self-diagnostic and predictive maintenance capabilities, which have the potential to reduce overall maintenance requirements and improve safety (Davies et al., 2021).

The high initial capital cost of SOE technology is a significant barrier to its market adoption. To overcome this challenge, targeted efforts towards optimizing manufacturing processes are essential for cost reduction. Prosser et al. (2024) identify the major cost drivers in SOE manufacturing, such as the electrolyte for electrolyte-supported cells (ESCs) and the hydrogen electrode for hydrogen electrode-supported cells (HSCs). By focusing on these areas, particularly on the less expensive HSCs, which use cheaper materials like Yttria-Stabilized Zirconia (YSZ) compared to 10-Scandia-Stabilized Zirconia (SSZ) in ESCs, significant cost savings can be achieved. Additionally, this study states that as manufacturing scale increases, the total manufacturing and auxiliary equipment costs decrease substantially. Furthermore, exploring partnerships with stakeholders interested in sustainable energy solutions can provide financial support and reduce the overall capital burden. Such collaborations can also be beneficial in optimizing the balance of plant (BOP) equipment capital cost, which Prosser et al. (2024) identify as the most significant contributor to the total capital investment (TCI) and subsequently to the Levelized Cost of Hydrogen (LCOH).

Unlike PEM-WE technology, SOE does not need platinum and iridium which are rare earth metals. However, SOE technology requires other rare earth metals like zirconium, lanthanum, yttrium, and scandium. The main reserve of these elements is located in China, but new reserves has been found in US, Myanmar and Australia and the production of these elements has started since 2016 (Flis and Wakim, 2023). Regarding the sustainability of critical mineral usage, more efficient recycling process should be considered.

Collaborations with research institutions and recycling industry might provide insights into sustainable alternatives. In conclusion, a strategic approach covering the process safety, cost reduction, maintenance optimization, and sustainable material use is essential for the future development of this technology. The study of Yenesew et al. (2023) demonstrates significant advancements in recycling process. High amount of recovery for nickel oxide (NiO) and YSZ from the electrode materials were seen. This research emphasizes that recovering and reusing the materials in SOE manufacturing is feasible and positively contributes to the circular economy. Collaborations with research institutions and the recycling industry might provide sustainable ways for electrode manufacturing. In conclusion, a strategic approach covering process safety, cost reduction, maintenance optimization, and sustainable material use is essential for the future development of SOE technology.

5.3. Scenario Analysis

Scenario analysis is a crucial tool employed in this research to ascertain the resilience and adaptability of the proposed model. This method is pivotal for evaluating how variations at any level within the model can influence its overall output. In this research, scenario analysis is utilized to measure the model's responsiveness to changes in the significance of different criteria. To achieve a comprehensive understanding, multiple scenarios are developed, each modifying the weight of a specific perspective. This alteration process is replicated across five key perspectives: social, economic, technical, environmental, and political. In this first scenario, the social perspectives enhanced significantly and an importance value of 0.96 is assigned and then the importance value of other perspectives (economic, technical, environmental, and political) are reduced to 0.01. This pattern is applied in the following scenarios, as shown in Table 5.8.

Table 5.8. The details of scenarios

Perspectives	Social	Economic	Technical	Environmental	Political
Scenario 1	0.96	0.01	0.01	0.01	0.01
Scenario 2	0.01	0.96	0.01	0.01	0.01
Scenario 3	0.01	0.01	0.96	0.01	0.01
Scenario 4	0.01	0.01	0.01	0.96	0.01
Scenario 5	0.01	0.01	0.01	0.01	0.96

In the initial scenario, the emphasis is predominantly placed on social perspectives by increasing the importance weights to 0.96. There is a notable shift in the dynamics of the technology alternatives' performance compared to the original results. When the total scores are scrutinized under this social-dominated scenario, significant variations are observed. For instance, SE-SMR technology which originally was scored 60.81, faces a decrease to 50.71 in the social-focused scenario. In the same way, E-SMR technology shows a slight decrease in its score from 62.80 to 59.93 but its ranking is improved from fifth to third. This pattern of fluctuation is evident across all technology alternatives. A remarkable change is observed in AWE technology which originally had a high score of 77.06, placing it second in the ranking. Under the social-dominated scenario, its score is dipped to 65.61, but it maintains its second-place ranking. On the other hand, AEM-WE technology experienced a decrease from 71.65 to 52.41, impacting its rank from fourth to fifth. The most significant shift is seen in PEM-WE technology which initial ranking was with a

score of 78.85. Under the social emphasis, its score reduced to 70.72, but it impressively is retained its top position. SOE technology also shows a decrease from an original score of 76.21 to 58.60, altering its rank from third to fourth. These changes highlight the profound impact of prioritizing the social perspective. It reshapes the landscape of technology alternatives, influencing their scores and rankings differently. Some alternatives like PEM-WE technology maintain their superiority despite the shift, while others like AWE and SOE technology experience a notable change in their scores, albeit with minimal impact on their overall standing. The results of Scenario 1 is tabulated in Table 5.9 and comparison graph is presented in Figure 5.3.

Table 5.9. The results of Scenario 1

Technology Alternatives	SE-SMR	E-SMR	P-MR	AWE	AEM WE	PEM WE	SOE
Social Perspectives	48.20	56.99	40.65	62.42	49.38	67.48	55.41
Economic Perspectives	0.58	0.61	0.47	0.68	0.61	0.71	0.60
Technical Perspectives	0.80	0.73	0.37	0.85	0.70	0.84	0.79
Environmental Perspectives	0.54	0.57	0.38	0.73	0.77	0.74	0.87
Political Perspectives	0.59	0.63	0.48	0.94	0.94	0.95	0.94
Total Score	50.71	59.53	42.35	65.61	52.41	70.72	58.60
Ranking	6	3	7	2	5	1	4

In Scenario 2, the importance of perspectives shifted significantly towards the economic perspectives, a dominant role had assigned them. This strategic alteration was resulted in interesting changes in the performance dynamics of the technology alternatives when compared to the original results and the social-dominated Scenario 1. When examining the total scores within this economically focused scenario, a distinct pattern is observed from both the original framework and the social-focused scenario. For instance, SE-SMR technology which originally scored 60.81, experienced a modest decline to 58.07, maintaining its sixth position. In contrast, while E-SMR technology score decreases slightly from 62.80 to 61.28, it is elevated its ranking from fifth to fourth. This varying trend is consistent across all technology alternatives. A significant observation is made with AWE technology which originally held a high score of 77.06, ranking second. In the economic scenario, it scored 68.33 but impressively retained its second-place ranking. Similarly, AEM-WE technology has a score change from 71.65 to 61.67, which shifted its rank from fourth to third. The most striking change is with PEM-WE technology. It is originally leading with a score of 78.85, it adapted well to the economic emphasis, marking a score of 71.00 and retaining its top

rank. SOE technology, on the other hand, exhibited a decrease from an original score of 76.21 to 60.57, dropping its rank from third to fifth. These findings are detailed in Table 5.10 and illustrated in the comparison graph presented in Figure 5.3.

Table 5.10. The results of Scenario 2

Technology Alternatives	SE-SMR	E-SMR	P-MR	AWE	AEM WE	PEM WE	SOE
Social Perspectives	0.50	0.59	0.42	0.65	0.51	0.70	0.58
Economic Perspectives	55.64	58.75	44.87	65.16	58.74	67.77	57.40
Technical Perspectives	0.80	0.73	0.37	0.85	0.70	0.84	0.79
Environmental Perspectives	0.54	0.57	0.38	0.73	0.77	0.74	0.87
Political Perspectives	0.59	0.63	0.48	0.94	0.94	0.95	0.94
Total Score	58.07	61.28	46.53	68.33	61.67	71.00	60.57
Ranking	6	4	7	2	3	1	5

In Scenario 3 of the technology evaluation, the technical perspectives were emphasized, and this change brought about notable changes in the technology alternatives. SE-SMR technology which had an original score of 60.81, experienced a rise to 78.59, improving its ranking from sixth to fourth. AWE technology secured its rank which initially scored 77.06. Under the technical dominance, its score remarkably escalated to 84.40. In contrast, AEM-WE technology underwent a decrease from an original score of 71.65 to 70.37, leading to a drop in its ranking from fourth to sixth. PEM-WE and SOE technologies remains same ranking as second and third, respectively. Some technologies, such as PEM-WE and AWE technology demonstrate robust adaptability and improvement under the technical emphasis, while others like AEM-WE technology experience a decline in their standings. The results of Scenario 3, in relation to the original scores and the outcomes of the previous scenarios, provide an insightful understanding of how changes in perspective weightings can significantly influence the evaluation of technology alternatives. These insights are comprehensively detailed in Table 5.11 and visually represented in the comparison graph included in Figure 5.3.

Table 5.11. The results of Scenario 3

Technology Alternatives	SE-SMR	E-SMR	P-MR	AWE	AEM WE	PEM WE	SOE
Social Perspectives	0.50	0.59	0.42	0.65	0.51	0.70	0.58
Economic Perspectives	0.58	0.61	0.47	0.68	0.61	0.71	0.60
Technical Perspectives	76.37	70.25	35.94	81.41	67.53	80.67	75.71
Environmental Perspectives	0.54	0.57	0.38	0.73	0.77	0.74	0.87
Political Perspectives	0.59	0.63	0.48	0.94	0.94	0.95	0.94
Total Score	78.59	72.65	37.69	84.40	70.37	83.77	78.69
Ranking	4	5	7	1	6	2	3

In Scenario 4, the focus turned towards the environmental perspective. This environmental emphasis introduces a new dynamic in the assessment of the technologies. Analysing the total scores within this environmentally focused scenario, we can observe distinctive change. SE-SMR technology which had an original score of 60.81, reduced to 54.61, but it maintained its sixth position. Meanwhile, E-SMR technology experienced a slight decrease in its score from 62.80 to 57.08 but kept its fifth rank. This trend of variations is consistent across all the technology alternatives. A noteworthy change occurred with AWE technology which originally had a high score of 77.06, ranking second. Under the environmental dominance, its score altered to 72.87, shifting its rank to fourth. On the other hand, AEM-WE technology improved significantly, moving from a score of 71.65 to 76.99, elevating its ranking from fourth to second. The most dramatic transformation is seen with SOE technology. It is originally holding the third rank with a score of 76.21, it responded exceptionally well to the environmental focus, achieving a score of 86.03 and securing the top position. Conversely, PEM-WE technology initially leading with a score of 78.85, observed a decrease to 74.61, resulting in a drop to the third rank. The contrasting results of Scenario 4, when compared with the original scores and the outcomes of the previous scenarios, offer valuable insights into how different perspective weightings can influence the evaluation of technology alternatives. These insights are comprehensively detailed in Table 5.12 and visually represented in the comparison graph included in Figure 5.3.

Table 5.12. The results of Scenario 4.

Technology Alternatives	SE-SMR	E-SMR	P-MR	AWE	AEM WE	PEM WE	SOE
Social Perspectives	0.50	0.59	0.42	0.65	0.51	0.70	0.58
Economic Perspectives	0.58	0.61	0.47	0.68	0.61	0.71	0.60
Technical Perspectives	0.80	0.73	0.37	0.85	0.70	0.84	0.79
Environmental Perspectives	52.15	54.51	36.15	69.76	74.23	71.41	83.12
Political Perspectives	0.59	0.63	0.48	0.94	0.94	0.95	0.94
Total Score	54.61	57.08	37.90	72.87	76.99	74.61	86.03
Ranking	6	5	7	4	2	3	1

In Scenario 5, the focus was intensely directed towards the political perspectives. This change in weighting, while profound, resulted in an interesting phenomenon: although the scores of the technology alternatives increased significantly, their rankings relative to each other remained consistent with the original results. Observing the total scores in this politically focused scenario, SE-SMR technology decreased slightly from its original score of 60.81 to 59.24 yet maintained its sixth position. E-SMR technology also saw a marginal change, moving from 62.80 to 62.91, but remained in fifth rank. Notably, AWE technology maintained in its second ranking despite its score increasing from 77.06 to 92.85. Similarly, AEM-WE technology experienced a substantial increase from 71.65 to 92.55 but stayed in its fourth position. PEM-WE technology had a significant increase from 78.85 to 93.90 and retained its top rank. SOE technology also exhibited a major increase in score from 76.21 to 92.78 but continued to hold its third rank. These observations underscore a critical aspect of the scenario: while the political perspective substantially elevated the scores, it did not disrupt the relative standing of the alternatives. This indicates that the high scores are reflective of their alignment with the desired political criteria, yet the internal ranking dynamics remain consistent. The results of Scenario 5, capturing both the score increases and the maintained rankings, are detailed in Table 5.13 and illustrated in the comparison graph included in Figure 5.3.

Table 5.13. The results of Scenario 5.

Technology Alternatives	SE-SMR	E-SMR	P-MR	AWE	AEM WE	PEM WE	SOE
Social Perspectives	0.50	0.59	0.42	0.65	0.51	0.70	0.58
Economic Perspectives	0.58	0.61	0.47	0.68	0.61	0.71	0.60
Technical Perspectives	0.80	0.73	0.37	0.85	0.70	0.84	0.79
Environmental Perspectives	0.54	0.57	0.38	0.73	0.77	0.74	0.87
Political Perspectives	56.82	60.41	46.30	89.95	89.95	90.91	89.95
Total Score	59.24	62.91	47.94	92.85	92.55	93.90	92.78
Ranking	6	5	7	2	4	1	3

In conclusion, the comprehensive evaluation of technology alternatives across different scenarios (social, economic, technical, environmental, and political) reveals insightful dynamics in technology assessment. Remarkably, despite significant variations in TE scores, the relative rankings of the alternatives remained largely consistent. This emphasizes their robustness and balanced performance across diverse evaluative lenses. For instance, PEM-WE and AWE technologies consistently exhibited top-tier performance, adapting well across all scenarios. Also, P-MR technology consistently ranked lowest, indicating specific areas for improvement as shown in Table 5.14. This multifaceted analysis does not only underscore the versatility and adaptability of certain technologies but also highlights the importance of considering a holistic set of criteria, encompassing social, economic, technical, environmental, and political factors, in the assessment of technological solutions. These insights provide valuable guidance for decision-making processes in technology selection and development, ensuring a comprehensive and balanced approach that aligns with varied and evolving stakeholder priorities.

Table 5.14. Summary of Scenario Analysis.

Scenario Descriptions	Technology Alternatives	SE-SMR	E-SMR	P-MR	AWE	AEM-WE	PEM-WE	SOE
Original Assessment	**TE Score**	**60.81**	**62.80**	**42.33**	**77.06**	**71.65**	**78.85**	**76.21**
	Ranking	**6**	**5**	**7**	**2**	**4**	**1**	**3**
Scenario 1 (Social)	**TE Score**	50.71	59.53	42.35	65.61	52.41	70.72	58.60
	Ranking	6	3	7	2	5	1	4
Scenario 2 (Economic)	**TE Score**	58.07	61.28	46.53	68.33	61.67	71.00	60.57
	Ranking	6	4	7	2	3	1	5
Scenario 3 (Technical)	**TE Score**	78.59	72.65	37.69	84.40	70.37	83.77	78.69
	Ranking	4	5	7	1	6	2	3
Scenario 4 (Environmental)	**TE Score**	54.61	57.08	37.90	72.87	76.99	74.61	86.03
	Ranking	6	5	7	4	2	3	1
Scenario 5 (Political)	**TE Score**	59.24	62.91	47.94	92.85	92.55	93.90	92.78
	Ranking	6	5	7	2	4	1	3

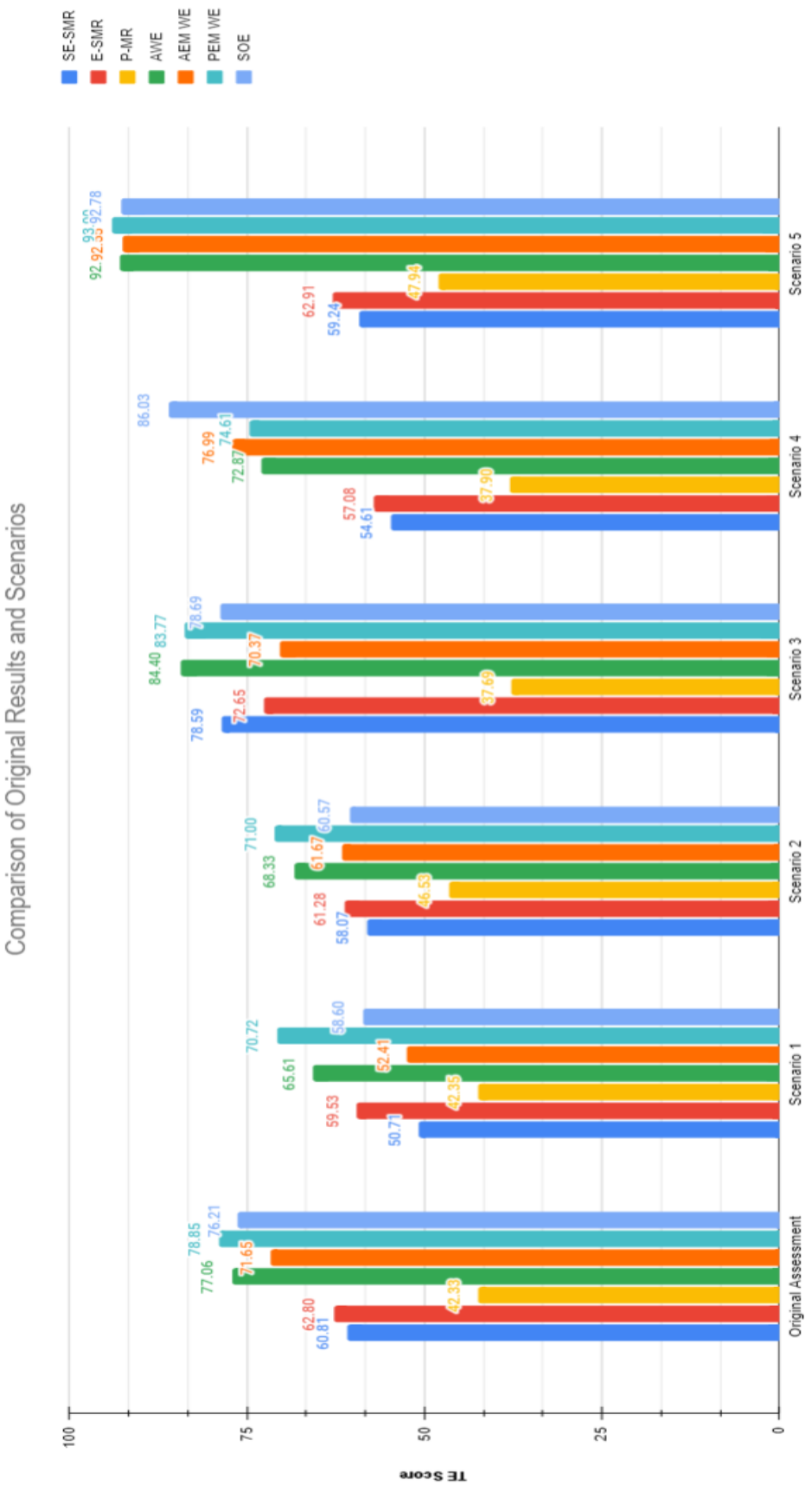

Figure 5.2. Comparison of Original Results and Scenarios

6. DISCUSSION

This section includes the discussion of HDM quantification results and case study application results. In addition to that, the generalizability of the HDM is also discussed.

6.1. Discussion of Perspectives

The analysis of perspectives provides a nuanced understanding of expert priorities and considerations in this field. The environmental perspective emerged as the most significant, with a weight of 0.234. This finding emphasizes the critical importance experts place on the environmental implications of implementing low-carbon technologies in the oil and gas sector. It reflects a growing awareness and concern within the industry regarding the environmental impact of its operations, highlighting the need for sustainable and eco-friendly solutions. Following closely, the economic perspective (weight of 0.223) and the technical perspective (weight of 0.211) were also highlighted as significant. The prominence of the economic perspective indicates that cost-effectiveness and financial viability are key considerations in the adoption of low-carbon technologies. The technical perspective's importance signifies the emphasis on the feasibility, efficiency, and reliability of these technologies. These findings suggest a balanced approach, where environmental concerns are weighed alongside economic and technical feasibilities. Interestingly, the political (0.189) and social (0.144) perspectives had lesser weight. This could imply that while these areas are relevant, they might not be the primary driving factors in decision-making processes within the context of this panel. However, it's important to note that their inclusion and weightage still signify a recognition of their relevance, albeit to a lesser extent compared to environmental, economic, and technical factors.

The results of perspective level quantification provide a comprehensive picture of the multi-dimensional considerations in the evaluation of low-carbon technologies. The higher weighting of the environmental perspective could be reflective of the industry's shifting focus towards sustainability and the mitigation of environmental impacts. The economic and technical aspects underscore the need for feasible and financially viable solutions, while the relatively lower weightage of political and social aspects might suggest that these are secondary considerations within the specific context of this expert panel. In conclusion, the findings reveal a strong inclination towards environmental sustainability, balanced with economic and technical practicalities, in the technology assessment for the oil and gas industry. This insight is crucial for

informing future strategies and policy formulations in the sector, ensuring a holistic approach to the adoption of low-carbon technologies.

6.2. Discussion of Social Criteria

The results of social criteria are pivotal in understanding the social dimensions considered by the experts in the context of low-carbon technology adoption. In this research study, public health and safety emerged as the most important criterion with a weight of 0.269. This highlights the experts' recognition of the direct impact of these technologies on the well-being and safety of the public. The prioritization of this criterion reflects a consensus on the need for technologies that are not only efficient but also safe for the community at large. The second most important criterion is the working conditions of employees, underscoring the importance of creating a safe work environment in the oil and gas sector. This aspect relates to ensuring that low-carbon technologies are implemented in a manner that safeguards the health and safety of the industry's workforce. Public acceptance was identified as the third most important criterion, with a weight of 0.186. This suggests that experts are aware of the need for societal buy-in and support for the successful implementation of these technologies. The sub-criteria under public acceptance – public awareness (weight of 0.537) and public concern (weight of 0.463) – further emphasize the importance of educating and addressing the concerns of the public in relation to these technologies. The criteria of employment and stakeholder pressure, with weights of 0.176 and 0.157 respectively, although less emphasized, still indicate the necessity of considering job creation, training, and gender equity (with respective weights of 0.394, 0.354, and 0.251) in the deployment of these technologies. These factors are essential for ensuring the technologies contribute positively to the economy and are aligned with the stakeholders' expectations. The health and safety of workers, within the working conditions criterion, received a higher importance (weight of 0.603) compared to working hours (weight of 0.397). This demonstrates a strong emphasis on ensuring employee safety over operational time concerns, aligning with the industry's increasing focus on health and safety standards.

In summary, the discussion based on results of social criteria highlights the significance of public health and safety, working conditions, public acceptance, employment opportunities, and stakeholder pressure in the social dimension of low-carbon technology assessment. These insights are instrumental in guiding the development and implementation of these technologies in a socially responsible and acceptable manner.

6.3. Discussion of Economic Criteria

The results of the quantification of economic criteria, provide a comprehensive insight into the relative importance of various economic factors affecting the low-carbon energy technologies. The criterion of market adoption and final product type emerged as the top two criteria, with weights of 0.249 and 0.242 respectively. This highlights the critical role of market forces and the nature of the final product in driving the adoption of low-carbon technologies. The high importance of market adoption indicates a recognition that market readiness and acceptance are key drivers for successful implementation. Similarly, the nature of the final product type demonstrates the need for these technologies to produce economically viable and marketable end products. Plant Cost, with a weight of 0.228, the cost of establishing and running a plant is identified as a significant factor. This underscores the importance of capital and operational expenditure in decisions related to the adoption of low-carbon technologies. R&D Investments: weighing in at 0.143, investments in R&D are accepted as significant but less critical than the top three criteria. This suggests that while innovation and development are important, they are perhaps seen as longer-term enablers rather than immediate drivers. Land usage and location has the lowest weight of 0.136. This criterion points to the relative importance of geographical and physical resource considerations in the implementation of these technologies.

Private R&D investments (weight of 0.534) were rated higher than governmental R&D investments, indicating a belief in the more significant role of private sector innovation and funding in this domain. Among the sub-criteria of plant cost, cost competitiveness (0.256) emerged as the most important, followed by feedstock cost (0.245), capital cost (0.227), operational cost (0.155), and transportation cost (0.121). This ranking highlights the importance of competitive pricing and cost management in feedstock and capital, emphasizing the need for cost-efficiency in all aspects of plant operation. the reliability of resources was deemed most significant (weight of 0.469), followed by the delivery of feedstock (0.272) and the required area for feedstock and plant construction (0.258). This implies a high value placed on resource availability and supply chain efficiency.

The panel exhibited a general consensus with a group disagreement value of 0.063 for economic criteria. However, notable disagreements arose in the R&D investments sub-criteria (disagreement value of 0.106), suggesting divergent views on the prioritization within this area. Such disagreement could indicate varying perceptions of the role and impact of R&D investments in the context of low-carbon technology implementation. The HAC analysis identified two distinct subgroups within the panel, each displaying unique preferences and priorities regarding R&D

investments. Subgroup A (12 experts) showed a slight preference for governmental R&D investments over private R&D investments. Their evaluations suggest a balanced view, with a mean preference of 0.450 for private and 0.550 for governmental investments. The low disagreement value of 0.052 indicates a general consensus in this subgroup, pointing towards a recognition of the importance of governmental investment in R&D, albeit without a significant bias over private investment. Subgroup B (7 experts), in contrast, displayed a clearer preference for private R&D investments, with a mean weight of 0.679 for private against 0.321 for governmental investments. This trend suggests that these experts view private investments as playing a more dominant role in R&D. The disagreement value of 0.053 within this subgroup, although slightly higher than Subgroup A, still indicates a considerable level of agreement among its members. The results of economic criteria show the complexity of funding preferences for R&D in the oil and gas sector, and these funding preferences are influenced by a variety of factors including the experts' professional backgrounds and geographical locations. These findings are critical for understanding the various attitudes towards investment sources in the oil and gas industry and can inform strategies for funding R&D projects in the deployment of low-carbon energy technologies.

6.4. Discussion of Technical Criteria

Process safety criterion was identified as the most critical technical criterion with a weight of 0.443. The emphasis on process safety highlights the paramount importance of ensuring the safe operation and handling of low-carbon technologies, likely due to the high risks and severe consequences associated with safety breaches in the oil and gas sector. Integration capability, with a weight of 0.210, is the second most significant criterion. This underscores the importance of minimizing disruptions and ensuring smooth operations during the implementation of new technologies. System efficiency criterion was ranked as third, with a weight of 0.189. System efficiency reflects the importance of optimizing energy use and utility consumption for cost savings, environmental impact reduction, and sustainable operations. TRL was the least emphasized but still significant criterion, with a weight of 0.156. This indicates the relevance of the maturity and reliability of technology, where a higher readiness level suggests a technology is more developed, tested, and closer to real-world deployment.

Energy efficiency (weight of 0.598) is more emphasized than utility consumption (weight of 0.402). This prioritization suggests a strong focus on reducing energy usage as a key component of system efficiency, leading to cost savings, and reduced environmental impact. Operational stability (weight of 0.630) is prioritized over easy maintenance (weight of 0.370). This ranking emphasizes

the critical importance of consistent and reliable system operations, which contribute to productivity, performance, and reduced risk of sudden shutdowns.

Expert Panel 10 which quantify the technical criteria and sub-criteria, showed a significant level of consensus, with group disagreement values of 0.123 for technical criteria, 0.170 for system efficiency sub-criteria, and 0.111 for process safety sub-criteria. These values indicate a moderate level of disagreement among experts, which could suggest diverse perspectives or interpretations of the criteria's importance. However, the F-test results imply a statistically significant agreement overall among the experts.

6.5. Discussion of Environmental Criteria

The study of quantification of environmental criteria is highly crucial for implementing low-carbon energy technologies in the oil and gas industry. The panel's assessment offers valuable insights into the prioritization of these environmental factors. Air emissions criterion received the highest weight (0.283), and it emphasizes the critical importance of mitigating atmospheric pollutants in the industry. The panel's focus here suggests a strong recognition of the need to reduce greenhouse gases and other emissions to combat climate change and environmental degradation. Usage of resources criterion has a weight of 0.264. This criterion underscores the significance of sustainable resource management. It reflects the growing emphasis on efficient and responsible use of resources, including water and critical minerals, essential for low-carbon energy technologies. Pollution criterion was ranked as third (weight of 0.255), this criterion highlights the broad environmental challenges of managing contaminants across various mediums like water, soil, and groundwater. The panel's focus here indicates a comprehensive approach to environmental stewardship. The criterion of co-benefitting has the lowest weight (0.200), and this criterion suggests that while the benefits and positive contributions to environmental initiatives are recognized, they are seen as less immediate or direct compared to the other criteria.

GHG emissions were deemed more important (weight of 0.678) compared to other air emissions (weight of 0.323). This prioritization signals a clear focus on combating climate change by targeting the main contributors to global warming. Soil and groundwater pollution emerged as the most crucial sub-criterion (weight of 0.352), followed by water pollution (weight of 0.298), hazardous waste generation (weight of 0.213), and solid waste generation (weight of 0.138). This ranking indicates a heightened awareness of the risks posed by soil and groundwater contamination and the necessity of protecting water resources. Lastly, freshwater usage was ranked as the most

important (weight of 0.457). It highlights the critical importance of water conservation in low-carbon energy technologies. Critical minerals and feedstock type followed with weights of 0.282 and 0.262, respectively, indicating a balanced concern for material resources essential in low-carbon energy technologies.

In summary, the results of this study show the complex and interconnected nature of environmental concerns in the implementation of low-carbon energy technologies in the oil and gas industry. The emphasis on air emissions, especially GHG emissions, aligns with global efforts to combat climate change. The attention given to resource usage and pollution control underscores a holistic approach to environmental protection. The results emphasize the need for comprehensive strategies that address multiple facets of environmental impact. These insights can guide policy makers, industry leaders, and technology developers in prioritizing and addressing key environmental challenges in their pursuit of sustainable and responsible energy solutions.

6.6. Discussion of Political Criteria

Energy security, with a weight of 0.377, is deemed as the most critical political criterion. This reflects the emphasis on maintaining a stable and uninterrupted energy supply, which is vital for both economic stability and national security. The prioritization of energy security indicates a recognition of the strategic importance of energy availability in political decision-making. Legal and regulatory instruments is following closely with a weight of 0.328, this criterion highlights the significance of regulatory frameworks and legal mechanisms in shaping energy policies and sustainable energy systems. The weight given to this criterion underlines the importance of a supportive legal environment for the successful implementation of low-carbon technologies. MBIs was ranked as third with a weight of 0.297. MBIs like emission trading and carbon tax are recognized for their role in economic tools and mechanisms. This suggests a growing recognition of the importance of market forces and economic incentives in driving the adoption of low-carbon technologies.

Governmental policies (weight of 0.575) were rated as more important than international regulations (weight of 0.425). This indicates a belief that domestic policy frameworks play a more critical role than international agreements in driving the adoption of low-carbon technologies. ETS emerged as the most crucial sub-criterion (weight of 0.392), it also highlights its effectiveness in regulating GHG emissions. The carbon tax was ranked as second (weight of 0.338) and reflects its role in influencing energy consumption patterns and promoting cleaner energy alternatives.

Subsidies ranked as third (weight of 0.268) and indicates their importance in ensuring the competitiveness and viability of preferred energy sources or technologies in the market.

The group disagreement values for political criteria, legal instruments sub-criteria, and MBIs sub-criteria were 0.130, 0.110, and 0.113, respectively. These values are above the threshold limit, and the statistical F-test is used for further analysis. The F-test values for political criteria and MBIs sub-criteria were lower than the critical F value at a 0.05 significance level. This indicates a statistically significant disagreement among the experts, highlighting the need for further analysis to understand these differences.

The HAC analysis revealed three distinct subgroups for political criteria. These subgroups showed low disagreement values, suggesting a higher degree of consensus within each subgroup. Subgroup A's preferences indicate a focus on energy security as a primary political concern, possibly reflecting a viewpoint that prioritizes national security and energy independence. Subgroup B's emphasis on legal instruments suggests a belief in the crucial role of regulatory frameworks and legal mechanisms in facilitating the adoption of low-carbon technologies. Subgroup C's balanced approach indicates an understanding of the interplay between different political factors and a more holistic view of the political landscape impacting low-carbon technology implementation. The existence of different subgroups with different priorities underscores the need for inclusive and multifaceted political strategies. Policymakers and industry stakeholders should consider these varied perspectives when designing and implementing policies and regulations. The emphasis on different aspects of political criteria by different subgroups suggests that a one-size-fits-all approach may not be effective. Instead, a more nuanced understanding and approach that considers the diverse priorities and concerns of different stakeholders could lead to more effective and broadly supported policies. The results of this analysis can serve as a guide for future discussions and decision-making processes, ensuring that a wide range of political considerations are considered in the pursuit of sustainable energy solutions.

6.7. Generalizability of Research Model

This comprehensive study, accomplished with the participation of 188 experts from oil and gas industry, academia, and different countries. It also underpins the robustness and wide applicability of this research model. The participation of experts from both developed and developing nations ensures that the model captures a global perspective, making it relevant and adaptable to different geopolitical and economic contexts. For instance, the insights from professionals in the USA's

research institutions and Norway's governmental organizations are complemented by those from the oil & gas sector in Spain, Italy, and Turkey, creating a balanced viewpoint that transcends regional biases.

The experts have diverse backgrounds including oil and gas, technology providers, research institutions, governmental organizations, and associations. The inclusion of a wide range of experts demonstrates the interdisciplinary nature of the research. This diversity guarantees that the model does not lean overly towards a single domain of expertise but instead encapsulates a holistic view of the sector. Moreover, the model also benefits from the inclusion of participants holding different roles within their organizations. This ranges from strategic positions like strategy and business development managers to more technical roles like process engineers. Such a range ensures that the model considers various organizational priorities and operational realities, making it more generalizable and implementable.

While the model's generalizability is strengthened by this diversity, the model may require adjustments when applied to specific local contexts, especially where unique environmental, regulatory, or socio-economic conditions. Future research could focus on these specific applications and explore the details of implementing the model in different local contexts.

In conclusion, the broad and diverse input from a wide array of experts across the globe ensures that the research model is not only comprehensive but also adaptable to a variety of contexts within the oil and gas industry for the evaluating the low-carbon energy technologies. This global and interdisciplinary approach significantly enhances the model’s generalizability and makes it a valuable tool for strategic decision-making in various sub-sectors and regions within the industry.

7. CONCLUSION

This final chapter encapsulates the core achievements and conclusions derived from this research and suggesting the potential areas for future work. The development and application of the HDM tool stand as a testament to the study's innovative approach and its practical implications for the industry.

7.1. Summary and Main Conclusion

The result of this research demonstrates that the developed model by HDM tool is robust and tailored for assessing low-carbon energy technologies within the oil and gas industry. This comprehensive research study, from conceptualization to application, illuminates a path for the energy intensive industries' critical energy transition towards sustainable practices. This model is capable of assisting the industrial companies in identifying the most suitable low-carbon energy technologies. When the fundamental framework of the decision-making model is examined, it is evident that the model elements in the perspective and criteria level, desirability curves and metrics are applicable to any oil and gas company. These aspects of the model have been assessed by the expert panels which are composed of professionals and academicians across various domains. These experts have affirmed the model's suitability for evaluating low-carbon energy technologies. In addition to that, the quantification of the model elements and desirability metrics have been reviewed and endorsed by expert panels, equipped with extensive knowledge in low-carbon energy technologies and oil industry. Iterative refinements of the model have been performed by interacting expert panels. Sub-criteria like "lack of knowledge" and "remuneration" were recalibrated and removed based on their acceptance rates. Therefore, more focused, and applicable model consisting of five perspectives, 21 criteria and 35 sub-criteria was formed. 138 subject matter experts evaluate the relative importance of various criteria and sub-criteria. The model's utility was confirmed through a case study in an actual organizational setting, focusing of hydrogen production technologies. As a result, generalizable model is formed and it can be integrated into the operations of any organization in the oil and gas sector, irrespective of the specific technology involved.

This research contributes a novel methodological approach to the field of sustainable energy technology assessment. Through an extensive literature review, expert panel validations, and a robust model quantification process, the model emerged as a practical tool for assessing various low-carbon energy technology alternatives, including clean hydrogen production technologies. The

application of the model in a case study with a specific oil and gas organization further demonstrates its effectiveness, offering valuable insights into how such models can guide strategic decisions and facilitate the adoption of low-carbon technologies in energy-intensive industries. Therefore, the developed model provides a structured, multi-criteria framework, allowing for a comprehensive analysis of technology alternatives, considering not just technical and environmental aspects but also socio-economic and political factors.

By integrating expert insights and real-world application, this research bridges the gap between theoretical models and practical industry applications. The case study application, in particular, highlights the model's practicality, offering actionable insights for industry stakeholders in making informed decisions about technology adoption. Moreover, the model offers a roadmap for industry stakeholders, guiding decision-makers in the oil and gas sector toward sustainable technological advancements. It serves as a valuable tool for aligning R&D strategies with the evolving demands and expectations associated with decarbonization strategies.

This research aligns with global sustainability goals, particularly in the context of the oil and gas industry's efforts to reduce emissions and transition to low-carbon technologies. It provides a framework for companies to evaluate and adopt technologies that are both effective and sustainable, contributing to the larger goal of mitigating climate change. Additionally, it offers a multi-perspective tool for aligning R&D strategies with industry's evolving demands and expectations, which is facilitated through a critical shift towards a low-carbon future. The model's comprehensive structure allows for the application of this model across different energy intensive sectors, it makes a valuable tool for various industries such as steel and glass industry which has started energy transition activities.

In conclusion, this study does not only fill identified gaps in the existing literature but also presents a practical, comprehensive analysis tool for evaluating low-carbon energy technologies. It emphasizes the importance of a holistic, multi-perspective approach in decision-making processes within the oil and gas sector, offering a valuable resource for guiding the industry towards a sustainable future. Future research may expand on this model, exploring its application in other sectors or incorporating emerging technologies and evolving market dynamics to maintain its relevance and effectiveness in the ever-evolving landscape of energy and sustainability.

7.2. Limitations and Future Work

This study focuses on the critical sides of selecting and evaluating low-carbon energy technologies for the oil and gas industry using the HDM tool. While the model presents a significant advancement in technology assessment, there are certain limitations must be acknowledged, such as expert-based ranking system limitations, sensitivity to external factors and temporal variability.

The HDM relies on the inputs and weights assigned by subject-matter experts to rank various technologies. While this approach is valuable for understanding industry perspectives, it does not directly determine the feasibility of projects in all aspects. The model should ideally be used in conjunction with other evaluative tools, like LCA or TEA, to provide a more comprehensive evaluation of technology viability. Also, the model's reliance on expert judgment means that it is inherently subjective and dependent on the knowledge and perspectives of the experts involved. Despite careful expert panel formation methodologies, inconsistency and disagreement analysis which were applied during the quantification phase, there may still be limitations in the experts' knowledge and potential biases, which could affect the validity and outcomes of the model.

The oil and gas industry, particularly in the arena of sustainable technology, is highly sensitive to external factors such as political shifts, international regulations, market dynamics, and organizational objectives. These factors can significantly influence the prioritization of various technologies, and the HDM, developed at a specific point in time, might not fully encapsulate these rapidly evolving considerations. For that reason, the model's structure and recommendations might require adjustments over time to remain relevant and effective.

In conclusion, while the HDM provides a robust framework for low-carbon energy technology evaluation, it is important to consider these limitations in its application and interpretation. Future adaptations of the model should aim to address these challenges to enhance its effectiveness and applicability in the ever-evolving landscape of the oil and gas industry.

REFERENCES

Abbas, M. S. (2016). *Consistency analysis for judgment quantification in hierarchical decision model* [Doctoral dissertation, Portland State University]. Dissertations and Theses. https://pdxscholar.library.pdx.edu/open_access_etds

Abdulrahman, I., Máša, V., & Teng, S. Y. (2021). Process intensification in the oil and gas industry: A technological framework. *Chemical Engineering and Processing-Process Intensification*, *159*, 108208.

Abiev, R. S., Sladkovskiy, D. A., Semikin, K. V., Murzin, D. Y., & Rebrov, E. V. (2020). Non-thermal plasma for process and energy intensification in dry reforming of methane. *Catalysts*, *10(11)*, 1358.

Abotah, R. (2015). *Evaluation of energy policy instruments for the adoption of renewable energy: Case of wind energy in the Pacific Northwest US* [Doctoral dissertation, Portland State University]. Dissertations and Theses. https://pdxscholar.library.pdx.edu/open_access_etds

Abotah, R., & Daim, T. U. (2017). Towards building a multi perspective policy development framework for transition into renewable energy. *Sustainable Energy Technologies and Assessments*, *21*, 67-88.

Achterberg, P. (2014). The changing face of public support for hydrogen technology explaining declining support among the Dutch (2008–2013). *International Journal of Hydrogen Energy*, *39(33)*, 18711-18717.

Ahmad, W. N. K. W., Rezaei, J., Sadaghiani, S., & Tavasszy, L. A. (2017). Evaluation of the external forces affecting the sustainability of oil and gas supply chain using Best Worst Method. *Journal of Cleaner Production*, *153*, 242-252.

Ajanovic, A., Sayer, M., & Haas, R. (2022). The economics and the environmental benignity of different colors of hydrogen. *International Journal of Hydrogen Energy*, *47(57)*, 24136-24154.

Alidi, A. S. (1996). Use of the analytic hierarchy process to measure the initial viability of industrial projects. *International Journal of Project Management, 14(4),* 205-208.

Anderson, J., Chiavari, J., de Coninck, H., Shackley, S., Sigurthorsson, G., Flach, T., ... & Curnow, P. (2009). Results from the project 'Acceptance of CO2 capture and storage: economics, policy and technology (ACCSEPT)'. *Energy Procedia*, *1(1),* 4649-4653.

Arning, K., Offermann-van Heek, J., Linzenich, A., Kätelhön, A., Sternberg, A., Bardow, A., & Ziefle, M. (2019). Same or different? Insights on public perception and acceptance of carbon capture and storage or utilization in Germany. *Energy Policy*, *125*, 235-249.

Barham, H. A. (2019). *Development of a Readiness Assessment Model for Evaluating Big Data Projects: Case Study of Smart City in Oregon, USA* [Doctoral dissertation, Portland State University]. Dissertations and Theses. https://pdxscholar.library.pdx.edu/open_access_etds

Barni, R., Benocci, R., Spinicchia, N., Roman, H. E., & Riccardi, C. (2019). An experimental study of plasma cracking of methane using DBDs aimed at hydrogen production. *Plasma Chemistry and Plasma Processing*, *39*, 241-258.

Beasy, K., Emery, S., Pryor, K., & Vo, T. A. (2023). Skilling the green hydrogen economy: A case study from Australia. *International Journal of Hydrogen Energy*, *48(52)*, 19811-19820.

Benson, C., Dimopoulos, C., Argyropoulos, C. D., Mikellidou, C. V., & Boustras, G. (2021). Assessing the common occupational health hazards and their health risks among oil and gas workers. *Safety Science*, *140*, 105-284.

Blanco, H., Codina, V., Laurent, A., Nijs, W., Maréchal, F., & Faaij, A. (2020). Life cycle assessment integration into energy system models: An application for Power-to-Methane in the EU. *Applied Energy*, *259,* 114-160.

Bögel, P., Oltra, C., Sala, R., Lores, M., Upham, P., Dütschke, E., ... & Wiemann, P. (2018). The role of attitudes in technology acceptance management: Reflections on the case of hydrogen fuel cells in Europe. *Journal of Cleaner Production*, *188,* 125-135.

Bossmann, T., Fournié, L., Humberset, L., & Khallouf, P. (2018). METIS Study S8-The role and potential of Power to-X in 2050. *DG ENER*, 50.

Boyce, J. K. (2018). Carbon pricing: effectiveness and equity. *Ecological Economics*, *150*, 52-61.

Branco, D. A. C., Gomes, G. L., & Szklo, A. S. (2010). Challenges and technological opportunities for the oil refining industry: A Brazilian refinery case. *Energy Policy, 38(6),* 3098-3105.

Breetz, H., Mildenberger, M., & Stokes, L. (2018). The political logics of clean energy transitions. *Business and Politics, 20(4),* 492-522.

Brennan, L., & Owende, P. (2010). Biofuels from microalgae—a review of technologies for production, processing, and extractions of biofuels and co-products. *Renewable and Sustainable Energy Reviews, 14(2),* 557-577.

Brinckerhoff, P., & DNV, G. (2015). Industrial Decarbonisation and Energy Efficiency Roadmaps to 2050: Oil Refining. *UK Department for Business, Energy & Industrial Strategy, London.*

Bukkholm, I. S. (2021). *Electric steam methane reforming-Economical and environmental implications of replacing methane with electricity for heating in a steam methane reformer* [Master's thesis, Norwegian University of Science and Technology]. Retrieved from ntnuopen.ntnu.no

Capa, A., García, R., Chen, D., Rubiera, F., Pevida, C., & Gil, M. V. (2020). On the effect of biogas composition on the H2 production by sorption enhanced steam reforming (SESR). *Renewable Energy*, *160*, 575-583.

Capobianco, N., Basile, V., Loia, F., & Vona, R. (2021). Toward a sustainable decommissioning of offshore platforms in the oil and gas industry: A PESTLE analysis. *Sustainability, 13(11),* 6266.

Carbon Tracker, (2021). Warming Projections Global Update Report retrieved from https://climateactiontracker.org/documents/853/CAT_2021-05-04_Briefing_Global-Update_Climate-Summit-Momentum.pdf.Date accessed May 2021.

Carlsson, M. (2018). How to Conceal a 395-acre Oil Handling Terminal. Paper presented at Science and Democracy Network (SDN), Munich, Germany. http://stsprogram.org/sdn/wp-content/uploads/2018/06/SDN_2018_CARLSSON.pdf.

Chan, L. (2013). *Developing a strategic policy choice framework for technological innovation: Case of Chinese pharmaceuticals* [Doctoral dissertation, Portland State University]. Dissertations and Theses. https://pdxscholar.library.pdx.edu/open_access_etds

Chan, Y. H., Loy, A. C. M., Cheah, K. W., Chai, S. Y. W., Ngu, L. H., How, B. S., ... & Lam, S. S. (2023). Hydrogen sulfide (H_2S) conversion to hydrogen (H_2) and value-added chemicals: Progress, challenges and outlook. *Chemical Engineering Journal*, *458*, 141398.

Chen, S., Feng, H., Zheng, J., Ye, J., Song, Y., Yang, H., & Zhou, M. (2020). Life cycle assessment and economic analysis of biomass energy technology in China: A brief review. *Processes*, *8(9)*, 1112.

Chen, Y., Zhang, Y., Fan, Y., Hu, K., & Zhao, J. (2017). A dynamic programming approach for modeling low-carbon fuel technology adoption considering learning-by-doing effect. *Applied Energy*, *185*, 825-835.

Cho, H. H., Strezov, V., & Evans, T. J. (2022). Environmental impact assessment of hydrogen production via steam methane reforming based on emissions data. *Energy Reports*, *8*, 13585-13595.

Clancy, J., & Feenstra, M. (2019). *Women, gender equality and the energy transition in the EU*. Publications Office of the European Union.

Clapp, M., Zalitis, C. M., & Ryan, M. (2023). Perspectives on current and future iridium demand and iridium oxide catalysts for PEM water electrolysis. *Catalysis Today*, *420*, 114140.

Concawe. (2020). Air emissions from the refining sector: Analysis of E-PRTR data 2007-2017. Retrieved from https://www.concawe.eu/wp-content/uploads/Rpt_20-4.pdf

Concawe. (2012). EU refinery energy systems and efficiency. Brussels: Concawe. Retrieved from https://www.concawe.eu/wp-content/uploads/rpt_12-03-2012-01520-01-e.pdf

Daim, T. U., Gerdsri, N., Kockan, I., Kocaoglu, D., (2011). Technology Development Envelope Approach for The Adoption of Future Powertrain Technologies: A Case Study on Ford Otosan Roadmapping Model. *Journal of Transportation Systems Engineering and Information Technology*, *11(2),* 58 – 69.

Daim, T. U., Lim, D., Gomez, F. A., Schwarz, J., & Jovanovic, S. (2014). Storage technologies for wind power in the Columbia River Gorge. *International Journal of Sustainable Energy, 33(1),* 1-15.

Daim, T. U., Yoon, B. S., Lindenberg, J., Grizzi, R., Estep, J., & Oliver, T. (2018). Strategic roadmapping of robotics technologies for the power industry: A multicriteria technology assessment. *Technological Forecasting and Social Change*, *131,* 49-66.

Dang, C., Xia, H., Yuan, S., Wei, X., & Cai, W. (2022). Green hydrogen production from sorption-enhanced steam reforming of biogas over a Pd/Ni–CaO-mayenite multifunctional catalyst. *Renewable Energy*, *201,* 314-322.

Davies, J., Dolci, F., & Weidner, E. (2021). *Historical Analysis of FCH 2 JU Electrolyser Projects: Evaluation of contributions towards advancing the State of the Art*, Publications Office of the European Commission, Luxembourg, doi:10.2760/951902.

De Abreu, M. C. S., Albuquerque, S. C., & De Oliveira, M. C. (2016). Institutional pressures on disclosure of carbon control issues by oil and gas companies. *Revista Base (Administração e Contabilidade) da UNISINOS*, *13(1),* 79-91.

De Rose, A., Buna, M., Strazza, C., Olivieri, N., Stevens, T., Peeters, L., & Tawil-Jamault, D. (2017). *Technology readiness level: Guidance principles for renewable energy technologies*, European Commission: Petten, The Netherlands, 17-27.

DNV GL. (2021). Technology Outlook 2030. Retrieved from https://www.dnv.com/to2030 . Date accessed May 2021.

Do, T. N., Kwon, H., Park, M., Kim, C., Kim, Y. T., & Kim, J. (2023). Carbon-neutral hydrogen production from natural gas via electrified steam reforming: Techno-economic-environmental perspective. *Energy Conversion and Management*, *279,* 116758.

Duch-Brown, N., & Costa-Campi, M. T. (2015). The diffusion of patented oil and gas technology with environmental uses: A forward patent citation analysis. *Energy Policy, 83,* 267-276.

Ehlers, J. C., Feidenhans'l, A. A., Therkildsen, K. T., & Larrazábal, G. O. (2023). Affordable Green Hydrogen from Alkaline Water Electrolysis: Key Research Needs from an Industrial Perspective. *ACS Energy Letters, 8(3),* 1502-1509.

Elgowainy, A., Han, J., Cai, H., Wang, M., Forman, G. S., & DiVita, V. B. (2014). Energy efficiency and greenhouse gas emission intensity of petroleum products at US refineries. *Environmental Science & Technology, 48(13),* 7612-7624.

Elshorbagy, W., & Alkamali, A. (2005). Solid waste generation from oil and gas industries in United Arab Emirates. *Journal of Hazardous Materials, 120(1-3),* 89-99.

Eppinger, E., Jain, A., Vimalnath, P., Gurtoo, A., Tietze, F., & Chea, R. H. (2021). Sustainability transitions in manufacturing: the role of intellectual property. *Current Opinion in Environmental Sustainability, 49,* 118-126.

Erickson, P., & Achakulwisut, P. (2021). How subsidies aided the US shale oil and gas boom. Retrieved from https://legacy-assets.eenews.net/open_files/assets/2021/06/23/document_ew_01.pdf

Ericson, S. J., Engel-Cox, J., & Arent, D. J. (2019). *Approaches for integrating renewable energy technologies in oil and gas operations* (No. NREL/TP-6A50-72842). National Renewable Energy Lab.(NREL), Golden, CO (United States).

Estep, J. (2017). *Development of a technology transfer score for evaluating research proposals: Case study of demand response technologies in the Pacific Northwest* [Doctoral dissertation, Portland State University]. Dissertations and Theses. https://pdxscholar.library.pdx.edu/open_access_etds

Estep, J., & Daim, T. U. (2018). Technology assessment: Demand response technologies in the Pacific Northwest. *Infrastructure and Technology Management: Contributions from the Energy, Healthcare and Transportation Sectors*, 177-210.

Estep, J., Daim, T., & Shaygan, A. (2021). R&D project evaluation: Technology transfer focus. *The Electricity Journal, 34(2),* 106904.

European Commission. (2017). Second Report on the State of the Energy Union: Monitoring progress towards the Energy Union objectives – key indicators. SWD (2017) 32 final. Retrieved from https://commission.europa.eu/system/files/2017-01/swd-energy-union-key-indicators_en.pdf

European Commission. (2018). FP7 Projects. Retrieved from https://data.europa.eu/data/datasets/cordisfp7projects?locale=en

European Commission. (2022). Horizon 2020 Projects. Retrieved from https://data.europa.eu/data/datasets/cordish2020projects?locale=en

European Commission. (2023). Horizon Europe Projects. Retrieved from https://data.europa.eu/data/datasets/cordis-eu-research-projects-under-horizon-europe-2021-2027?locale=en

Faheem, H. H., Tanveer, H. U., Abbas, S. Z., & Maqbool, F. (2021). Comparative study of conventional steam-methane-reforming (SMR) and auto-thermal-reforming (ATR) with their hybrid sorption enhanced (SE-SMR & SE-ATR) and environmentally benign process models for the hydrogen production. *Fuel*, *297,* 120769.

Fahim, M. A., Al-Sahhaf, T. A., & Elkilani, A. (2010). *Fundamentals of petroleum refining.* Elsevier.

Fasihi, M., Efimova, O., & Breyer, C. (2019). Techno-economic assessment of CO2 direct air capture plants. *Journal of Cleaner Production, 224,* 957-980.

Fayomi, O. S. I., Akande, I. G., & Odigie, S. (2019, December). Economic impact of corrosion in oil sectors and prevention: An overview. *In Journal of Physics: Conference Series* (Vol. 1378, No. 2, p. 022037). IOP Publishing.

Feng, X. U., WANG, Y. M., Fan, L. I., NIE, X. Y., & ZHU, L. H. (2021). Hydrogen production by the steam reforming and partial oxidation of methane under the dielectric barrier discharge. *Journal of Fuel Chemistry and Technology, 49(3),* 367-373.

Fenwick, D., & Daim, T. U. (2011). Choosing a hybrid car using a hierarchical decision model. *International Journal of Sustainable Society*, *3(3)*, 243-257.

Fernández-Dacosta, C., Shen, L., Schakel, W., Ramirez, A., & Kramer, G. J. (2019). Potential and challenges of low-carbon energy options: Comparative assessment of alternative fuels for the transport sector. *Applied Energy*, *236*, 590-606.

Fleiter, T., Al-Dabbas, K., Clement, A., & Rehfeldt, M. (2023). *METIS 3, study S5. The impact of industry transition on a CO_2-neutral European energy system.* Publications Office of the European Union.

Flis, G., & Wakim, G. (2023). Solid Oxide Electrolysis: A Technology Status Assessment. Retrieved from https://cdn.catf.us/wp-content/uploads/2023/11/15092028/solid-oxide-electrolysis-report.pdf

Fragkiadakis, K., Fragkos, P., & Paroussos, L. (2020). Low-carbon R&D can boost EU growth and competitiveness. *Energies*, *13(19)*, 5236.

Fritsche, U. R., Berndes, G., Cowie, A. L., Dale, V. H., Kline, K. L., Johnson, F. X., ... & Woods, J. (2017). Energy and land use. *Work. Pap. Glob. L. Outlook*, 14-15.

From, T. N., Partoon, B., Rautenbach, M., Østberg, M., Bentien, A., Aasberg-Petersen, K., & Mortensen, P. M. (2023). Electrified steam methane reforming of biogas for sustainable syngas manufacturing and next-generation of plant design: A pilot plant study. *Chemical Engineering Journal*, 147205.

Garrone, P., & Grilli, L. (2010). Is there a relationship between public expenditures in energy R&D and carbon emissions per GDP? An empirical investigation. *Energy Policy*, *38(10)*, 5600-5613.

Gerdsri, N., Assakul, P., & Vatananan, R. S. (2010). An activity guideline for technology roadmapping implementation. *Technology Analysis & Strategic Management*, *22(2)*, 229-242.

Gholipour, Y., Hasheminasab, H., Kharrazi, M., & Streimikis, J. (2018). Sustainability criteria assessment for life-cycle phases of petroleum refinery projects by madm technique. *Business Administration and Management*, *3*, 75-87

Giadedi, A. (2020). *A Scoring Model to Evaluate Offshore Oil Projects: Case of Eni and Mellitah Oil & Gas* [Doctoral dissertation, Portland State University]. Dissertations and Theses. https://pdxscholar.library.pdx.edu/ open_access_etds

Giadedi, A., & Daim, T. U. (2022). A scoring model to evaluate offshore oil projects. *Engineering Management Journal, 34(3),* 436-449.

Gibson, E., Daim, T. U., & Dabic, M. (2019). Evaluating university industry collaborative research centers. *Technological Forecasting and Social Change, 146,* 181-202.

Gibson, E.C. (2016). *A Measurement System for Science and Engineering Research Center Performance Evaluation* [Doctoral dissertation, Portland State University]. Dissertations and Theses. https://pdxscholar.library.pdx.edu/ open_access_etds

Gillespie, D. F., & Clark, B. D. (1979). Visual Impact Assessment in British Oil and Gas Developments. *Our National Landscape. GH Eisner and RC Smardon, Tech. Coord., Gen. Tech. Rep. PSW, 35,* 645-653.

Gillingham, K., & Sweeney, J. (2012). Barriers to implementing low-carbon technologies. *Climate Change Economics, 3(04),* 1250019.

Glanz, S., & Schönauer, A. L. (2021). Towards a low-carbon society via hydrogen and carbon capture and storage: Social acceptance from a stakeholder perspective. *Journal of Sustainable Development of Energy, Water and Environment Systems, 9(1),* 9-0.

Glenk, G., Holler, P., & Reichelstein, S. (2023). Advances in Power-to-Gas technologies: cost and conversion efficiency. *Energy & Environmental Science, 16(12),* 6058-6070.

Golkhatmi, S. Z., Asghar, M. I., & Lund, P. D. (2022). A review on solid oxide fuel cell durability: Latest progress, mechanisms, and study tools. *Renewable and Sustainable Energy Reviews, 161,* 112339.

Gracceva, F., & Zeniewski, P. (2014). A systemic approach to assessing energy security in a low-carbon EU energy system. *Applied Energy, 123,* 335-348.

Green, J., Hadden, J., Hale, T., & Mahdavi, P. (2022). Transition, hedge, or resist? Understanding political and economic behavior toward decarbonization in the oil and gas industry. *Review of International Political Economy, 29(6),* 2036-2063.

Gudde, N., Larivé, J. F., & Yugo, M. (2019). CO_2 reduction technologies. Opportunities within the EU Refining System (2030/2050). *Concawe Special Task Force, Brussels.*

Gul, E., Baldinelli, G., Farooqui, A., Bartocci, P., & Shamim, T. (2023). AEM-electrolyzer based hydrogen integrated renewable energy system optimisation model for distributed communities. *Energy Conversion and Management, 285,* 117025.

Guo, X., Fu, L., & Sun, X. (2021). Can environmental regulations promote greenhouse gas abatement in OECD countries? Command-and-control vs. market-based policies. *Sustainability, 13(12),* 6913.

Hafstead, M. A., Metcalf, G. E., & Williams, R. C. (2016). Adding Quantity Certainty to a Carbon Tax. *Resources for the Future Discussion Paper*, 16-43.

Halderen, M. V., Bhatt, M., Van Riel, C. B., & Brown, T. (2013). Managing Impressions in the Face of Rising Institutional Pressures: A Comparative Case Analysis. *In Academy of Management Proceedings*, *1*, 15648.

Hartley, P. R., & Medlock III, K. B. (2017). The valley of death for new energy technologies. *The Energy Journal, 38(3),* 33-62.

Hasheminasab, H., Gholipour, Y., Kharrazi, M., & Streimikiene, D. (2018a). Life cycle approach in sustainability assessment for petroleum refinery projects with fuzzy-AHP. *Energy & Environment, 29(7),* 1208-1223.

Hasheminasab, H., Gholipour, Y., Kharrazi, M., & Streimikiene, D. (2018b). A novel metric of sustainability for petroleum refinery projects. *Journal of Cleaner Production, 171,* 1215-1224.

Herbertson, J. (2020). The Oil and Gas Industry, Low-Emission Pathways, and the Energy Transition. *Oxford Energy Forum, 121,* 9-14.

Hess, D. J., & Sovacool, B. K. (2020). Sociotechnical matters: Reviewing and integrating science and technology studies with energy social science. *Energy Research & Social Science, 65,* 101462.

Hogaboam, L., & Daim, T. (2018). Technology adoption potential of medical devices: The case of wearable sensor products for pervasive care in neurosurgery and orthopedics. *Health Policy and Technology, 7(4),* 409-419.

Hogaboam, L., Ragel, B., & Daim, T. (2014, July). Development of a Hierarchical Decision Model (HDM) for health technology assessment (HTA) to design and implement a new patient care database for low back pain. *In Proceedings of PICMET'14 Conference: Portland International Center for Management of Engineering and Technology; Infrastructure and Service Integration* (pp. 3511-3517). IEEE.

Hötte, K., Pichler, A., & Lafond, F. (2021). The rise of science in low-carbon energy technologies. *Renewable and Sustainable Energy Reviews, 139,* 110654.

Huang, Y., Fan, Y., & Chen, C. W. (2014). An integrated biofuel supply chain to cope with feedstock seasonality and uncertainty. *Transportation Science, 48(4),* 540-554.

Intepe, G., Bozdag, E., & Koc, T. (2013). The selection of technology forecasting method using a multi-criteria interval-valued intuitionistic fuzzy group decision making approach. *Computers & Industrial Engineering, 65(2),* 277-285.

International Association of Oil & Gas Producers. (2018). Asset Integrity: The Key to Managing Major Incident Risks. Retrieved November 4, 2023, from https://www.iogp.org/bookstore/product/asset-integrity-the-key-to-managing-major-incident-risks/

International Energy Agency. (2020). *World Energy Outlook 2020*. Paris: IEA. Retrieved from https://www.iea.org/reports/world-energy-outlook-2020. License: CC BY 4.0.

International Energy Agency. (2021). *World Energy Outlook 2021*. Paris: IEA. Retrieved from https://www.iea.org/reports/world-energy-outlook-2021. License: CC BY 4.0.

International Energy Agency. (2023a). *World Energy Outlook 2023.* Paris: IEA. Retrieved from https://www.iea.org/reports/world-energy-outlook-2021. License: CC BY 4.0.

International Energy Agency. (2023b). *Hydrogen Patents for a Clean Energy Future.* Paris: IEA. Retrieved from https://www.iea.org/reports/hydrogen-patents-for-a-clean-energy-future. License: CC BY 4.0.

International Renewable Energy Agency. (2019). Global energy transformation: A roadmap to 2050 (2019 ed). Abu Dhabi: IRENA. Retrieved from https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Apr/IRENA_Global_Energy_Transformation_2019.pdf?rev=6ea97044a1274c6c8ffe4a116ab17b8f

Ionomr Innovations Inc. (2020). Hydrogen Production Cost by AEM Water Electrolysis. Retrieved from https://ionomr.com/wp-content/uploads/2021/02/FM-7024-A-Hydrogen-Production-Cost-by-AEM-White-Paper-copy.pdf

IPCC, (2023). *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Geneva, Switzerland, 184 pp., doi: 10.59327/IPCC/AR6-9789291691647.

IPIECA. (2022). Energy Efficient Design for Carbon Dioxide Reduction 2022. Retrieved from https://www.ipieca.org/resources/energy-efficiency-database/energy-efficient-design-for-carbon-dioxide-reduction-2022

IRENA. (2020). *Global Renewables Outlook: Energy transformation 2050*, International Renewable Energy Agency, Abu Dhabi.

Iskin, I. (2014). *An assessment model for energy efficiency program planning in electric utilities: Case of the Pacific of northwest USA* [Doctoral dissertation, Portland State University]. Dissertations and Theses. https://pdxscholar.library.pdx.edu/ open_access_etds

Iskin, I., Daim, T., Kayakutlu, G., & Altuntas, M. (2012). Exploring renewable energy pricing with analytic network process—Comparing a developed and a developing economy. *Energy Economics, 34(4),* 882-891.

Jahanger, A., Ozturk, I., Onwe, J. C., Joseph, T. E., & Hossain, M. R. (2023). Do technology and renewable energy contribute to energy efficiency and carbon neutrality? Evidence from top ten manufacturing countries. *Sustainable Energy Technologies and Assessments, 56*, 103084.

Jannasch, A. K., Pihl, H., Persson, M., Svensson, E., Harvey, S., & Wiertzema, H. (2020). Opportunities and barriers for implementation of Power-to-X (P2X) technologies in the West Sweden Chemicals and Materials Clusters process industries. Retrieved from https://www.johannebergsciencepark.com/sites/default/files/M%C3%B6jligheter%20och%20hinder%20P2X_final.pdf

Johansson, D., Rootzén, J., Berntsson, T., & Johnsson, F. (2012). Assessment of strategies for CO2 abatement in the European petroleum refining industry. *Energy, 42(1)*, 375-386.

Kaiser, M. J. (2017). A review of refinery complexity applications. *Petroleum Science, 14*, 167-194.

Kalbar, P. P., Karmakar, S., & Asolekar, S. R. (2012). Selection of an appropriate wastewater treatment technology: A scenario-based multiple-attribute decision-making approach. *Journal of Environmental Management, 113*, 158-169.

Kamali, F. P., Borges, J. A. R., Osseweijer, P., & Posada, J. A. (2018). Towards social sustainability: Screening potential social and governance issues for biojet fuel supply chains in Brazil. *Renewable and Sustainable Energy Reviews, 92*, 50-61.

Khalifa, R. I., & Daim, T. U. (2021). Project assessment tools evaluation and selection using the hierarchical decision modeling: Case of state departments of transportation in the United States. *Journal of Management in Engineering, 37(1)*, 05020015.

Khanam, M. (2020). *A Market Diffusion Potential (MDP) Assessment Model for Residential Energy Efficient (EE) Technologies in the U.S.* [Doctoral dissertation, Portland State University]. Dissertations and Theses. https://pdxscholar.library.pdx.edu/ open_access_etds

Khanam, M., & Daim, T. (2021). A market diffusion potential (MDP) assessment model for residential energy efficient (EE) technologies in the US. *Renewable and Sustainable Energy Reviews, 144*, 110968.

Kim, J., Lee, H., Huh, S. C., Bae, J. H., Choe, W., Han, D., ... & Park, S. (2023). Competitive formation of NO, NO_2, and O_3 in an air-flowing plasma reactor: A central role of the flow rate. *Chemical Engineering Journal*, *468*, 143636.

Kim, J., Ryu, D., & Sovacool, B. K. (2021). Critically assessing and projecting the frequency, severity, and cost of major energy accidents. *The Extractive Industries and Society*, *8(2)*, 100885.

Kim, S. S., Jorat, M., Voecks, G., Kuthi, A., Surampudi, S., & Kent, R. L. (2020). Hydrogen from steam methane reforming by catalytic nonthermal plasma using a dielectric barrier discharge reactor. *AIChE Journal*, *66(4)*, e16880.

King, B., Patel, D., Chen, J. Z., Drapanauskaite, D., Handler, R., Nozaki, T., & Baltrusaitis, J. (2021). Comprehensive process and environmental impact analysis of integrated DBD plasma steam methane reforming. *Fuel*, *304*, 121328.

Kocaoglu, D. F. (1983). A participative approach to program evaluation. *IEEE Transactions on Engineering Management*, *(3)*, 112-118.

Konadu, D. D., Mourão, Z. S., Allwood, J. M., Richards, K. S., Kopec, G., McMahon, R., & Fenner, R. (2015). Land use implications of future energy system trajectories—The case of the UK 2050 Carbon Plan. *Energy Policy*, *86*, 328-337.

Koponen, J., Kosonen, A., Ruuskanen, V., Huoman, K., Niemelä, M., & Ahola, J. (2017). Control and energy efficiency of PEM water electrolyzers in renewable energy systems. *International Journal of Hydrogen Energy*, *42(50)*, 29648-29660.

Krahn, S., Gerdes, K., & Sutter, H. (2008). Department of energy technology readiness assessments-process guide and training plan. *Dept. Energy, Washington, DC, USA, Tech. Rep. DOE G*, 413-3.

Krishnan, V., & McCalley, J. D. (2016). The role of bio-renewables in national energy and transportation systems portfolio planning for low carbon economy. *Renewable Energy*, *91*, 207-223.

Lap, T., Benders, R., van der Hilst, F., & Faaij, A. (2020). How does the interplay between resource availability, intersectoral competition and reliability affect a low-carbon power generation mix in Brazil for 2050? *Energy*, 195, 116948.

Lavoie, J. R. (2019). *A scoring model to assess organizations' technology transfer capabilities: The case of a power utility in the Northwest USA* [Doctoral dissertation, Portland State University]. Dissertations and Theses. https://pdxscholar.library.pdx.edu/ open_access_etds

Lavoie, J. R., Daim, T., & Carayannis, E. G. (2020). Technology transfer evaluation: Driving organizational changes through a hierarchical scoring model. *IEEE Transactions on Engineering Management, 69(6),* 3392-3406.

Lelieveld, J., Klingmüller, K., Pozzer, A., Burnett, R. T., Haines, A., & Ramanathan, V. (2019). Effects of fossil fuel and total anthropogenic emission removal on public health and climate. *Proceedings of the National Academy of Sciences, 116(15),* 7192-7197.

Li, Q., Liu, G., Cai, B., Leamon, G., Liu, L. C., Chen, Z. A., & Li, X. (2017). Public awareness of the environmental impact and management of carbon dioxide capture, utilization and storage technology: The views of educated people in China. *Clean Technologies and Environmental Policy, 19,* 2041-2056.

Li, R. Y. M., Wang, Q., Zeng, L., & Chen, H. (2023a). A study on public perceptions of carbon neutrality in China: has the idea of ESG been encompassed? *Frontiers in Environmental Science, 10,* 949959.

Li, Q., Molina Villarino, A., Peltier, C. R., Macbeth, A. J., Yang, Y., Kim, M. J., ... & Abruna, H. D. (2023b). Anion Exchange Membrane Water Electrolysis: The Future of Green Hydrogen. *The Journal of Physical Chemistry C, 127(17),* 7901-7912.

Lima-de-Oliveira, R., & Sturgeon, T. (2017). From resource extraction to knowledge creation: Oil-rich states, oil companies and the promotion of local R&D. MIT-IPC Working Paper 17-003. Retrieved from https://ipc.mit.edu/wp-content/uploads/2023/07/From-Resource-Extraction-to-Knowledge-Creation-Oil-Rich-States-Oil-Companies-and-the-Promotion-of-Local-RD.pdf

Linares, P., & Pérez-Arriaga, I. (2009). Promoting investment in low-carbon energy technologies. *European Review of Energy Markets, 3(2),* 1-23.

Liu, H., Yu, J., Xu, J., Fan, Y., & Bao, X. (2007). Identification of key oil refining technologies for China National Petroleum Co.(CNPC). *Energy Policy, 35(4),* 2635-2647.

Liu, Z., Wang, S., & Ouyang, Y. (2017). Reliable biomass supply chain design under feedstock seasonality and probabilistic facility disruptions. *Energies, 10(11),* 1895.

Lo, S. L. Y., How, B. S., Leong, W. D., Teng, S. Y., Rhamdhani, M. A., & Sunarso, J. (2021). Techno-economic analysis for biomass supply chain: A state-of-the-art review. *Renewable and Sustainable Energy Reviews, 135,* 110164.

Luthra, S., Kumar, S., Garg, D., & Haleem, A. (2015). Barriers to renewable/sustainable energy technologies adoption: Indian perspective. *Renewable and Sustainable Energy Reviews, 41,* 762-776.

Makhsoos, A., Kandidayeni, M., Pollet, B. G., & Boulon, L. (2023). A perspective on increasing the efficiency of proton exchange membrane water electrolyzers–a review. *International Journal of Hydrogen Energy.48 (41),* 15341-15370

Mander, S. and Minas, A.M., 2019. *Understanding public responses to low carbon technologies*. European Parliament.

Merk, C., Nordø, Å. D., Andersen, G., Lægreid, O. M., & Tvinnereim, E. (2022). Don't send us your waste gases: Public attitudes toward international carbon dioxide transportation and storage in Europe. *Energy Research & Social Science, 87,* 102450.

Metcalf, G. E. (2009). Tax policies for low-carbon technologies. *National Tax Journal, 62(3),* 519-533.

Miller, H. A. (2022). Green hydrogen from anion exchange membrane water electrolysis. *Current Opinion in Electrochemistry,* 101122.

Mion, A., Galli, F., Mocellin, P., Guffanti, S., & Pauletto, G. (2022). Electrified methane reforming decarbonises methanol synthesis. *Journal of CO_2 Utilization, 58,* 101911.

Miura, T., Takahashi, K., Takaki, K., & Nishida, Y. (2020). Influence of waveform of applied voltage on H 2 production from methane reforming using dielectric barrier discharge. *IEEE Transactions on Plasma Science, 49(1),* 147-153.

Morgan, M. G. (2014). Use (and abuse) of expert elicitation in support of decision making for public policy. *Proceedings of the National Academy of Sciences, 111(20),* 7176-7184.

Moschovi, A. M., Zagoraiou, E., Polyzou, E., & Yakoumis, I. (2021). Recycling of Critical Raw Materials from Hydrogen Chemical Storage Stacks (PEMWE), Membrane Electrode Assemblies (MEA) and Electrocatalysts. *IOP Conference Series: Materials Science and Engineering 1024(1),* 012008.

Motealleh, B., Liu, Z., Masel, R. I., Sculley, J. P., Ni, Z. R., & Meroueh, L. (2021). Next-generation anion exchange membrane water electrolyzers operating for commercially relevant lifetimes. *International Journal of Hydrogen Energy, 46(5),* 3379-3386.

Murrant, D., & Radcliffe, J. (2018). Assessing energy storage technology options using a multi-criteria decision analysis-based framework. *Applied Energy, 231,* 788-802.

Naik, S. N., Goud, V. V., Rout, P. K., & Dalai, A. K. (2010). Production of first- and second-generation biofuels: a comprehensive review. *Renewable and Sustainable Energy Reviews, 14(2),* 578-597.

Nami, H., Rizvandi, O. B., Chatzichristodoulou, C., Hendriksen, P. V., & Frandsen, H. L. (2022). Techno-economic analysis of current and emerging electrolysis technologies for green hydrogen production. *Energy Conversion and Management, 269,* 116162.

Narimisa, M. R. (2013). An Environmental and Social Impact Assessment Model (ESIAM) for oil refinery: a case study of TEHRAN oil refinery. *Life Science Journal, 10(7),* 630-638

Nesbitt, E. R. (2020). Using waste carbon feedstocks to produce chemicals. *Industrial Biotechnology, 16(3),* 147-163.

Nilsson, P. A., Apeland, S., Dale, H. M., Decarre, S., Eldrup, N. H., & Hansen, H. R. (2010). The costs of CO_2 transport-Post-demonstration CCS in the EU. *European Technology Platform for Zero Emission Fossil Fuel Power Plants.*

Olabi, A. G., Alami, A. H., Ayoub, M., Aljaghoub, H., Alasad, S., Inayat, A., ... & Sayed, E. T. (2023). Membrane-based carbon capture: Recent progress, challenges, and their role in achieving the sustainable development goals. *Chemosphere*, 137996.

Olfe-Kräutlein, B. (2020). Advancing CCU technologies pursuant to the SDGs: a challenge for policy making. *Frontiers in Energy Research, 8,* 198.

Ouimet, R. J., Glenn, J. R., De Porcellinis, D., Motz, A. R., Carmo, M., & Ayers, K. E. (2022). The Role of Electrocatalysts in the Development of Gigawatt-Scale PEM Electrolyzers. *ACS Catalysis, 12(10),* 6159-6171.

Pandejpong, T. (2016). Strategic Planning: Model Development for Strategic Decision for Technology Selection in the Petrochemical Industry. In T. U., Daim. *Hierarchical Decision Modeling: Essays in Honor of Dundar F. Kocaoglu* (pp. 165-179). Cham: Springer International Publishing.

Pandejpong, T., & Kocaoglu, D. F. (2001, July). Model development for strategic decision for technology selection in the petrochemical industry. *In PICMET'01. Portland International Conference on Management of Engineering and Technology.* Proceedings Vol. 1: Book of Summaries (IEEE Cat. No. 01CH37199) (Vol. 1, pp. 119-vol). IEEE.

Panoutsou, C., Germer, S., Karka, P., Papadokostantakis, S., Kroyan, Y., Wojcieszyk, M., ... & Landalv, I. (2021). Advanced biofuels to decarbonise European transport by 2030: Markets, challenges, and policies that impact their successful market uptake. *Energy Strategy Reviews, 34,* 100633.

Parker, N., Williams, R., Dominguez-Faus, R., & Scheitrum, D. (2017). Renewable natural gas in California: An assessment of the technical and economic potential. *Energy Policy, 111,* 235-245.

Parkes, K. R. (2012). Shift schedules on North Sea oil/gas installations: A systematic review of their impact on performance, safety and health. *Safety Science, 50(7),* 1636-1651.

Pasimeni, F., Fiorini, A., & Georgakaki, A. (2019). Assessing private R&D spending in Europe for climate change mitigation technologies via patent data. *World Patent Information, 59,* 101927.

Persons, T. M., & Mackin, M. (2020*). Technology readiness assessment guide: best practices for evaluating the readiness of technology for use in acquisition programs and projects* (Report No. AD1105846). US Government Accountability Office Washington United States. Retrieved from https://apps.dtic.mil /sti/pdfs/AD1105846.pdf

Phan, K. (2013). Innovation measurement: A decision framework to determine innovativeness of a company [Doctoral dissertation, Portland State University]. Dissertations and Theses. https://pdxscholar.library.pdx.edu/ open_access_etds

Pianta, S., Rinscheid, A., & Weber, E. U. (2021). Carbon capture and storage in the United States: perceptions, preferences, and lessons for policy. *Energy Policy, 151,* 112149.

Pichtel, J. (2016). Oil and gas production wastewater: Soil contamination and pollution prevention. *Applied and Environmental Soil Science,* 2707989

Polatidis, H., Haralambopoulos, D. A., Munda, G., & Vreeker, R. (2006). Selecting an appropriate multi-criteria decision analysis technique for renewable energy planning. *Energy Sources, Part B, 1(2),* 181-193.

Popoola, L. T., Grema, A. S., Latinwo, G. K., Gutti, B., & Balogun, A. S. (2013). Corrosion problems during oil and gas production and its mitigation. *International Journal of Industrial Chemistry, 4,* 1-15.

Price, E. (2017). Durability and degradation issues in PEM electrolysis cells and its components. *Johnson Matthey Technology Review, 61(1),* 47-51.

Prosser, J. H., James, B. D., Murphy, B. M., Wendt, D. S., Casteel, M. J., Westover, T. L., & Knighton, L. T. (2024). Cost analysis of hydrogen production by high-temperature solid oxide electrolysis. *International Journal of Hydrogen Energy, Part C. 49,* 207-227

Radelyuk, I., Tussupova, K., Klemeš, J. J., & Persson, K. M. (2021). Oil refinery and water pollution in the context of sustainable development: Developing and developed countries. *Journal of Cleaner Production, 302*, 126987.

Reay, D., Ramshaw, C., & Harvey, A. (2013). *Process Intensification: Engineering for efficiency, sustainability and flexibility*. Butterworth-Heinemann.

Ren, J., & Sovacool, B. K. (2015). Prioritizing low-carbon energy sources to enhance China's energy security. *Energy Conversion and Management, 92,* 129-136.

Riedmayer, R., Paren, B. A., Schofield, L., Shao-Horn, Y., & Mallapragada, D. (2023). Proton Exchange Membrane Electrolysis Performance Targets for Achieving 2050 Expansion Goals Constrained by Iridium Supply. *Energy & Fuels. 37(12),* 8614-8623

S&P Global Market Intelligence. (2020). Path to net-zero: Climate change takes center stage at more US oil companies. Retrieved from https://www.spglobal. com/marketintelligence /en/news-insights/latest-news-headlines/path-to-net-zero-climate-change-takes-center-stage-atmore-us-oil-companies-61440277

Santoro, C., Lavacchi, A., Mustarelli, P., Di Noto, V., Elbaz, L., Dekel, D. R., & Jaouen, F. (2022). What is next in anion-exchange membrane water electrolyzers? Bottlenecks, benefits, and future. *ChemSusChem, 15(8),* e202200027.

Scott, M., & Powells, G. (2020). Towards a new social science research agenda for hydrogen transitions: Social practices, energy justice, and place attachment. *Energy Research & Social Science, 61,* 101346.

Selliers, D. de, & Spataru, C. (2020). The role of the oil and gas industry in the transition towards a circular economy. *In 785th International Conference on Economics, Management and Social Study (ICEMSS),* London, UK, March 2020. Retrieved from https://www.researchgate.net /publication/342134238

Serov, A., Kovnir, K., Shatruk, M., & Kolen'ko, Y. V. (2021). Critical review of platinum group metal-free materials for water electrolysis: Transition from the laboratory to the market: Earth-

abundant borides and phosphides as catalysts for sustainable hydrogen production. *Johnson Matthey Technology Review, 65(2),* 207-226.

Seto, K. C., Davis, S. J., Mitchell, R. B., Stokes, E. C., Unruh, G., & Ürge-Vorsatz, D. (2016). Carbon lock-in: types, causes, and policy implications. *Annual Review of Environment and Resources, 41,* 425-452.

Shaygan, A., & Daim, T. (2023). Technology management maturity assessment model in healthcare research centers. *Technovation, 120,* 102444.

Sheikh, N., Daim, T., & Kocaoglu, D. F. (2011, July). Use of multiple perspectives and decision modeling for PV technology assessment. *In 2011 Proceedings of PICMET'11: Technology Management in the Energy Smart World (PICMET)* (pp. 1-21). IEEE.

Shrivastava, S., & Unnikrishnan, S. (2019). Review of life cycle assessment and environmental impacts from the oil & Gas sector. *In 28th International Conference for the International Association of Management of Technology: Managing Technology for Inclusive and Sustainable Growth, IAMOT 2019* (pp. 972-984). Excel India Publishers.

Skiba, R. (2020). Competency Standards for Emerging Hydrogen Related Activities. *Open Journal of Safety Science and Technology, 10,* 42-52.

Skjærseth, J. B. (2013). Governance by EU emissions trading: resistance or innovation in the oil industry? *International Environmental Agreements: Politics, Law and Economics, 13,* 31-48.

Smith, E., Morris, J., Kheshgi, H., Teletzke, G., Herzog, H., & Paltsev, S. (2021). The cost of CO_2 transport and storage in global integrated assessment modeling. *International Journal of Greenhouse Gas Control, 109,* 103367.

Soler, A. (2020). Role of e-fuels in the European transport system-Literature review. *Concawe: Brussels, Belgium.*

Soltani, S. M., Lahiri, A., Bahzad, H., Clough, P., Gorbounov, M., & Yan, Y. (2021). Sorption-enhanced steam methane reforming for combined CO_2 capture and hydrogen production: a state-of-the-art review. *Carbon Capture Science & Technology, 1,* 100003.

Sovacool, B. K., & Monyei, C. G. (2021). Positive externalities of decarbonization: quantifying the full potential of avoided deaths and displaced carbon emissions from renewable energy and nuclear power. *Environmental Science & Technology, 55(8),* 5258-5271.

Sovacool, B. K., Andersen, R., Sorensen, S., Sorensen, K., Tienda, V., Vainorius, A., ... & Bjørn-Thygesen, F. (2016). Balancing safety with sustainability: assessing the risk of accidents for modern low-carbon energy systems. *Journal of Cleaner Production, 112,* 3952-3965.

Squadrito, G., Maggio, G., & Nicita, A. (2023). The green hydrogen revolution. *Renewable Energy, 216,* 119041.

Stafford, W. H. L., Lotter, G. A., von Maltitz, G. P., & Brent, A. C. (2019). Biofuels technology development in Southern Africa. *Development Southern Africa, 36(2),* 155-174.

Sun, P., Elgowainy, A., Wang, M., Han, J., & Henderson, R. J. (2018). Estimation of US refinery water consumption and allocation to refinery products. *Fuel, 221,* 542-557.

Talaei, A., Oni, A. O., Ahiduzzaman, M., Roychaudhuri, P. S., Rutherford, J., & Kumar, A. (2020). Assessment of the impacts of process-level energy efficiency improvement on greenhouse gas mitigation potential in the petroleum refining sector. *Energy, 191,* 116243.

Tan, H., Wong-Parodi, G., & Xu, J. (2020). Not under my backyard? Psychological distance, local acceptance, and shale gas development in China. *Energy Research & Social Science, 61,* 101336.

TANECO. (2009). *Environmental and Social Impact Assessment (ESIA) for the Oil Refinery (Stage 1) of the TANECO Oil Refining and Petrochemical Complex*. Nizhnekamsk, Republic of Tatarstan, Russian Federation.

Tang, L., Wang, H., Li, L., Yang, K., & Mi, Z. (2020). Quantitative models in emission trading system research: A literature review. *Renewable and Sustainable Energy Reviews, 132,* 110052.

Tayebi, M., Bemani, A., Fetanat, A., & Fehresti-Sani, M. (2022). A decision support system for sustainability prioritization of air pollution control technologies in energy and carbon management: Oil & gas industry of Iran. *Journal of Natural Gas Science and Engineering, 99,* 104416.

Telford, S., Mazhar, M. I., & Howard, I. (2011, January). Condition based maintenance (CBM) in the oil and gas industry: An overview of methods and techniques. *In Proceedings of the 2011 international conference on industrial engineering and operations management, Kuala Lumpur, Malaysia* (pp. 22-24).

Torjai, L., Nagy, J., & Bai, A. (2015). Decision hierarchy, competitive priorities and indicators in large-scale 'herbaceous biomass to energy'supply chains. *Biomass and Bioenergy, 80*, 321-329.

Troldborg, M., Heslop, S., & Hough, R. L. (2014). Assessing the sustainability of renewable energy technologies using multi-criteria analysis: Suitability of approach for national-scale assessments and associated uncertainties. *Renewable and Sustainable Energy Reviews, 39*, 1173-1184.

U.S. Environmental Protection Agency. (2010). Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from Industrial, Commercial, and Institutional Boilers. Office of Air and Radiation, Office of Air Quality Planning and Standards. Retrieved from https://www.epa.gov/sites/default/files/2015-12/documents/iciboilers.pdf

Udemu, C., & Font-Palma, C. (2023). Modelling of sorption-enhanced steam reforming (SE-SR) process in fluidised bed reactors for low-carbon hydrogen production: A review. *Fuel*, *340*, 127588.

United Nations Framework Convention on Climate Change. (2015). Paris Agreement. Retrieved from https://unfccc.int/sites/default/files/english_paris_agreement.pdf

United Nations Framework Convention on Climate Change. (2017). Technological Innovation for the Paris Agreement: Implementing nationally determined contributions, national adaptation plans and mid-century strategies (TEC Brief #10). Retrieved from https://unfccc.int/ttclear/misc_/StaticFiles/gnwoerk_static/brief10/8c3ce94c20144fd5a8b0c06fefff6633/57440a5fa1244fd8b8cd13eb4413b4f6.pdf

Upham, P., Sovacool, B., & Ghosh, B. (2022). Just transitions for industrial decarbonisation: A framework for innovation, participation, and justice. *Renewable and Sustainable Energy Reviews, 167*, 112699.

Vincent, I., Kruger, A., & Bessarabov, D. (2017). Development of efficient membrane electrode assembly for low cost hydrogen production by anion exchange membrane electrolysis. *International Journal of Hydrogen Energy, 42(16),* 10752-10761.

Vincent, I., Lee, E. C., & Kim, H. M. (2021). Comprehensive impedance investigation of low-cost anion exchange membrane electrolysis for large-scale hydrogen production. *Scientific Reports, 11(1),* 293.

Wang, B., Xie, H. L., Ren, H. Y., Li, X., Chen, L., & Wu, B. C. (2019). Application of AHP, TOPSIS, and TFNs to plant selection for phytoremediation of petroleum-contaminated soils in shale gas and oil fields. *Journal of Cleaner Production, 233,* 13-22.

Wene, C.O. (2008). Energy technology learning through deployment in competitive markets. *The Engineering Economist, 53(4),* 340-364.

Williams, C. L. (2019). The deserving professional: Job insecurity and gender inequality in the oil and gas industry. *Labour & Industry: a Journal of the Social and Economic Relations of Work, 29(2),* 199-212.

Yan, L., Li, K., Sui, H., He, B., Geng, C., & Fang, B. (2023). Simulation of Sorption-Enhanced Steam Methane Reforming over Ni-Based Catalyst in a Pressurized Dual Fluidized Bed Reactor. *Inorganics, 11(3),* 107.

Yáñez, É., Meerman, H., Ramírez, A., Castillo, É., & Faaij, A. (2022). Fully integrated CO_2 mitigation strategy for an existing refinery: A case study in Colombia. *Applied Energy, 313,* 118771.

Yang, H., Kaczur, J. J., Sajjad, S. D., & Masel, R. I. (2020). Performance and long-term stability of CO_2 conversion to formic acid using a three-compartment electrolyzer design. *Journal of CO_2 Utilization, 42,* 101349.

Yeh, S., Lutsey, N. P., & Parker, N. C. (2009). Assessment of technologies to meet a low carbon fuel standard. *Environmental Science & Technology, 43(18),* 6907-6914

Yenesew, G. T., Quarez, E., La Salle, A. L. G., Nicollet, C., & Joubert, O. (2023). Recycling and characterization of end-of-life solid oxide fuel/electrolyzer ceramic material cell components. *Resources, Conservation and Recycling, 190,* 106809.

Yin, C., Gu, H., & Zhang, S. (2020). Measuring technological collaborations on carbon capture and storage based on patents: A social network analysis approach. *Journal of Cleaner Production, 274,* 122867.

Zhang, X., Li, Y., Zhao, W., Guo, J., Yin, P., & Ling, T. (2023). Technical factors affecting the performance of anion exchange membrane water electrolyzer. *International Journal of Minerals, Metallurgy and Materials, 30(11),* 2259-2269.

Zhao, F., Fan, Y., & Zhang, S. (2021). Assessment of efficiency improvement and emission mitigation potentials in China's petroleum refining industry. *Journal of Cleaner Production, 280,* 124482.

Zhou, Y., Fang, W., Li, M., & Liu, W. (2018). Exploring the impacts of a low-carbon policy instrument: A case of carbon tax on transportation in China. *Resources, Conservation and Recycling, 139,* 307-314.

APPENDIX A. CONSENT FORM

CONSENT FORM FOR PARTICIPATION TO RESEARCH

Research Title: Multi-Perspective Technology Assessment for Petroleum Industry

Researcher: Özgül Ayyıldız
Address: Institute of Environmental Sciences, Boğaziçi University
Contact Information: ozgul.ayyildiz@boun.edu.tr, +90 506 523 4401

Dear Sir/Madam,

Thank you for accepting to participate in this research, in partial fulfillment of the requirements for a Ph.D. degree under the supervision of Prof. Dr. Ayşen Erdinçler, Boğaziçi University, Institute of Environmental Sciences and Prof. Dr. Tuğrul Daim, Portland State University, Engineering and Technology Management Department. The main aim of this research is to develop a holistic framework for assessing the best low carbon energy technology alternatives for the oil and gas industry in order to achieve emission reduction goals and investigate which criteria have the highest impact on selecting the low carbon energy technologies.

You are being asked to participate in this study because of your experience in low carbon energy technologies and the oil and gas industry.

This form consists of key information about the research study and also includes the possible benefits and as well as the risks for you. If you have any questions about this study, please ask the researcher before you decide to participate.

Why is this research being conducted?

Like many governments, major oil companies state climate neutrality and targets to achieve net-zero emission by 2050, there is no multi-dimensional approach in order to assess low-carbon energy technologies for the process industries. The oil and gas industry are the major carbon emission contributor among the process industries. This research aims to provide a holistic framework that can be used for assessing the low carbon energy alternatives for the oil and gas industry to achieve the emission reduction goals and investigate the impact factors of each criterion to evaluate the best technology alternatives for technology road-mapping activities of an

organization. The hierarchical decision modelling (HDM) is being used for the development of the assessment model and a decision-making tool will be developed for multi perspective technology assessment for the petroleum industry.

How long will I be in this study?

Participation in this study will take approximately 10 minutes each time for responding to the validation and quantification of questionnaires. The questionnaires will be sent out to you once or two times during August 2021 - July 2023. If you are invited for a case study, it will take around 1 hour.

What will happen if I decide to participate in this research?

If you agree to participate in this research, you will be one of the experts within the one or two expert panels which will validate and quantify the research model. If a case study will be determined, you may be also invited as an expert to provide opinions for the case study. You will be informed about any upcoming news that may affect your willingness to participate in this research.

What will happen to the information collected?

The collected information will be used to validate and quantify the research model. The information and analysis results will be the input of the Ph.D. dissertation, which will be assessed by Boğaziçi University. Any specific data about your organization or personal data will not be needed. Only your insights and expert opinions about the literature-based model will be collected. Your sensitive personal data will be kept confidential.

How will my privacy and data confidentiality be protected?

Your name and responses will be kept confidential and will not be shared with third parties. Any data which is related to your identification will be stored in an encrypted folder in the researcher’s computer and only accessible by the researcher. Thesis Review Committee may be permitted access to inspect the research records. A restricted version of private information may be reviewed but any data will not be shared with them. Any personal data, your name, and other identifiable information will not be published in the research documents. The collected data will be destroyed within two years after the completion of the research.

What are the benefits of participating in this research?

Regarding the potential benefits of participating in this research, you will be informed about the research outputs and/or implement the research model in your organization.

What are the risks to participate in this research?

There are no foreseeable risks to participate in this research.

What are the responsibilities if I decide to participate in this research?

If you decide to participate in this research, you will be responsible for responding to the questionnaires for validating and quantifying the research model or providing the insights for the case study.

Will I be paid for participating in this research?

There will be no financial compensation for your participation in this research.

Will it cost me money to participate in this research?

There will be no cost for participating in this research.

What if I want to withdraw from participating in this research?

Participation in this research is totally voluntary. You have the right to withdraw from this research at any time, and without affecting your relationship with the researcher or Boğaziçi University.

Who can I contact with questions regarding this research?

If you have any questions, any concerns about this research, you can contact the researcher via the contact addresses given above.

Consent Statement

Your participation in this study indicates that you have read and understood the information provided above. You are not waiving any of your legal rights as a research participant. You have had an opportunity to ask questions and all questions have been answered.

APPENDIX B. INVITATION LETTER

Dear Sir/Madam,

My name is Özgül Ayyıldız and I am a PhD student at Boğaziçi University, at the Institute of Environmental Sciences. My research topic is “a multi perspective technology assessment for the petroleum refining industry”. The main aim of my research is to develop a holistic framework for assessing the best low-carbon energy technology alternatives for the petroleum refining industry in order to achieve emission reduction goals and investigate which criteria have the highest impact on selecting these technologies. The hierarchical decision modelling (HDM) is used as a multi-perspective decision-making tool. The model has five perspectives (social, technical, environmental, economic, and political) and has factors, and sub-factors under each perspective.

This research is being conducted in partial fulfilment of the requirements of a Ph.D. degree under the supervision of Prof. Dr. Tugrul U. Daim from Portland State University and Prof. Dr. Ayşen Erdinçler from Boğaziçi University.

I have investigated a subject matter expert list of low-carbon energy technologies and petroleum refining professionals. I would like to invite you as a potential expert due to your background, remarkable qualifications, and experience in this area. I believe that your participation will make a significant contribution to my research and current state of knowledge in the energy industry. If you accept the invitation to participate in the expert panels, I will send you the web-based survey instruments to ask for your opinion. The estimated time for answering the survey is around 10 minutes.

Attached to this e-mail, you will find the consent form for participation. The consent form explains that your personal information will be kept confidential and will not be shared with any third party and you can withdraw from participation at any time.

I would be honoured if you accepted my invitation and joined the expert panel. I would be glad if you could also suggest other experts in low-carbon energy technologies and the petroleum refining sector as potential panel participants.

Please reply at your earliest convenience with one of the following responses:

[ ] Yes, I will join your Expert Panels

[ ] No, I will not be able to join your Expert Panels

[ ] I suggest the following experts as potential participants for this research

Name:

E-mail address:

I am looking forward to hearing from you soon. Thanks in advance.

Best Regards,
Ozgul Ayyildiz

APPENDIX C. HIERARCHICAL DECISION MODEL SOFTWARE TOOL

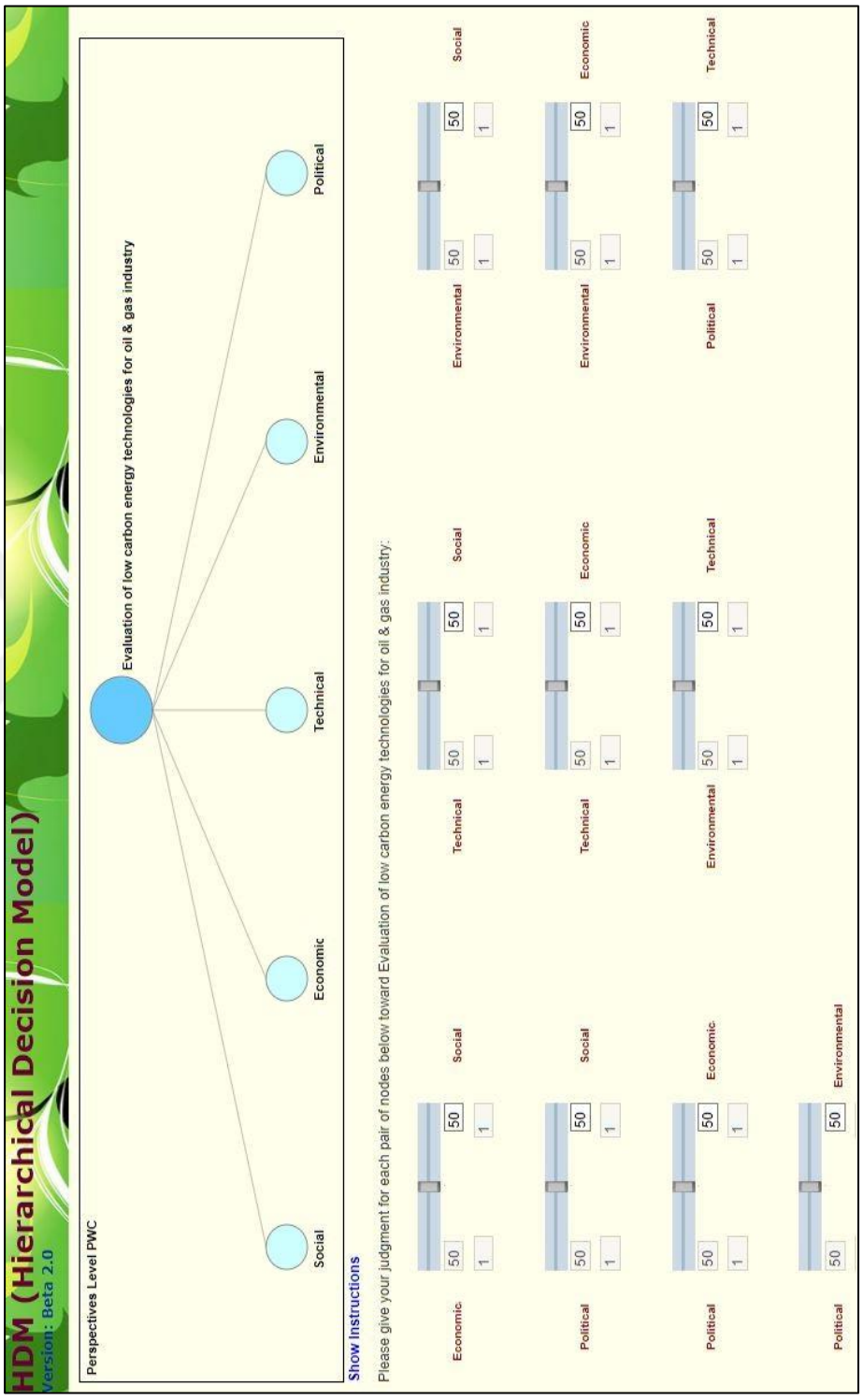

Figure C.1. HDM Software screen for the perspective level of model.

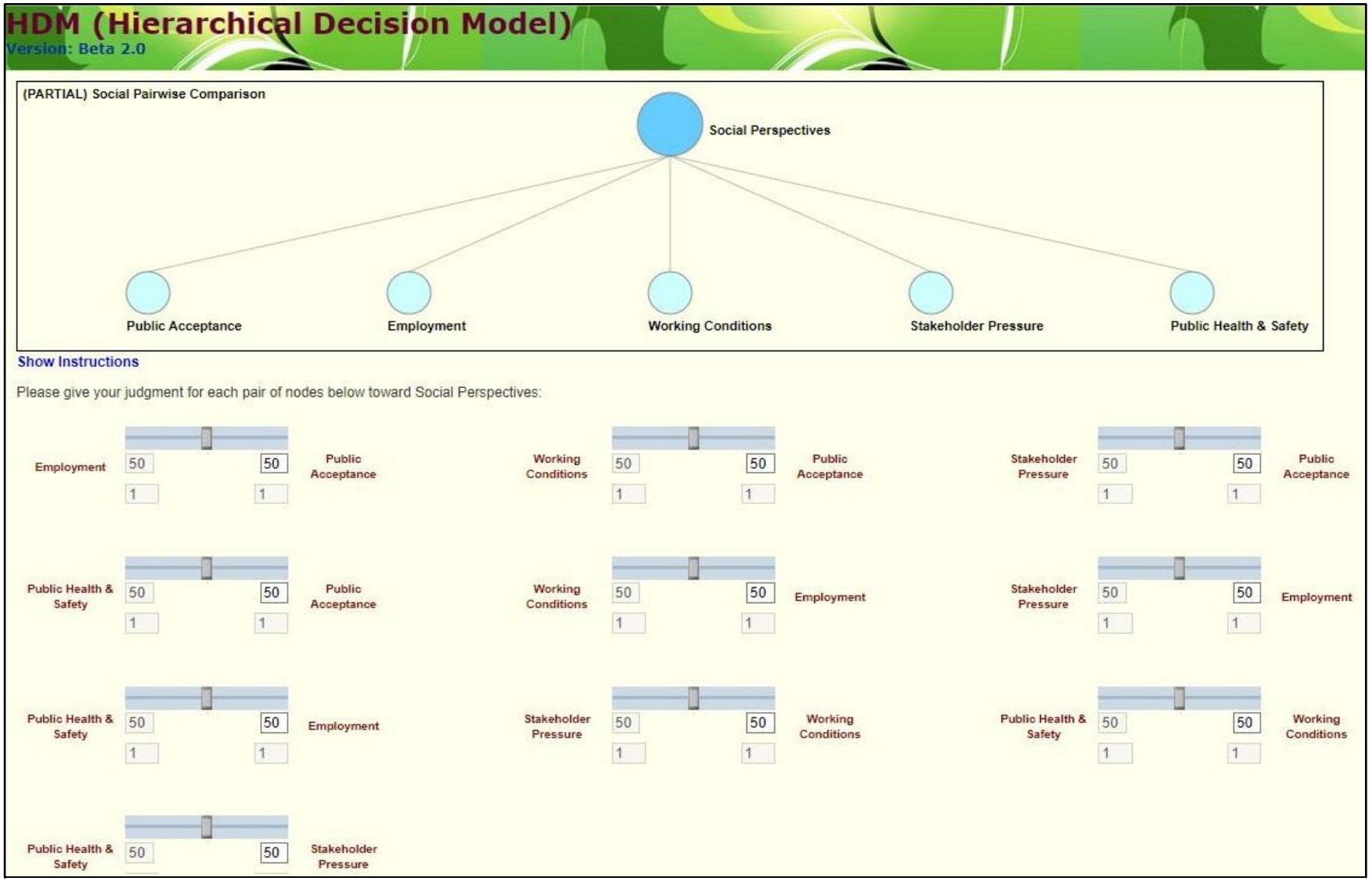

Figure C.3. HDM Software screen for social criteria of model.

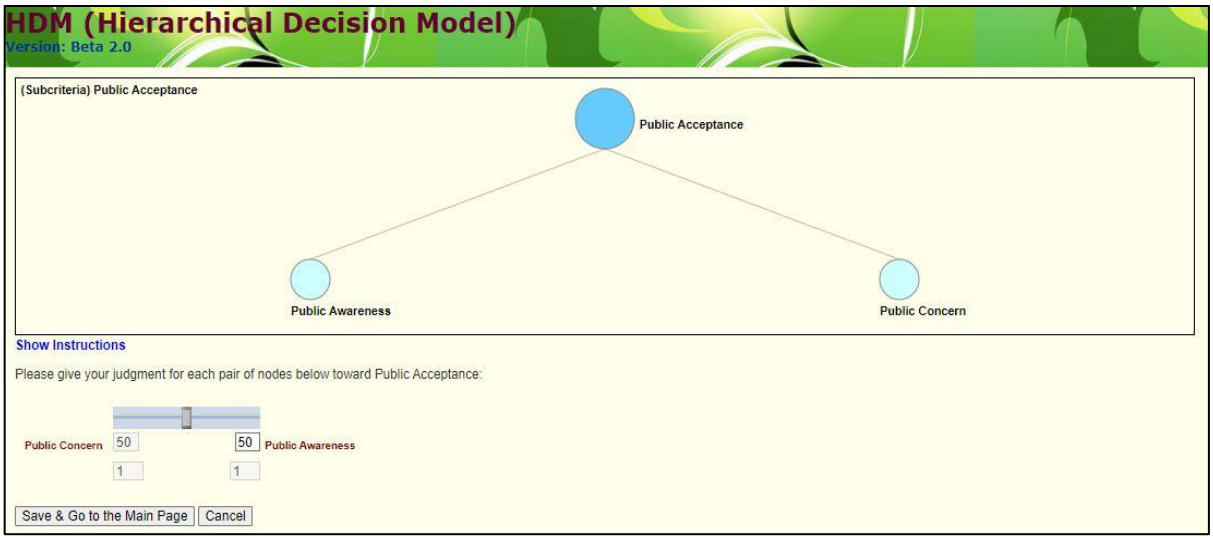

Figure C.5. HDM Software screen for public acceptance sub-criteria of model.

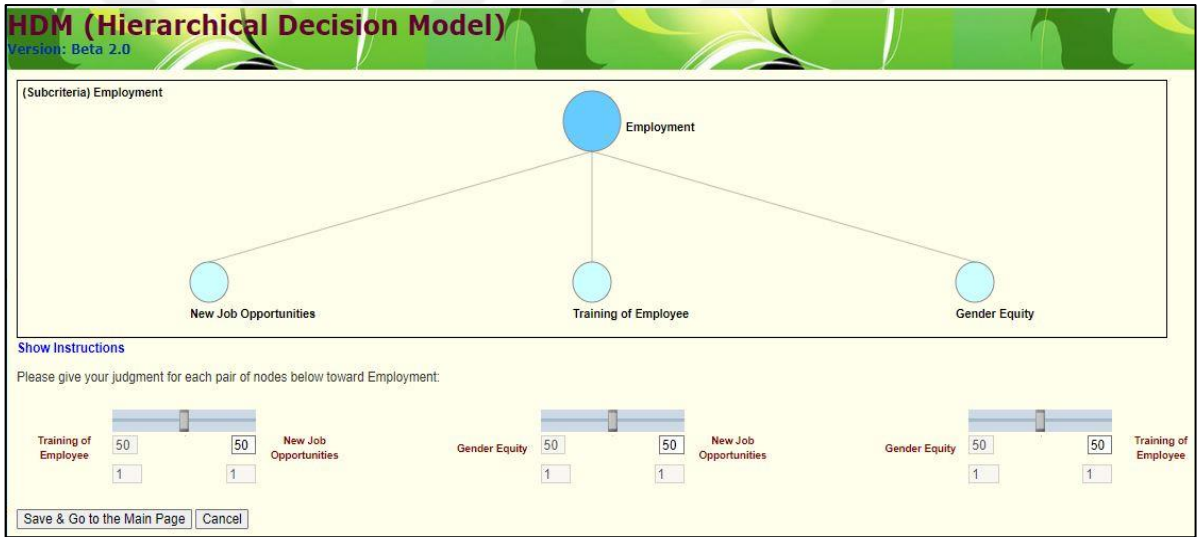

Figure C.6. HDM Software screen for employment sub-criteria of model.

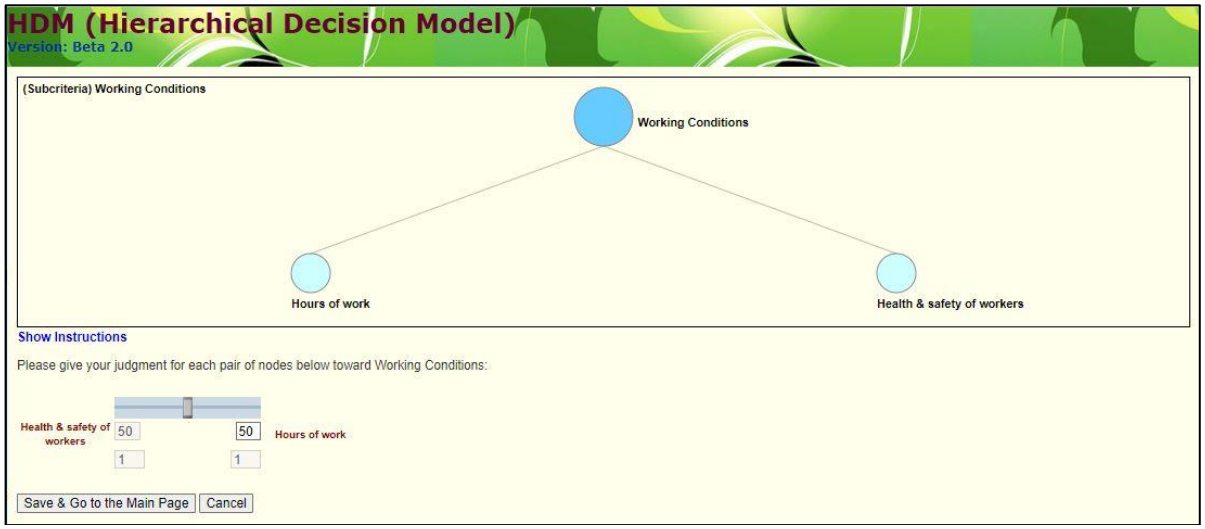

Figure C.7. HDM Software screen for working conditions sub-criteria of model.

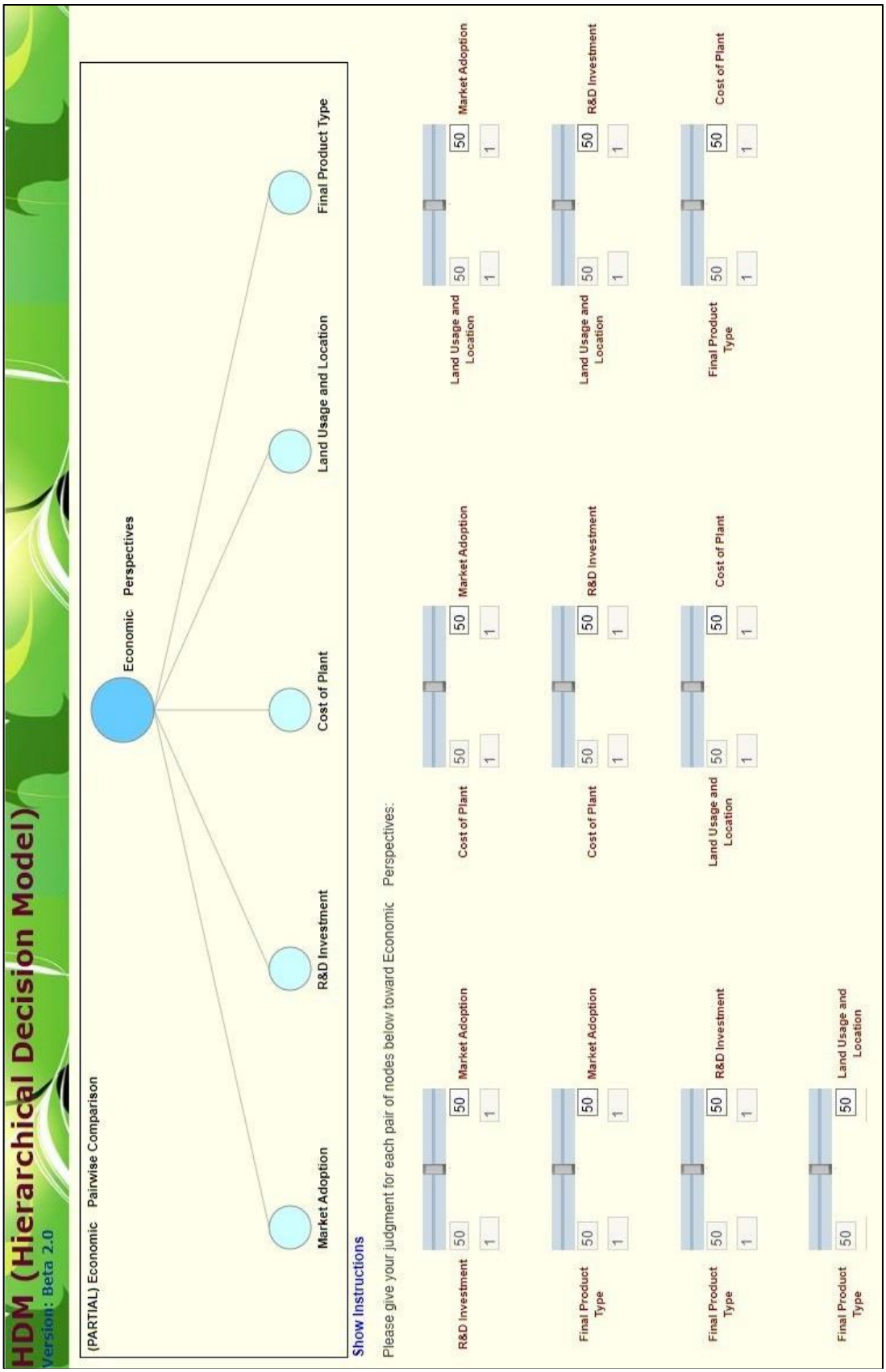

Figure C.8. HDM Software screen for economic criteria of model.

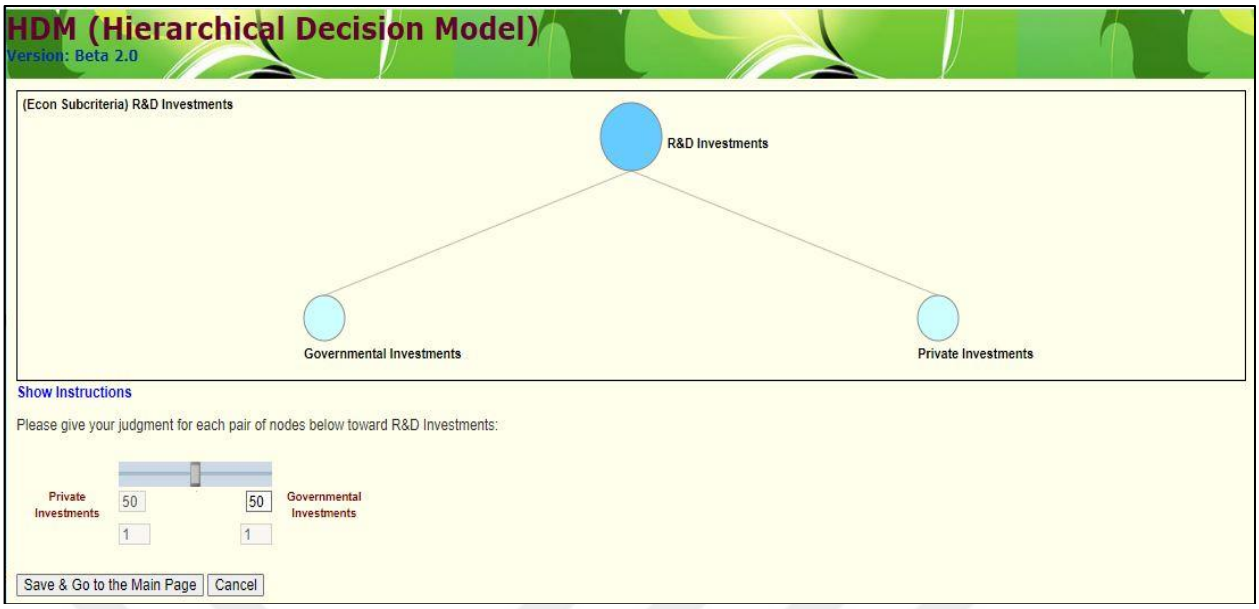

Figure C.10. HDM Software screen for R&D investments sub-criteria of model.

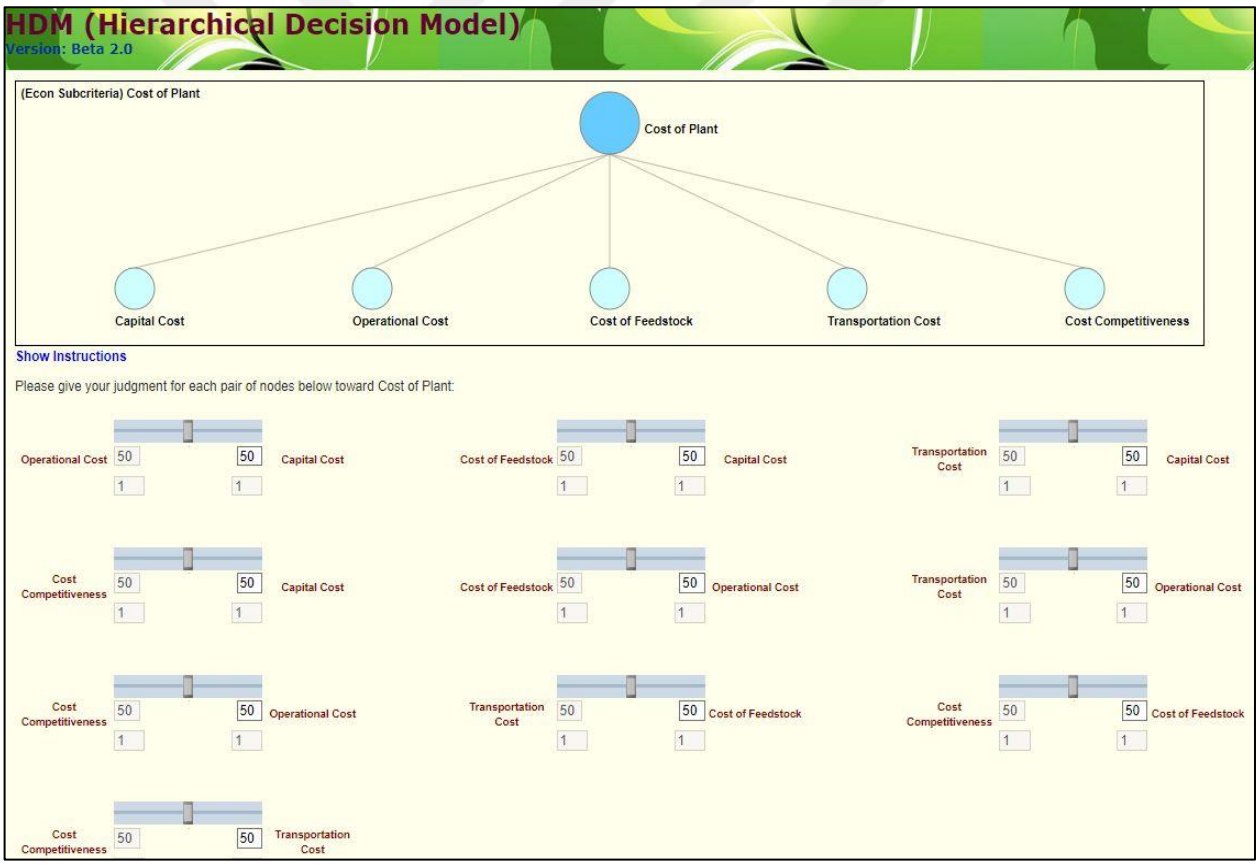

Figure C.11. HDM Software screen for cost of plant sub-criteria of model.

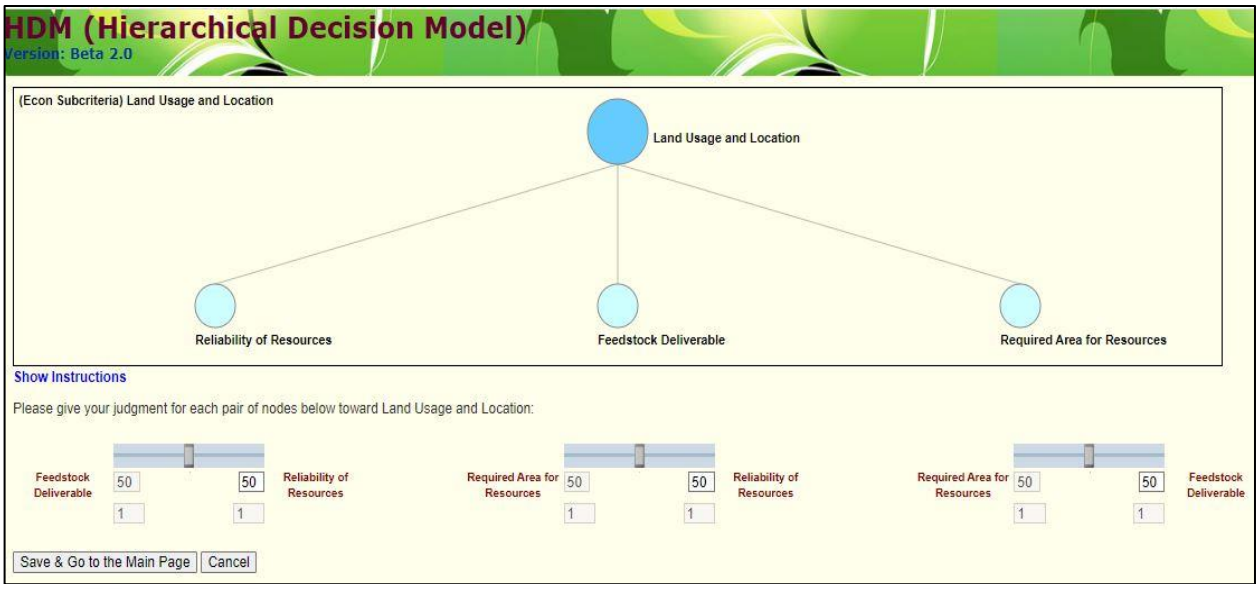

Figure C.12. HDM Software screen for land usage sub-criteria of model.

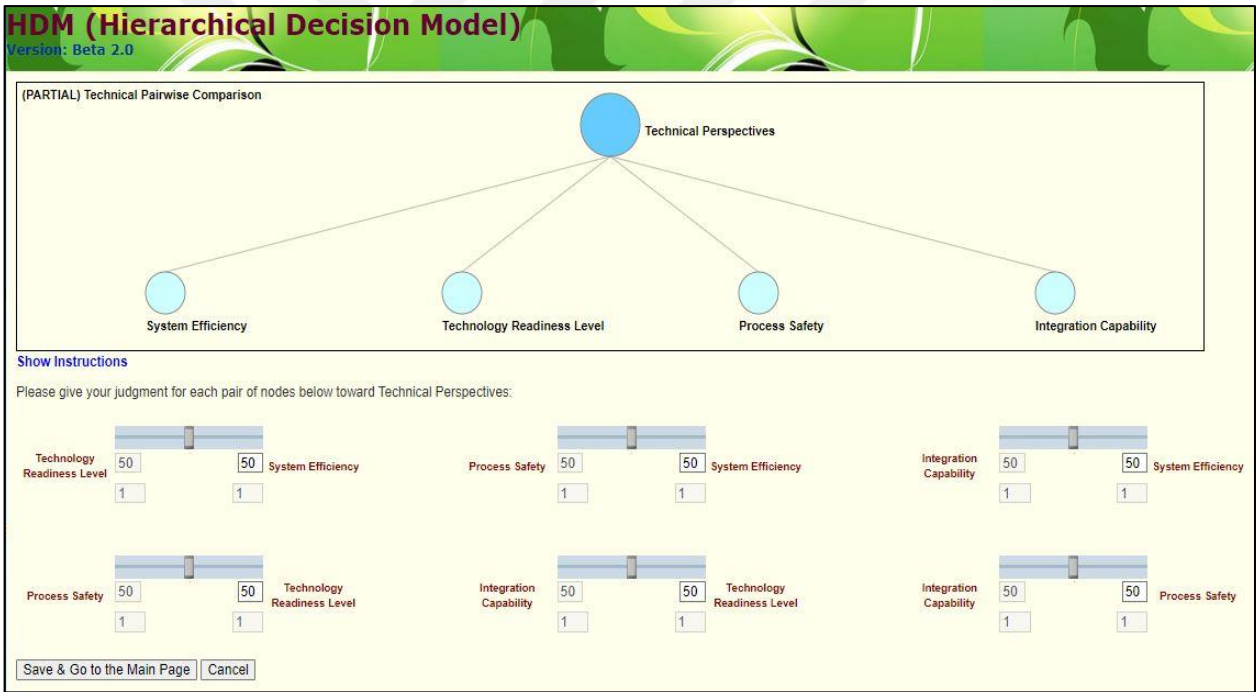

Figure C.13. HDM Software screen for technical criteria of model

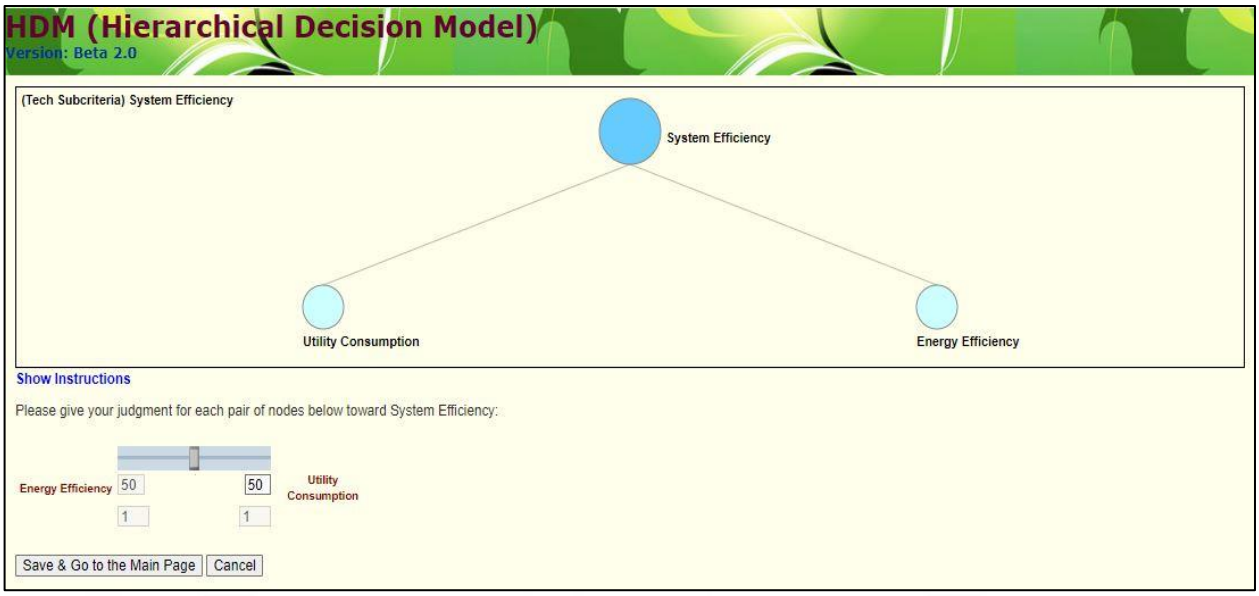

Figure C.14. HDM Software screen for system efficiency sub-criteria of model

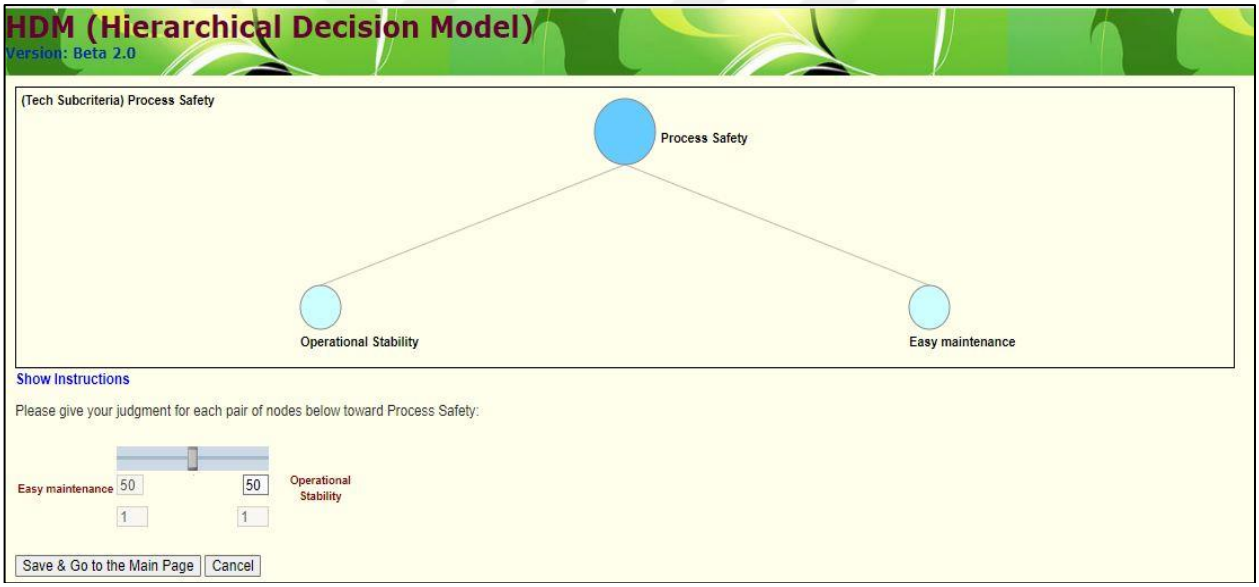

Figure C.15. HDM Software screen for process safety sub-criteria of model

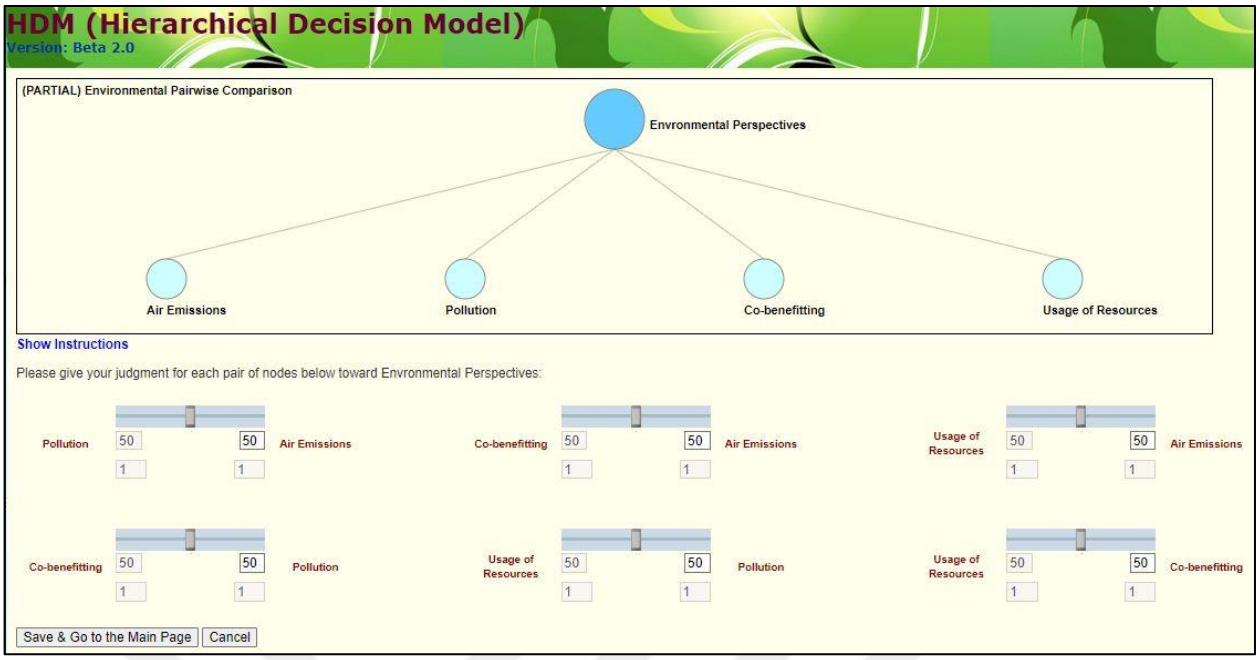

Figure C.16. HDM Software screen for environmental criteria of model

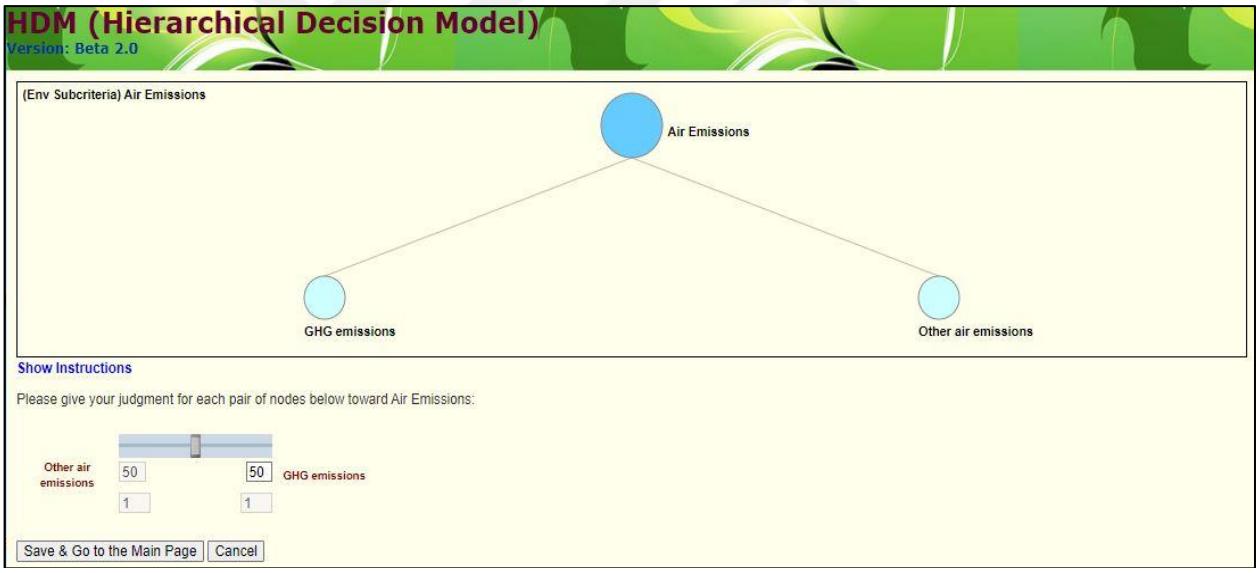

Figure C.17. HDM Software screen for air emissions sub-criteria of model

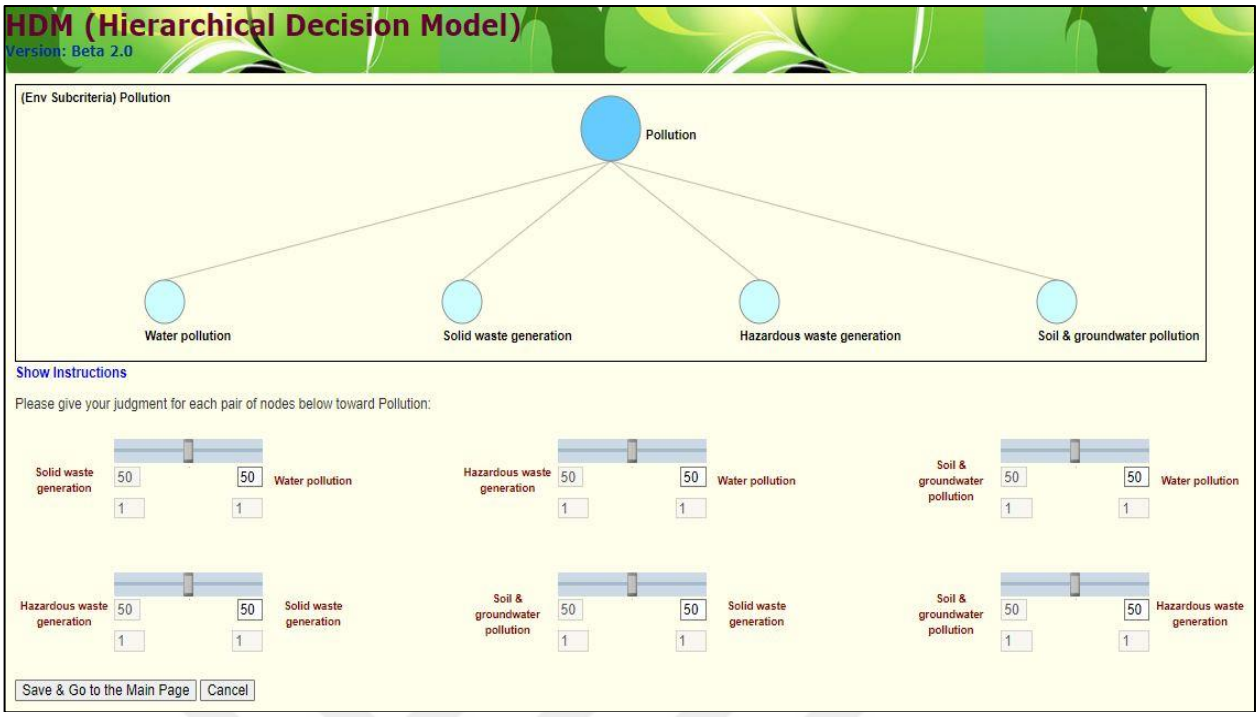

Figure C.18. HDM Software screen for pollution sub-criteria of model

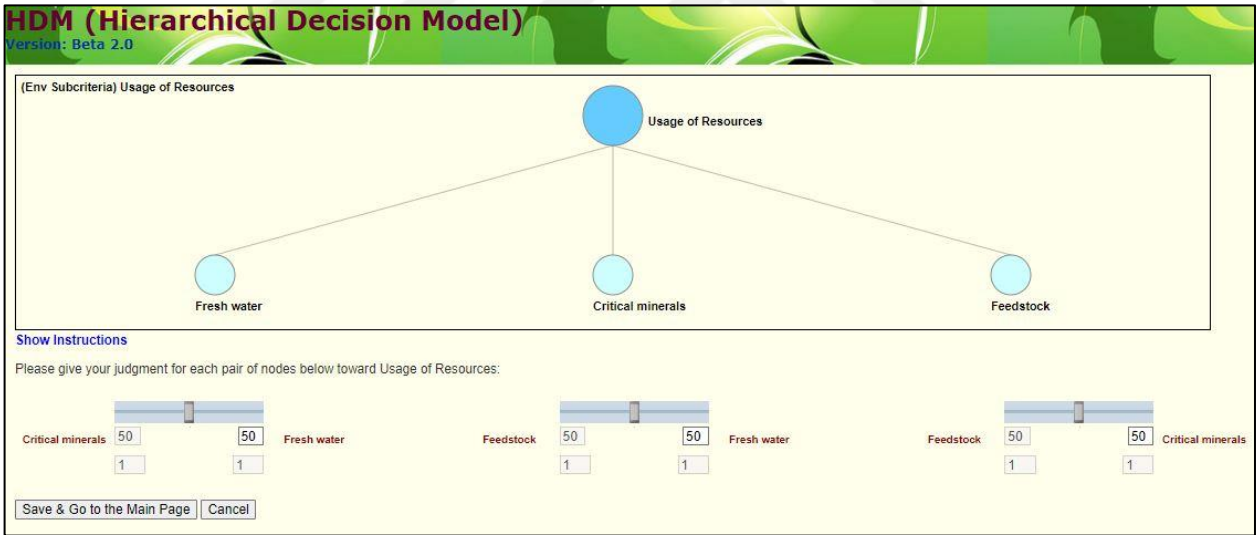

Figure C.19. HDM Software screen for usage of resources sub-criteria of model

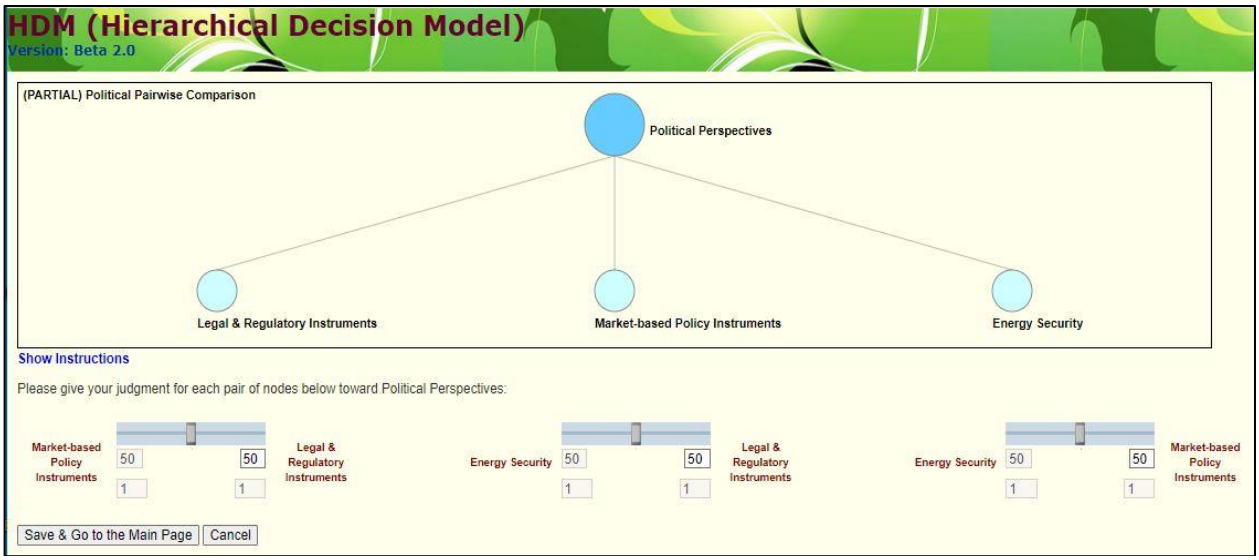

Figure C.20. HDM Software screen for political criteria of model

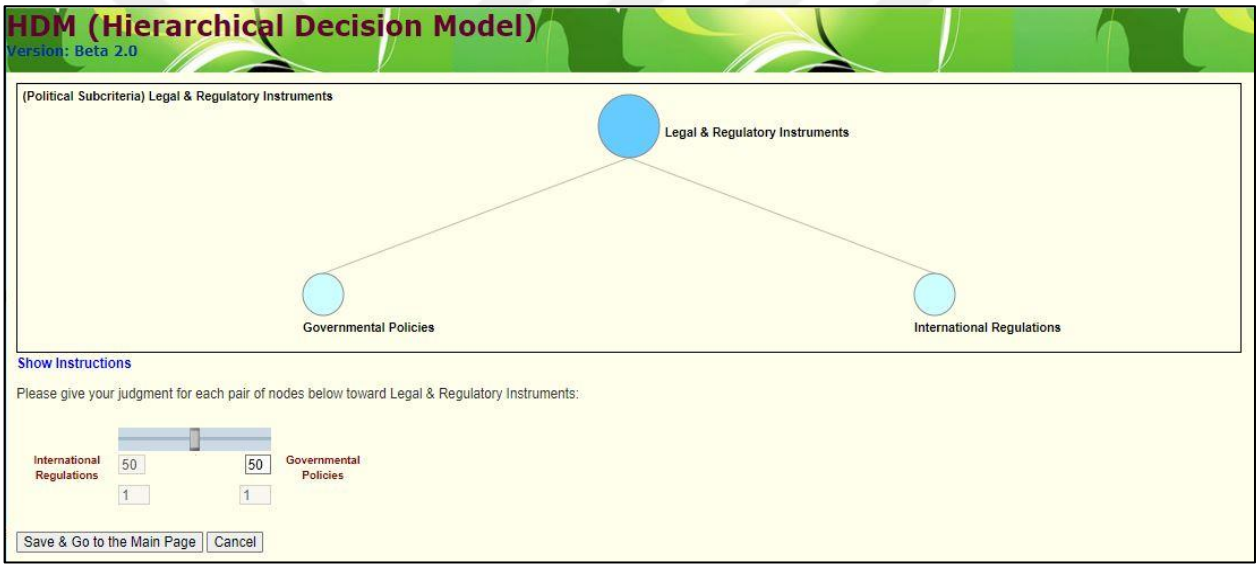

Figure C.21. HDM Software screen for legal instruments sub-criteria of model

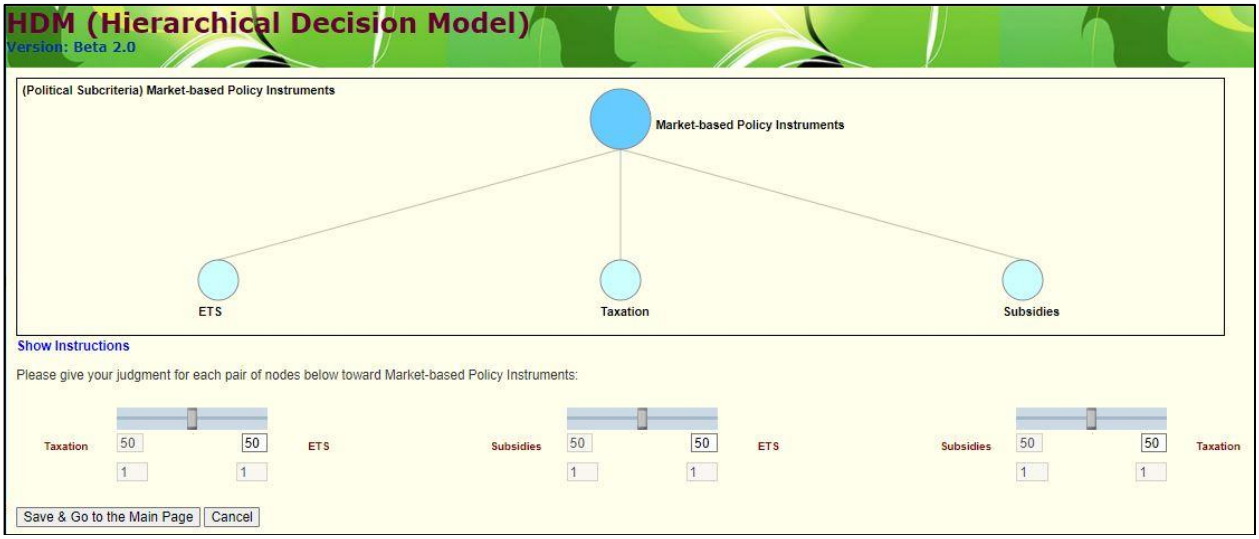

Figure C.22. HDM Software screen for market-based instruments sub-criteria of model

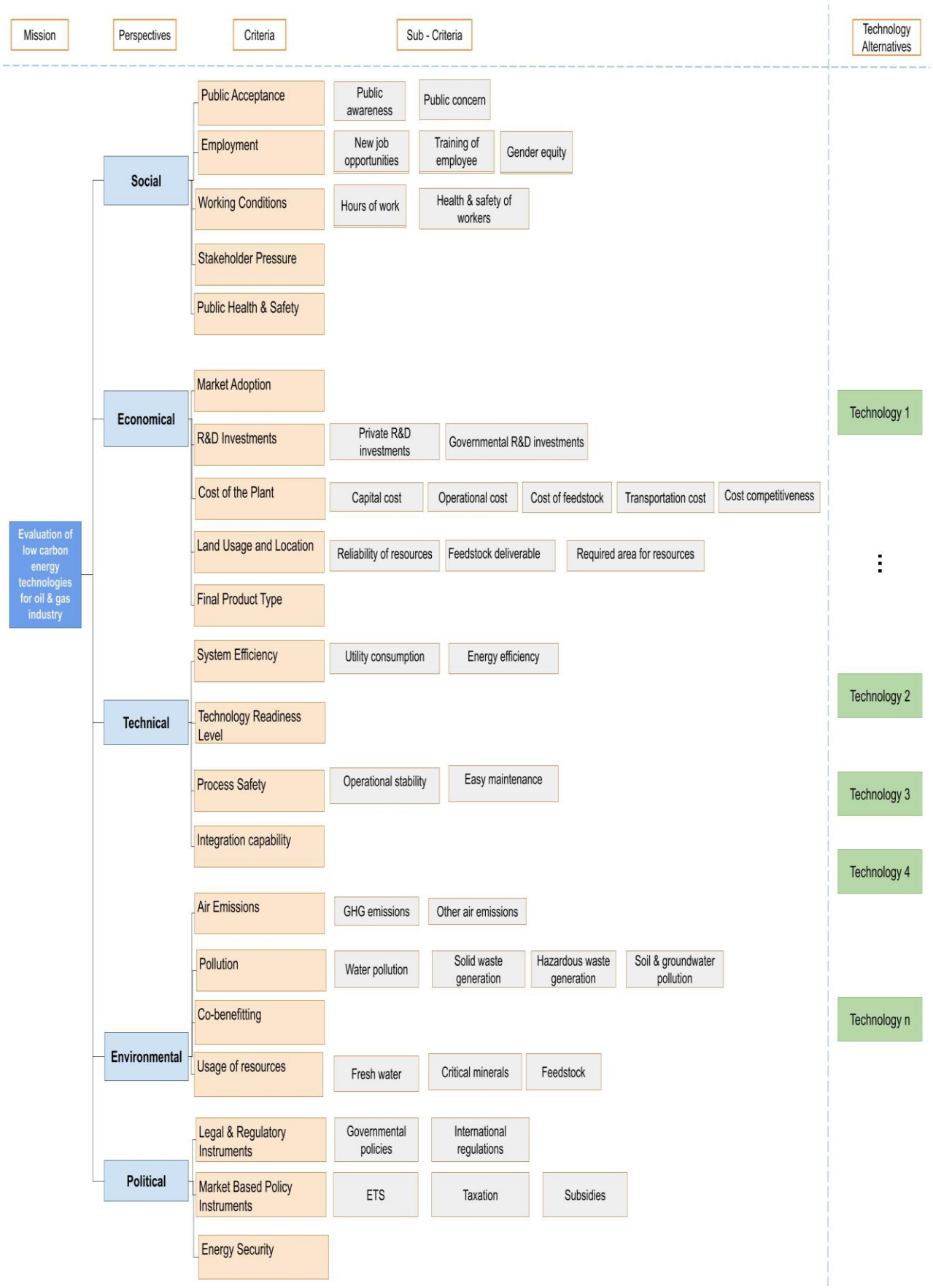

Figure C.23. Model Drawing

APPENDIX D. SAMPLE R CODE FOR HIERARCHICAL CLUSTERING ANALYSIS

```
# Load the data
data <- read.csv("C:/Users/Ozgul/Desktop/LRIs.csv")

# Extract the ratings and standardize the data
X <- data[,2:4]
X_std <- scale(X)

# Compute the pairwise distances
dist <- dist(X_std, method="euclidean")

# Perform hierarchical clustering
hc <- hclust(dist, method="complete")

# Visualize the dendrogram
plot(hc, labels=data$Expert.No.)

# Determine the optimal number of clusters
k <- 4
labels <- cutree(hc, k=k)
print(labels)

# Visualize the dendrogram with identified clusters highlighted in red
plot(hc, labels=data$Expert.No.)
rect.hclust(hc, k =4,border="red")
```