TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Mechanical and Industrial Engineering

FUZZY AHP-TOPSIS BASED DECISION-MAKING APPROACH FOR EVALUATING GREEN ENERGY ALTERNATIVES IN ESTONIA

FUZZY AHP-TOPSIS PÕHINE OTSUSTUSTUSPROTSESS ROHEENERGIA ALTERNATIIVIDE HINDAMISEKS

MASTER THESIS

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Department of Mechanical and Industrial Engineering

THESIS TASK

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Thesis topic:

Fuzzy AHP-TOPSIS Based Decision-Making Approach for Evaluating Green Energy Alternatives in Estonia

Fuzzy Ahp-Topsis Põhine Otsustustusprotsess Roheenergia Alternatiivide Hindamiseks

Thesis main objectives:

1. Ranking the green energy alternatives based on expert opinions
2. Overseeing potential development areas of green energy alternatives
3. Suggesting potential usage ares and applicaple solutions to selected alternatives

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Defining Criterias and the Alternatives	
2.	Creating Expert Surveys and Mathematical Modelling	
3.	Constructing the thesis and revising	

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PREFACE

Renewable energy has emerged as an indispensable solution to prevent the pressing challenges posed by climate change and the surging demand for sustainable energy sources. Against this backdrop, the assessment and identification of fitting green energy alternatives assume an influential role in steering nations towards a future that is both environmentally conscious and sustainable. This undertaking delves deeply into the meticulous evaluation of green energy alternatives in Estonia, with a distinct emphasis on crafting a decision-making approach that ingeniously incorporates the cutting-edge methodologies of Fuzzy Analytical Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS).

The study is noticeable because of this project lies in its solid dedication to crafting a holistic framework that empowers policymakers, energy stakeholders, and decision makers to effectively appraise and prioritize renewable energy options. By skillfully harnessing the competence of Fuzzy AHP and TOPSIS, the approach engenders a methodical and robust evaluation of criteria and alternatives, deftly accounting for the complexities and uncertainties that permeate subjective judgments. Through the deft application of this pioneering approach, the project aspires to deliver invaluable insights that underpin informed decision-making in the realm of green energy.

This preface provides a purposeful foundation for the subsequent chapters, wherein an immersive exploration of the project's comprehensive methodology, evaluation process, and consequential findings shall be undertaken. By synergistically combining expertise in renewable energy, decision analysis, and sustainable development, this project ardently strives to propel the overarching objective of attaining an energy landscape in Estonia that is ecologically sustainable and accustomed to the needs of future generations.

With an trusty commitment to advancing the frontiers of knowledge, author aspires for this project to transcend its role as a mere source of information, and instead serve as an resolute support of enlightenment for researchers, practitioners, and policymakers alike. In doing so, it shall enable them to navigate the complex decision making process of green energy choices, thus catalyzing transformative change and signaling a greener and more sustainable future not just in Estonia, but across the globe.

Keywords: Renewable energy, green energy, Fuzzy AHP, Fuzzy TOPSIS

Abstract

This research introduces an innovative decision-making approach tailored to assess green energy alternatives in Estonia, integrating the Fuzzy Analytical Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). The aim is to establish a robust and discreet framework for evaluating and ranking various renewable energy options. Through meticulous formulation, the criteria and alternatives are intricately defined, incorporating the specific requirements of green energy and informed expert recommendations. The Fuzzy AHP method expertly prioritizes the criteria, effectively addressing the inherent uncertainties and subjectivity associated with decision-making. Subsequently, the Fuzzy TOPSIS method adeptly determines the rankings of the alternatives based on their proximity to the ideal solution, ensuring a well-balanced assessment. The outcome of the evaluation method reveals the most suitable green energy alternative for the given Estonian case study. By providing invaluable insights and facilitating informed decision-making, this novel approach significantly contributes to the advancement of sustainable energy development, propelling Estonia towards a greener and more sustainable future.

1.Introduction

The concept of sustainability is not a modern phenomenon that arose solely in the 20th century. It has been present since the 16th century and has gained significance over time. As stated by Gończ, Skirke, Kleizen, and Barber (Gończ, 2007), sustainability is a notion that predates our common understanding. Historical allusions to sustainability can be traced back to the late 18th century when Thomas Jefferson, an American President, made references to it. Additionally, in the late 19th century, a German Forestry Code emphasized the importance of planting more trees than cutting them down (Gończ, 2007).

However, it was in 1972 that sustainable development gained considerable attention with the release of the first report by the Club of Rome, titled "The Limits to Growth" (Gończ, 2007). The idea became more widely known in 1987 with the publication of the influential report "Our Common Future" by the Brundtland Commission, also known as the World Commission on Environment and Development (Gończ, 2007). The Earth Summit held in 1992 in Rio de Janeiro marked a significant milestone as global leaders convened to address the harmonization of economic development and environmental protection (Gończ, 2007).

As we progressed into the 19th century, witnessing successive industrial revolutions, the importance of sustainable development grew exponentially. Researchers and industry leaders began to focus on various facets of sustainability, encompassing sustainable economies, education, industries, production, and energy. These topics emerged as pivotal areas of exploration for both researchers and industry professionals.

In the present era, adopting environmentally friendly technologies has become imperative for nations worldwide (Yong Qin, 2022). The urgency arises from mounting environmental concerns that intensify with each passing moment. This pressing need stems from an augmented awareness and a collective aspiration to forge a sustainable and enduring future for forthcoming generations (Mohamedazeem M. Mohideen, 2021). Consequently, there has been a surge in demand for sustainable energy sources and a heightened emphasis on manufacturing practices linked to these energy alternatives.

To summarize, sustainability is not a recent notion but rather a concept rooted in history. Presently, nations, industries, and researchers must prioritize sustainability and confront the pressing environmental challenges we confront globally.

The purpose of this study is to thoroughly examine and evaluate the potential areas for development of diverse green energy alternatives in Estonia, guided by the author's unique perspective. To accomplish this objective, a series of meticulous tasks will be carried out, including the careful selection of economic criteria and alternative options, a comprehensive analysis and comparison of these alternatives, and the formulation of preliminary recommendations.

Considerable attention will be given to the thoughtful selection of specific economic criteria and alternative options to ensure a comprehensive evaluation of the potential of green energy solutions in Estonia. Factors such as energy efficiency, environmental impact, technical feasibility, social acceptance, and energy security will be carefully considered during the selection process. The alternatives under evaluation will encompass solar power, wind energy, biomass, geothermal, and hydroelectric power.

A comprehensive analysis and comparison of the selected alternatives will be conducted in a systematic manner. Expert opinions and relevant data will be meticulously incorporated, encompassing both quantitative and qualitative information. Resource availability, cost-effectiveness, energy security, energy production potential, social acceptance, environmental impact, and technological feasibility will be diligently assessed. Through this rigorous analysis, the inherent strengths and weaknesses of each alternative will be methodically explored.

The obtained results will undergo an in-depth examination to identify potential development areas for green energy alternatives in Estonia. Emerging trends, patterns, and opportunities will be meticulously scrutinized. The analysis will encompass the alignment of green energy alternatives with Estonia's energy goals, regulatory frameworks, and societal acceptance. These thorough analyses will serve as the foundation for the author's distinct perspective on the development potential of green energy alternatives in Estonia.

Based on the analysis and interpretation of the results, the author will present their unique viewpoint and preliminary recommendations, aimed at promoting the advancement of green energy alternatives. The vision will encompass strategic recommendations, policy suggestions, and practical approaches, all carefully crafted to foster the growth of sustainable energy sources. Striking a delicate balance between environmental considerations, economic feasibility, and societal benefits will be of paramount importance. Technological advancements, investment opportunities, public awareness, and international best practices will be thoughtfully integrated to shape the author's vision.

In conclusion, this study aims to explore the potential development areas of green energy alternatives in Estonia, underpinned by the author's unique perspective. Through the meticulous selection of economic criteria, comprehensive analysis and comparison of alternatives, and the formulation of preliminary recommendations, this research seeks to make significant contributions towards the advancement of sustainable energy options in Estonia.

2. Green energy

Green energy is a vital energy source, predominantly produced from renewable energy technologies such as solar energy, wind power, geothermal energy, biomass, and hydroelectric power. These technologies function in diverse ways, harnessing power from the sun through solar panels or utilizing wind turbines and water movement to generate energy.

For energy to be classified as green, energy production must not produce pollution like conventional fossil fuels. Subsequently, not all renewable energy sources employed by industry qualify as green. For instance, renewable power generation utilizing organic material from sustainable forests may be renewable. However, it fails to meet the green energy criteria due to combustion-related carbon dioxide emissions.

In contrast to fossil fuel sources like natural gas or coal, which require millions of years to form, green energy sources are typically naturally replenished quickly. Additionally, green energy sources often avoid environmentally damaging mining or drilling operations, thereby mitigating potential harm to ecosystems. Midilli mentions in his research (Midilli, (2006)) examining the relations between green energy sources and sustainability makes it clear that green technology is directly related to sustainable development. Adding to this point Midilli (Midilli, (2006)) adds three reasons why green energy makes a direct impact on sustainable development.

Green energy sources typically have a lower environmental impact than conventional ones, making them a more sustainable choice. (Midilli, (2006)) The wide variety of available green energy resources offers various options for their utilization in different sectors. (Midilli, (2006)) One significant advantage of green energy is its inherent non-depletable nature. When utilized thoughtfully and in inappropriate applications, these resources can provide a reliable and sustainable energy supply indefinitely. (Midilli, (2006)) This characteristic ensures long-term energy security and alleviates concerns related to resource depletion. (Midilli, (2006)) Furthermore, green energy resources promote system decentralization and encourage localized solutions that operate independently, to some extent, separate from the national energy grid. (Midilli, (2006)) This decentralization enhances overall system flexibility and benefits small, isolated communities economically. Additionally, using smaller-scale green energy equipment often results in shorter development cycles, from initial design to operational deployment. (Midilli, (2006)) This aspect provides greater adaptability in responding to unpredictable growth and changes in energy demand enabling efficient adjustments within the dynamic energy sector. (Midilli, (2006)).

Considering green energy and green energy sources is important part of the general sustainable development processes its important look these sources also separately and examine how they work.

2.1. Wind Energy

Wind energy refers to the utilization of wind force as a source of energy. This is achieved through the operation of wind turbines, which convert the kinetic energy present in air currents into electrical energy. The core components responsible for this conversion process include the rotor, which converts the kinetic energy into mechanical energy, and the generator, which subsequently transforms the mechanical energy into electrical energy. Wind energy holds significant importance as a renewable, efficient, and well-established energy source, playing a crucial role in facilitating the ongoing energy transition and the imperative task of decarbonizing the economy.

Konstantinidis also explains wind energy in his research that he released in 2016; Wind power, i.e., the kinetic energy of the wind, is a renewable energy source that is used among others mainly to produce electrical power. The global wind resources (land and near-shore) are estimated to be 72 TW which is seven times the world’s electricity demand and five times the world’s energy demand. (Konstantinidis, 2016)

2.2. Solar Energy

Solar power refers to the utilization of energy derived from the sun, which can be converted into thermal or electrical energy. Solar technologies have the capability to capitalize on this rich energy source for various purposes, such as electricity generation, lighting, ensuring comfortable indoor environments, and heating water for residential, commercial, or industrial applications. Notably, solar energy exhibits remarkable versatility as an energy technology. It can be implemented in two different forms: distributed generation, where solar installations are located at or near the point of consumption, or centralized utility-scale solar power plants, resembling traditional power plants. This adaptability enables solar energy to accommodate different scales and locations, catering to diverse energy needs and facilitating a sustainable and resilient energy infrastructure. In different articles about solar energy, it mentions that the sun can produce three different types of solar energy.

These are,

- Heat from the sun's rays,
- Power from the sunlight (Biçen, 2018) and
- The power provided by air and water movement caused by the effect of the sun (Bedeloglu A., 2010).

2.3. Hydrogen Energy

Hydrogen is clean alternative for natural gas(methane) also hydrogen is existing in very large quantities in the world being approximately 75% of the earth. (https://www.nationalgrid.com/, 2023).

When natural gas is combusted, it generates heat energy, but it also produces carbon dioxide as a byproduct, which, when released into the atmosphere, contributes to climate change. In contrast, burning hydrogen as a fuel does not emit carbon dioxide, making it a cleaner and more environmentally friendly alternative.

2.4. Biomass Energy

Biomass energy is a renewable energy source that harnesses organic materials derived from plants, animals, and other biological sources for various energy applications (Hansen, 2018). It involves the conversion of biomass through distinct processes to generate heat, produce electricity, or create fuel (McKendry, 2002). The organic matter utilized in biomass energy encompasses agricultural residues, forestry residues, dedicated energy crops, and organic waste materials (Ragauskas, 2006). These biomass feedstocks undergo different conversion techniques to release their energy content effectively (Demirbas, 2011).

Direct combustion represents a common method wherein biomass is combusted to generate heat for space heating, water heating, or industrial purposes (Hansen, 2018). Anaerobic digestion, an alternative approach, involves the decomposition of organic matter in the absence of oxygen, leading to the production of biogas rich in methane that can be utilized for thermal energy, electricity generation, or as a fuel source (McKendry, 2002). One noteworthy advantage of biomass energy lies in its potential to mitigate greenhouse gas emissions and combat climate change (Ragauskas, 2006). Although biomass combustion emits carbon dioxide, it is considered carbon neutral as the carbon released during combustion is offset by the carbon absorbed during biomass growth (Sikkema, 2019).

Furthermore, biomass energy presents opportunities for effective waste management and resource utilization (Hansen, 2018). By employing agricultural residues, forestry residues, and organic waste as feedstocks, biomass energy systems can divert these materials from landfills, contributing to more sustainable waste management practices (Sikkema, 2019). However, it is crucial to ensure the sustainable sourcing of biomass feedstocks, considering considerations such as land use, biodiversity, and local ecosystems (Demirbas, 2011). Thoughtful planning and management strategies are necessary to ensure that biomass resources are harvested and utilized in a manner that aligns with social, economic, and environmental sustainability objectives (Hansen, 2018).

2.5. Hydropower Energy

Hydropower energy, also referred to as hydroelectric power, constitutes a renewable energy form that harnesses the kinetic and potential energy inherent in flowing water to generate electricity (Munoz-Hernandez, 2020) (IPCC, 2011). It stands as one of the earliest and most widely adopted sources of renewable energy worldwide.

The process of hydropower generation involves the construction of dams or diversion structures to regulate water flow in rivers or streams, consequently establishing a reservoir or elevated water head (Porse, 2018). Upon release from the reservoir, water passes through turbines, thereby initiating rotational motion. These turbines are mechanically connected to generators, which effectuate the conversion of mechanical energy into electrical energy (Bragg-Sitton, 2014). Subsequently, the electricity generated is transmitted through power lines to residential, commercial, and industrial consumers.

Various types of hydropower systems exist, each characterized by distinct attributes. Storage hydropower, commonly known as reservoir hydropower, entails the construction of substantial dams to create water reservoirs. During periods of heightened electricity demand, water is discharged from the reservoir, passing through the turbines to generate electricity. Conversely, run-of-river hydropower systems operate without the necessity of reservoirs, leveraging the natural flow of rivers or streams to facilitate electricity generation. Another variant, pumped storage hydropower, involves the cyclic transfer of water between a lower reservoir and an upper reservoir. During periods of low electricity demand, water is pumped to the upper reservoir, subsequently being released to the lower reservoir to generate electricity during peak demand periods (Lehner, 2011).

A primary advantage of hydropower lies in its ability to offer a consistent and dependable electricity supply. Unlike solar or wind power, which are contingent upon weather conditions, hydropower operates continuously, provided an adequate water supply is available (Sadorsky, 2014).

Moreover, hydropower represents a clean and environmentally sustainable energy source, devoid of greenhouse gas emissions during operational phases. Consequently, hydropower contributes significantly to carbon emission reduction and serves as a mitigation measure against climate change (Scherer, 2020)

However, it is important to recognize that the construction of large dams for hydropower projects can impart substantial environmental and societal consequences. Ecosystem alterations, community displacement, and disruption of natural habitats are among the potential repercussions (Dams, 2000). Thus, meticulous planning, comprehensive environmental assessments, and inclusive stakeholder engagement are indispensable in ensuring the sustainable and responsible development of hydropower initiatives.

Collectively, hydropower energy assumes a prominent role in the global transition towards renewable energy sources. Its capacity to generate clean, reliable, and abundant electricity renders it a pivotal contributor to energy portfolio diversification and the gradual phasing out of fossil fuel dependence.

2.6. Geothermal Energy

Geothermal energy, a remarkable and renewable energy source, stems from the vast reservoirs of natural heat concealed within the Earth's crust (Tester, 2006). This fascinating form of energy taps into the remarkable thermal energy generated by the gradual decay of radioactive elements and the lingering heat from the planet's primal formation, delivering an unyielding and sustainable power supply.

The extraction of geothermal energy necessitates delving into geothermal reservoirs, which are clandestine chambers permeated by scorching water and steam, where temperatures soar to remarkable heights (DiPippo, 2012). Drilling deep wells enables the capture of pressurized fluids, which are subsequently propelled to the surface. This captivating process culminates in the conversion of harnessed heat energy into readily exploitable electricity via ingenious geothermal power plants.

Geothermal power plants embody a diverse range of sophisticated technologies crafted to metamorphose thermal energy into a formidable electrical force. A preeminent method involves harnessing high-pressure steam extracted from the geothermal reservoirs to power steam turbines, vigorously propelling them into motion and igniting the generation of electricity. Alternatively, binary cycle power plants ingeniously exploit the thermal vigor of the geothermal fluid to heat a secondary liquid boasting a lower boiling point. This masterfully orchestrated interplay induces the secondary fluid to vaporize, propelling a turbine and heralding the advent of electricity (Lund, 2011).

The allure of geothermal energy extends far beyond its capacity for electricity generation. A stellar hallmark lies in its ability to operate as a low-carbon emissary, exhibiting minimal greenhouse gas emissions in stark contrast to the conventional realms of fossil fuel-powered electricity (Cotter E. S., 2019). Furthermore, geothermal power plants command a comparatively modest spatial footprint, curbing the potential environmental ramifications that afflict other conventional power installations (Cotter E. S., 2019)

Beyond the realm of electricity generation, geothermal energy unfurls its captivating applications in the realm of direct use systems, wherein the captivating yet temperate geothermal resources facilitate space heating and cooling endeavors across diverse sectors. Geothermal heat pumps assume center stage, adroitly extracting heat from the Earth's embrace during chilly months, thereby providing cozy warmth, and orchestrating a symphony of cooling respite during sweltering spells. These ingenious heat pumps unfailingly deliver energy-efficient, economical, and sustainable solutions for heating and cooling requirements (Hughes, 2018).

Nevertheless, the availability of geothermal resources is spatially delimited, necessitating comprehensive geological explorations, intricate resource characterization, and meticulous assessment of subsurface fluid properties to pinpoint viable sites for optimal energy extraction (Árnason, 2017).

To conclude, geothermal energy stands as an invaluable and sustainable treasure trove of renewable energy. Its adept harnessing of the Earth's abundant natural heat reservoirs bestows an unwavering and steadfast power supply, while simultaneously mitigating environmental repercussions. The trajectory of geothermal energy is poised for remarkable growth, as ceaseless technological advancements and fervent exploration endeavors hold the key to unlocking its boundless potential, ultimately catalyzing a paradigm shift toward a cleaner, greener, and unequivocally sustainable energy landscape.

2.7. Green Energy in Estonia

Estonia, an integral constituent of the European Union, is embarking on a transformative journey in its energy sector, diminishing reliance on oil shale and embracing renewable energy sources (Holttinen, 2019). This chapter presents the diversifying renewable energy resources in Estonia, their consumption, and their applications across diverse sectors.

2.7.1. Categorization of Green Energy Sources in Estonia

Estonia’s renewable energy arsenal comprises predominantly of wind energy, biomass, and solar energy.

Wind Energy:

Estonia’s coastal regions and islands proffer significant wind potential, catalyzing the evolution of wind energy as an indispensable component of the nation’s renewable energy matrix (Estonian Wind Power Association, 2020). The proliferation of wind farms across the country attests to this trend (Holttinen, 2019).

Biomass Energy:

Biomass, specifically wood chips, and pellets, plays a significant role in Estonia’s renewable energy production. The country’s extensive forest coverage furnishes a sustainable source for biomass energy (Kikas, 2017). Adherence to responsible forestry practices is paramount for maintaining the sustainability of this source (Kikas, 2017).

Solar Energy:

Despite geographical limitations leading to limited solar exposure, solar energy has emerged as a feasible and sustainable energy source. The growing installations of photovoltaic panels, especially in residential areas, indicate this trend (Melliger, 2018).

Hydrogen Energy:

There is a growing interest in hydrogen as an energy carrier, and many countries worldwide are actively researching and developing this area. They are also investing in hydrogen technologies and infrastructure through government initiatives and partnerships with private companies (IEA, 2021)

Research suggests that hydrogen can help reduce carbon emissions in sectors like transportation and industry, where relying solely on electricity may not be enough (Piia Viks-Binsol (Civitta), 2022). Hydrogen's ability to scale up and adapt to various energy needs makes it a valuable resource for achieving a sustainable energy future.

2.7.2. Consumption Patterns of Green Energy in Estonia

Renewable energy consumption in Estonia spans several sectors, including electricity generation, heating, and transportation.

Electricity Generation

Wind energy contributes significantly to electricity production in Estonia due to the augmented capacity of wind farms (Holttinen, 2019). Solar power, although less dominant, contributes to the national electricity grid (Melliger, 2018).

Heating

Biomass, particularly in the form of wood chips and pellets, is extensively utilized for district and residential heating (Kikas, 2017). The transition from oil shale to biomass for heating purposes marks a tangible reduction in the country’s carbon footprint (Kikas, 2017).

Transportation

Estonia is progressively transitioning towards renewable energy in the transportation sector, especially electric vehicles (EVs), consistent with global trends (Kester, 2018). The country’s efforts to expand the EV charging infrastructure further validates this shift (Kester et al., 2018).

Energy Efficiency Patterns in Estonia

According to research has been done by Statistics Estonia, country has become more and more independent in terms of energy adding to this point energy production from renewable sources is keep increasing yearly.

Detailed information can be seen Figure 1 below that has been generated by Statistics Estonia. (Statistics Estonia, 2023).

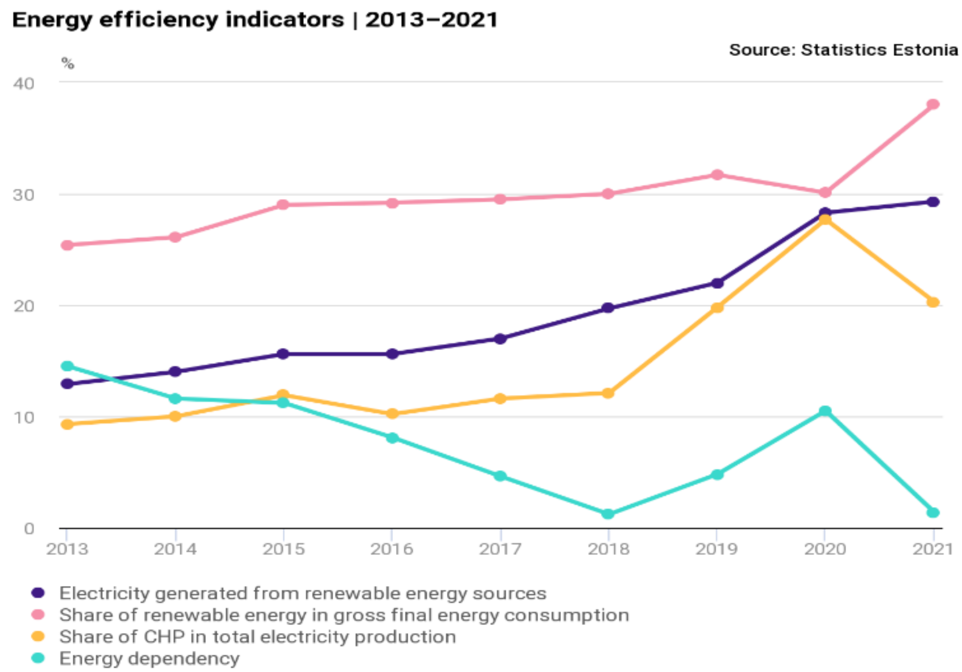

Figure 1 - Energy efficiency indicators in Estonia

2.7.3. Industrial Applications of Green Energy in Estonia

Estonia's renewable energy sources are being innovatively applied to foster environmental sustainability and stimulate economic growth. For instance, wind energy is being utilized in water desalination processes, offering a sustainable solution to regional water scarcity issues (Aghahosseini, 2020). Solar power is being integrated into smart grid systems, thereby enhancing energy efficiency and grid reliability (Melliger, 2018). Biomass energy is used in the production of biofuel, contributing to sustainable waste management (Kikas, 2017).

Estonia's transition towards a green energy economy underscores the country's commitment to mitigating climate change and promoting sustainable development (Holttinen, 2019). However, this transition necessitates continuous investments in technology, infrastructure, and policy development to ensure sustainable and efficient utilization of these renewable energy sources.

3.Methodology

In this study, an innovative and intricate integrated fuzzy MCDM (Multi-Criteria Decision Making) framework is set to effectively prioritize various alternatives for renewable energy specifically tailored to the geographical context of Estonia. The proposed model entails a synergistic amalgamation of two advanced methodologies, namely fuzzy AHP (Analytic Hierarchy Process) and fuzzy TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution), creating a sophisticated and sophisticated decision-making approach.

3.1 Multi-Criteria Decision Making (MCDM)

Multi-Criteria Decision Making (MCDM) is an essential approach that enables decision-makers to consider and evaluate multiple criteria when making complex decisions. MCDM plays a critical role in addressing intricate decision problems across diverse domains, assisting in the assessment of alternatives based on multiple factors and objectives ((Belton, 2002; Chan, 2008)

MCDM poses inherent challenges, including managing conflicting criteria, handling uncertainties, and accounting for subjective preferences. These challenges necessitate sophisticated techniques to effectively analyze and synthesize diverse criteria, facilitating informed decision-making (Roy, 1996) (Zanakis, 1998)

3.2. Fuzzy MCDM

The first exploration into FAHP was conducted by Van Laarhoven and Pedrycz (Laarhoven, 1983). They conducted a comparative analysis of fuzzy ratios using triangular membership functions. Buckley (Buckley, 1985), on the other hand, examined comparison ratios but opted for the utilization of trapezoidal membership functions.

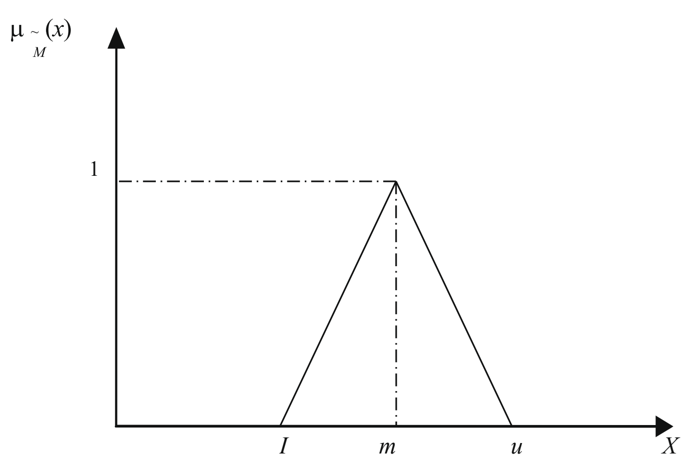

Figure 2 Triangular Membership Function

Linguistic scale for importance	Triangular **fuzzy** scale	Triangular fuzzy reciprocal scale
Equal	(1, 1, 1)	(1, 1, 1)
Moderate	(2/3, 1, 3/2)	(2/3, 1, 3/2)
Strong	(1, 3/2, 2)	(1/2, 2/3, 1)
Very strong	(3/2, 2, 5/2)	(2/5, 1/2, 2/3)
Extremely preferred	(5/2, 3, 7/2)	(2/7, 1/3, 2/5)

Table 1 Triangular fuzzy conversion scale

In a pioneering study conducted by Stam, Minghe, and Haines in 1996 (Antonie Stam, 1996), they unveiled the groundbreaking implementation of artificial intelligence techniques to determine preference ratings within the analytic hierarchy method. This study pushed the boundaries of conventional decision-making processes, showcasing the vast potential of advanced technologies to optimize and streamline preference evaluation. (Neşe Yalçın Seçme, 2009)

An important contribution was made by (Chang, 1996)), who introduced the extent analysis method. This innovative approach involved leveraging triangular fuzzy numbers to facilitate pair-wise comparisons. By integrating principles of fuzzy logic, which adeptly accommodate uncertainty and ambiguity, Chang aimed to enhance the flexibility and precision of decision-making.

The following year witnessed Chang's proposal of an algorithm meticulously tailored for assessing tactical missile systems using fuzzy AHP. By harnessing the power of fuzzy logic, this algorithm facilitated a comprehensive and nuanced evaluation of complex systems, adeptly considering multiple interconnected factors. (Chang, 1996))

In 1998, Kahraman, Ulukan, and Tolga put forth a fuzzy objective and subjective method based on fuzzy AHP. This method ingeniously combined quantitative and qualitative evaluations, leveraging the inherent advantages of fuzzy logic to capture the multifaceted nature of decision-making. (Cengiz Kahraman E. T., 2000)

Deng's seminal work in 1999 focused on multiple criteria analysis with fuzzy pairwise comparisons, expertly incorporating qualitative assessments. By assigning fuzzy values to pairwise comparisons, this approach adeptly accounted for the subjective nature of evaluations, providing a structured framework for decision-making. (Deng, 1999)

Lee, Pham, and Zhang's 1999 revision of the core principles underlying AHP introduced a novel methodology grounded in stochastic optimization. This visionary approach aimed to ensure global coherence while accommodating the inherent fuzziness and uncertainty of the comparison process, offering decision-makers a robust toolset for decision-making under complex circumstances. (Mindy Lee, 1999)

Cheng, Yang, and Hwang's 1999 utilization of AHP with linguistic variable intervals enabled the assessment of weapon systems. By incorporating linguistic variables, this method provided decision-makers with an intuitive means of expressing preferences, facilitating a comprehensive and user-friendly evaluation process. (Ching-Hsue Cheng, 1999)

Leung and Cao's 2000 contribution introduced a refined definition of fuzzy coherence, ingeniously accounting for tolerance deviations within the realm of fuzzy AHP. This enhanced definition aimed to elevate the consistency and reliability of decision-making processes by adroitly considering imprecision and uncertainties associated with fuzzy sets. (L.C. Leung, 2000)

The application of fuzzy AHP extended to diverse domains. In 2003 and 2004, Kahraman and colleagues explored the application of fuzzy AHP to solve complex facility location problems and conduct comprehensive multiple criteria comparisons of catering companies, respectively. These groundbreaking studies showcased the versatility and effectiveness of fuzzy AHP in addressing intricate decision-making challenges across industries. (Cengiz Kahraman D. R., 2003) (Cengiz Kahraman U. C., 2004)

Kulak and Kahraman's 2005 study focused on selecting transportation companies using a combination of fuzzy axiomatic design and fuzzy AHP, comparing the results with a fuzzy multi-attribute axiomatic design approach. This meticulous research provided insights into different decision-making frameworks, enriching the existing knowledge base with valuable findings. (Osman Kulak, 2005)

Wang, Chu, and Wu's 2007 research delved into the selection of optimum maintenance strategies for various machineries using fuzzy AHP. By evaluating different strategies, decision-makers could make well-informed maintenance decisions tailored to specific requirements, enhancing overall efficiency. (Ling Wang, 2007)

In 2009, Ertuğrul and Karakaşoğlu harnessed the potential of fuzzy AHP for the performance evaluation of Turkish cement firms, ranking the companies using the TOPSIS method. This study provided decision-makers with valuable insights into firm performance and rankings, facilitating informed decision-making practices. (İrfan Ertuğrul, 2009)

Collectively, these multifaceted studies demonstrate the broad applications of fuzzy AHP across industries and decision-making contexts. By adeptly incorporating fuzzy logic, decision-makers gain the tools to navigate uncertainties, complexities, and subjective evaluations, ultimately leading to informed and effective decision-making outcomes.

Fuzzy MCDM methodologies extend traditional MCDM approaches by integrating fuzzy logic to handle imprecise judgments and uncertainties. Fuzzy AHP and fuzzy TOPSIS are notable examples of fuzzy MCDM techniques that employ linguistic variables and fuzzy sets to capture and model subjective assessments and uncertainties accurately (Buckley, 1985).

In recent times, fuzzy AHP has witnessed remarkable progress and found applications in a variety of fields, including healthcare, environmental management, and business decision-making (Md Kamal Hossain, 2020) (Behnam Tashayo, 2020) (Irina Canco, 2021)

Researchers have diligently explored the amalgamation of fuzzy AHP with other decision-making techniques, such as fuzzy TOPSIS and fuzzy ELECTRE, with the intention of augmenting the resilience and effectiveness of decision-making processes (Murat Kirişci, 2022)

The development of hybrid models, harmoniously blending fuzzy AHP with machine learning algorithms and artificial intelligence techniques, has exhibited encouraging outcomes in tackling intricate decision problems (Marko Radovanovic, 2020).

Studies have also centered their efforts on refining the fuzzy AHP methodology, including the assimilation of interval-valued fuzzy numbers and the consideration of group decision-making scenarios (Yitao Wu, 2020).
The advancement of fuzzy AHP is propelled by the mounting demand for comprehensive and accurate decision-making frameworks within the intricate and uncertain realm of contemporary business environments (Dragan Vukasović, 2021).

3.2. Decision Making Model and Step-by-Step Process

Choosing and operating the right green energy option is crucial for individuals involved in industrial and social development. It not only helps protect the environment but also supports economic growth and societal well-being. By selecting and using the most suitable renewable energy source, industries can reduce their carbon emissions, decrease reliance on fossil fuels, and mitigate the impacts of climate change. This shift to sustainable energy also encourages innovation, creates job opportunities, and enhances energy security. Moreover, adopting renewable energy aligns with global efforts to achieve sustainable development goals and transition to a cleaner future. Therefore, making informed decisions about green energy alternatives is essential for individuals, organizations, and governments aiming to create a greener and more sustainable world.

The risk analysis provides an overview of the current situation and forms a base for choosing the best alternative in future endeavors.

The proposed green energy alternatives evaluation model includes these modules:

- Choosing Alternatives and Criteria
- Creating the hierarchy model
- Prioritization of the main criteria (Fuzzy AHP) ;
- Prioritization of the sub criteria (Fuzzy AHP) ;
- Prioritization of alternatives (Fuzzy TOPSIS).

3.2.1. Choosing the Alternatives and Criteria

The sustainable development of Estonia relies on judiciously selecting and implementing green energy alternatives.

Hydropower offers considerable potential for renewable energy generation, particularly in areas rich in water resources. However, Estonia lacks substantial natural water resources such as large rivers or waterfalls, rendering hydropower economically unviable and environmentally unsound. Moreover, the limited potential for large-scale hydropower projects in Estonia, along with potential ecological ramifications, solidify the decision to exclude this option from further evaluation. (Europe, n.d.).

Similarly, geothermal energy relies on the availability of high-temperature geothermal reservoirs or accessible hot springs, which Estonia lacks. Geological constraints and the absence of favorable heat flow patterns further contribute to the impracticality of large-scale geothermal energy projects in Estonia. Alexander Richter mentions in his recent article that Estonia started to investigate the feasibility and potential of geothermal energy but it would be fair to say that geo thermal research in the country is still premature. (Richter, 2022)

Consequently, geothermal energy is unsuitable for addressing the country's green energy needs.

Considering the exclusion of hydropower and geothermal alternatives, the focus now shifts to wind, solar, hydrogen, and biomass alternatives for evaluating green energy options in Estonia from an industrial engineering perspective.

Wind energy emerges as a viable alternative due to Estonia's geographical characteristics, including a substantial coastline and favorable wind conditions. By harnessing onshore and offshore wind farms, Estonia can significantly expand its renewable energy capacity while mitigating carbon emissions from conventional energy sources (Pascal Vuichard, June 2022).

Solar energy exhibits tremendous potential in Estonia, given the country's favorable solar irradiation levels, particularly during the summer months.

Estonia boasts ample suitable areas for solar installations, which can effectively complement wind energy by diversifying the renewable energy mix and ensuring a stable supply of electricity even during periods of low wind availability. Embracing solar energy aligns with Estonia's commitment to sustainable development and enhances energy security (Noman Shabbir, 2022).

Hydrogen, as an energy carrier, holds promise for energy storage and various applications across sectors. By capitalizing on existing renewable energy infrastructure, Estonia can produce green hydrogen through electrolysis, utilizing excess renewable electricity. This approach facilitates the balancing of intermittent renewable energy sources and paves the way for clean energy utilization in transportation and industrial sectors (Andrijanovits, 2012)

Biomass, comprising forestry residues, agricultural waste, and dedicated energy crops, constitutes a significant renewable energy resource in Estonia. Biomass-based energy systems, such as biogas production and biomass combustion, provide a reliable and sustainable source of renewable energy. Leveraging biomass resources reduces dependence on fossil fuels and offers a feasible solution for district heating and power generation, promoting a circular economy (Harri Moora, 2017).

3.2.2. Criteria Selection

To effectively evaluate and prioritize renewable energy resources, a meticulously curated set of criteria has been adopted. These criteria were meticulously chosen based on their utmost relevance to the research objectives and their profound significance in the decision-making process concerning the adoption of renewable energy. Encompassing multifaceted dimensions, including the intricate assessment of environmental impact, the rigorous scrutiny of economic viability, the meticulous evaluation of technical feasibility, the astute analysis of social acceptance, and the comprehensive examination of energy security, the meticulously designed evaluation framework presents an all-encompassing approach for the meticulous assessment and rigorous comparison of diverse renewable energy alternatives.

Economical Feasiblity:

The meticulous examination of cost-effectiveness assumes a paramount role in determining the economic feasibility and financial viability of renewable energy alternatives. The comprehensive research studies by (M. M. Samy, 2021), which delve deeply into the meticulous economic analysis and intricate financial modeling of renewable energy projects, serve as a resounding testament to the profound importance of this criterion.

Environmental Impact:

The meticulous consideration of the intricate environmental implications and profound sustainability of renewable energy options serves as an indispensable cornerstone of responsible decision-making. Credible and esteemed references such as (IPCC, 2011)and (Qazi, 2019) meticulously explore the intricate nuances through comprehensive life cycle assessments and meticulous environmental impact analyses of diverse renewable energy sources, thereby adding substantial gravitas to the meticulous selection of this criterion.

Technical Feasibility:

The rigorous criterion of technical feasibility assumes a pivotal role in the meticulous evaluation of the readiness and advanced maturity of diverse renewable energy technologies. The in-depth research studies by (IEA, 2021) and (Fthenakis V. &., 2009), which intricately elucidate the remarkable technological advancements and profound integration potential of renewable energy systems, serve as resounding endorsements for the astute selection of this criterion.

Resource Availability:

The comprehensive assessment of the vast potential and remarkable availability of renewable energy resources within the study area serves as the fundamental pillar of this informed decision-making process (Andrijanovits, 2012). The meticulous research contributions by (Noman Shabbir, 2022), which delve deep into the meticulous evaluation of solar energy potential and wind resource availability, respectively, serve as compelling pillars of support for the scrupulous selection of this criterion.

Social Acceptance:

The meticulous incorporation of intricate societal perspectives and the astute consideration of widespread public acceptance emerge as indispensable prerequisites for the successful implementation of renewable energy projects.

Energy Security:

The comprehensive analysis of the remarkable contributions of renewable energy sources to the intricate realm of energy security assumes paramount importance in the meticulous realm of long-term planning (Foo, 2015).

By seamlessly integrating these meticulously curated comprehensive criteria, the ingeniously designed evaluation framework ensures a holistic approach in scrupulously assessing the profound suitability of diverse renewable energy alternatives. The multidimensional nature of these meticulously chosen criteria facilitates a comprehensive analysis, which expertly navigates the intricate intricacies of not only the technical and economic aspects but also the profound environmental, social, and strategic dimensions that intricately interplay in the meticulous realm of renewable energy decision-making.

3.2.3. Fuzzy AHP Step-by-step

Fuzzy AHP steps are as follows.

Step1. Setting the hierarchical chart and defining fuzzy numbers for performing the pair-wise comparisons as explained in section 3.2.

Step2. The fuzzy numbers create the pair-wise comparisons matrix by using the fuzzy numbers.

The pair-wise comparison matrix can be shown as follows**:**

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & 1 \end{bmatrix}$$

In the context of employing fuzzy AHP methodology, knowledgeable individuals utilize a comprehensive matrix for pairwise comparisons that incorporates triangular fuzzy numbers.

These unique numbers consist of three discreet components: the minimum value (l), the central value (m), and the maximum value (u). Each component signifies distinct characteristics associated with the numbers used for comparisons.

Step3. Calculation of Si for each row of the pair-wise comparison matrix

The calculation for the triangular fuzzy number can be expressed through the utilization of the following formula:

$$S_i = \sum_{j=1}^{m} M_{gi}^{j} \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{j} \right]^{-1}$$

In the given formula, the row number is denoted by 'i', and the column number is represented by 'j'.

The elements M_{gi}^{j} within the formula pertain to the triangular fuzzy numbers employed in the pairwise comparison matrices.

The values of $\sum_{j=1}^{m} M_{gi}^{j}$, $\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{i}$ and $\left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{i}\right]^{-1}$ can be calculated by following steps.

$$\sum_{j=1}^{m} M_{gi}^{j} = \left(\sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j \right)$$

$$\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{i} = \left(\sum_{i=1}^{n} l_i, \sum_{i=1}^{n} m_i, \sum_{i=1}^{n} u_i \right)$$

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

In the given formulas, the first, second, and third components of the fuzzy numbers are represented as l_i ,m_i and u_i, respectively.

Step4. Determine the relative magnitude of S_i in comparison to each other.

In the broader context, when examining two triangular fuzzy numbers, denoted as $M_1 = (l_1, m_1, u_1)$ and $M_2 = (l_2, m_2, u_2)$, the determination of the relative magnitude of M_1 in relation to M_2 can be explicated based on a defined criterion.
This comparison is visually illustrated in an accompanying figure to facilitate a comprehensive understanding.

$$V(M_2 \geq M_1) = hgt(M_1 \cap M_2) = \mu_{M_2}(d) = \begin{cases} 1 & if\ m_2 \geq m_1 \\ 0 & if\ l_1 \geq u_2 \\ \dfrac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} & otherwise \end{cases}$$

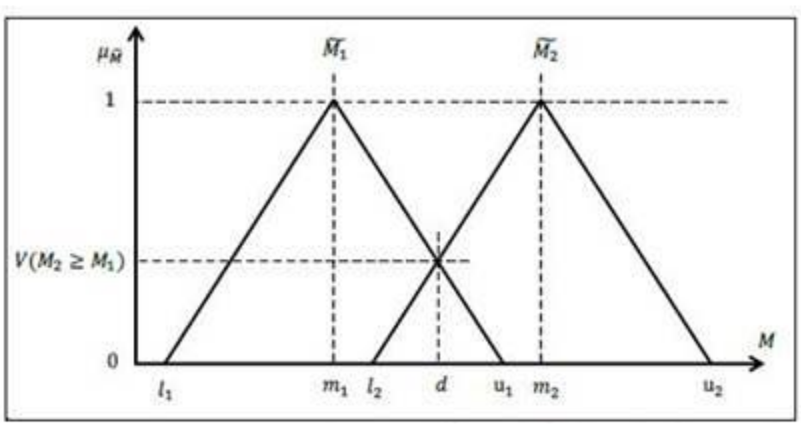

Figure 3 Triangular Fuzzy Numbers Representation

However, the determination of the magnitude of a triangular fuzzy number originating from k, when considering it as another triangular fuzzy number, involves the utilization of the following complex formula:

$$\begin{aligned} V(M \geq M_1, M_2, \cdots, M_k) &= V[(M \geq M_1)\ and\ (M \geq M_2)\ and\ \cdots\ (M \geq M_{1k})] \\ &= Min\ V(M \geq M_1) \quad i = 1,2,3, \dots, k \end{aligned}$$

Step5. Calculate the weights assigned to the criteria and alternatives within the pair-wise comparison matrix.

$$d'(A_i) = Min\ V(S_i \geq S_k) \qquad k = 1,2, \dots, n \quad , k \neq i$$

Hence, the unnormalized weight vector can be represented in the following manner.

$$W' = (d'(A_1), d'(A_2), \dots, d'(A_n))^T \quad A_i\ (i = 1,2, \dots, n)$$

3.2.4. Hierarchy Model

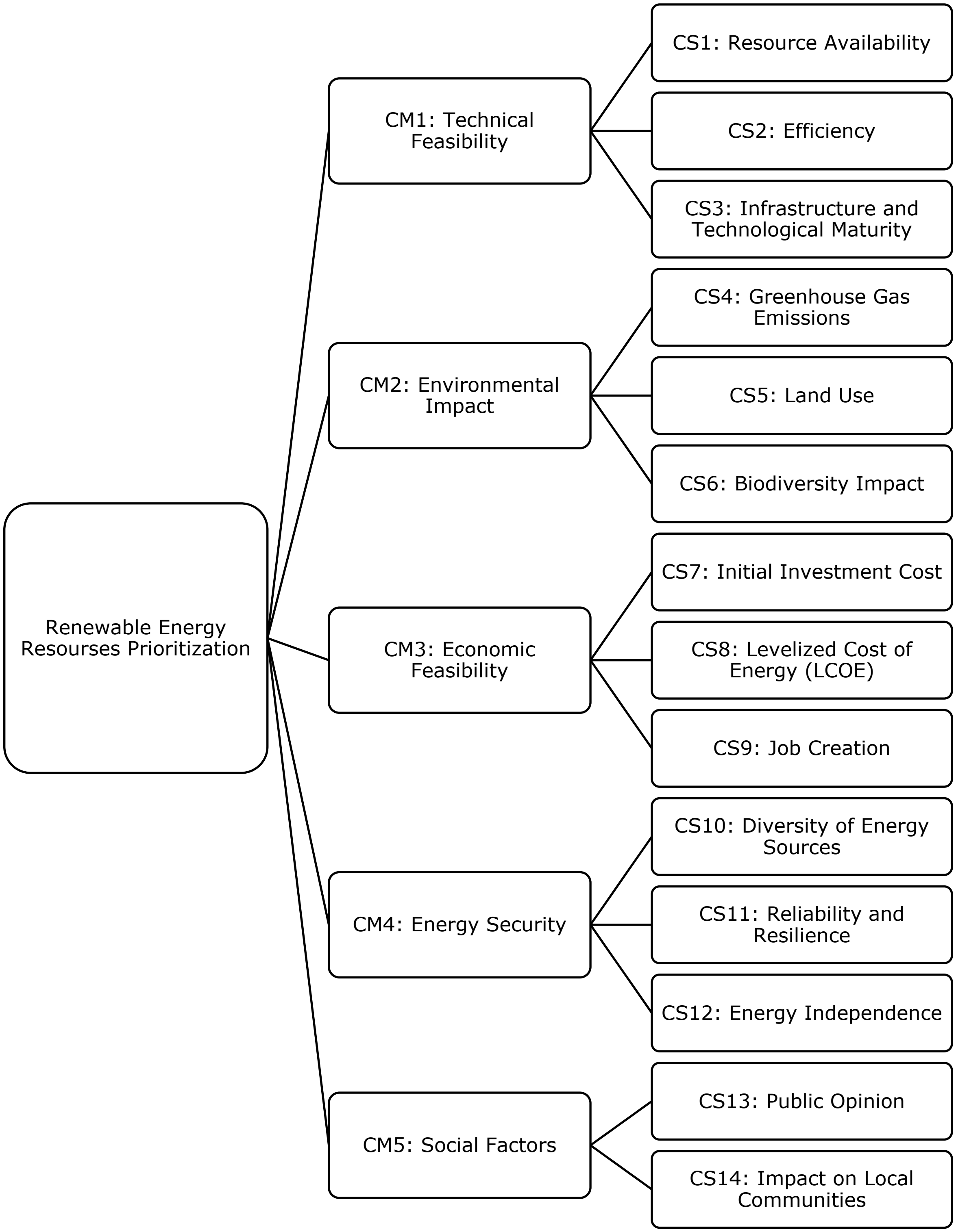

Figure 4 - Decision hierarchy tree for criteria and indicators.

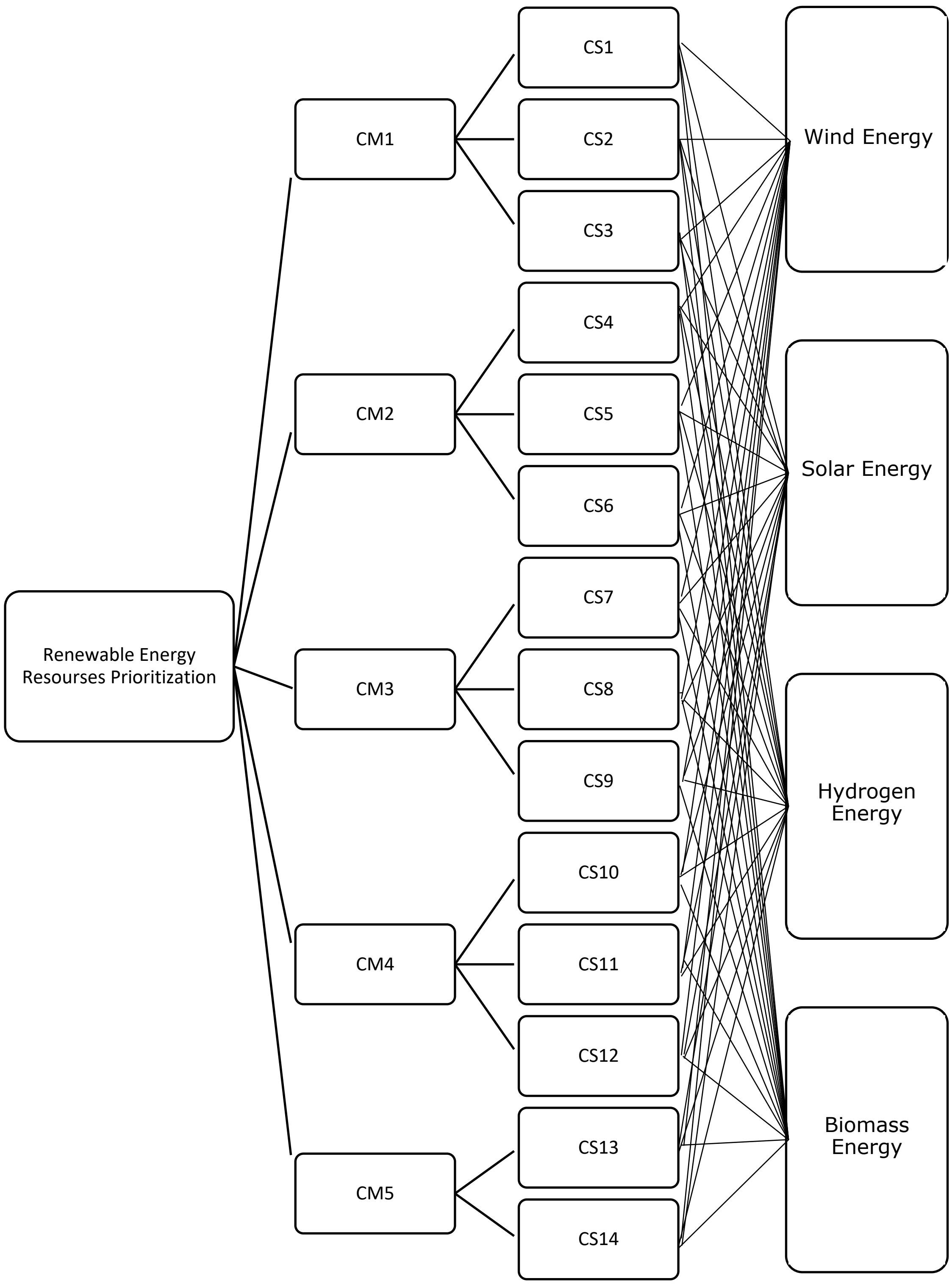

Figure 5 - MCDM Hierarch Table based on selected alternatives.

4. Results

To apply a prioritization Expert Opinion Questionnaire has been conducted and according to answers of each expert comparison table has been created.

Step 1. The fuzzy set theory, a brainchild of Zadeh, is an extensively utilized strategy for conducting pair-wise comparisons. Central to this process is the fuzzy Analytic Hierarchy Process (AHP) method, designed for critiquing different factors, and which relies heavily on the notion of triangular fuzzy numbers (TFN).

A TFN is represented as $M = (l, m, u)$, where each element 'l' and 'u' signifies the lowest and highest values respectively, and 'm' embodies the median value of M. The association function of this system is signified by the condition where $l \leq m \leq u$. (Chang, 1996))

$$\mu_M(x) = \begin{cases} \frac{x}{m-l} - \frac{l}{m-l}, x \in [l, m], \\ \frac{x}{m-u} - \frac{u}{m-u}, x \in [m, u], \\ 0, \qquad otherwise, \end{cases}$$

The basic operation with fuzzy numbers is as follows.

$M1\ (\oplus)\ M2 = (l1 + l2, m1 + m2, u1 + u2)$,

$M1\ (\otimes)\ M2 \approx (l1l2, m1m2, u1u2)$,

$M - 1 \approx (1/u1\ ,1/m1, 1/l1)$.

Criteria has been evaluated by the experts as linguistic variables. Linguistic variables can be seen in Table 2 down below.

Linguistic Variables	***Fuzzy Triangular***	***Reciprocal Fuzzy***
Equally Preferred (EI)	1, 1, 1	1, 1, 1
Slightly Preferred (SMI)	1, 2, 3	1/3, 1/2, 1
Moderately Preferred (MMI)	2, 3, 4	1/4, 1/3,1/2
Absolutely Preferred (AMI)	3, 4, 5	1/5, 1/4, 1/3

Table 2 - Linguistic Variables for Criteria

In May 2023, we put together a team of six experienced decision-makers. Their task was to compare and evaluate alternatives using a well-explained form we shared. We sent this form to each expert using different means, such as email, text messages, and even face-to-face chats.

The form came with thorough instructions to make it easier to understand. Despite seeming a bit overwhelming at first sight, it took each expert about ten minutes to complete.

One of our experts gave their feedback saying the form and criteria's actually gave them a chance to evaluate green energy in wider perspective. The aim of this effort was to better understand our topic.

You can see grades given by the experts in tables 2 through 7.

Expert 1		M1	M2	M3	M4	M5
	M1	EI	Equally Important (EI)	Slightly Less Important (SLI)	Slightly More Important (SMI)	Slightly More Important (SMI)
	M2		EI	Slightly More Important (SMI)	Slightly More Important (SMI)	Equally Important (EI)
	M3			EI	Slightly More Important (SMI)	Equally Important (EI)
	M4				EI	Moderately More Important (MMI)
	M5					EI

Table 3 - Expert 1 - Main Criteria Evaluation Table

Expert 2		M1	M2	M3	M4	M5
	M1	EI	Equally Important (EI)	Moderately More Important (MMI)	Slightly More Important (SMI)	Equally Important (EI)
	M2		EI	Absolutely More Important (AMI)	Equally Important (EI)	Slightly More Important (SMI)
	M3			EI	Moderately More Important (MMI)	Equally Important (EI)
	M4				EI	Equally Important (EI)
	M5					EI

Table 4 - Expert 2 - Main Criteria Evaluation Table

Expert 3		M1	M2	M3	M4	M5
	M1	EI	Moderately Less Important (MLI)	Equally Important (EI)	Slightly Less Important (SLI)	Moderately Less Important (MLI)
	M2		EI	Moderately More Important (MMI)	Moderately More Important (MMI)	Equally Important (EI)
	M3			EI	Moderately Less Important (MLI)	Slightly Less Important (SLI)
	M4				EI	Equally Important (EI)
	M5					EI

Table 5 - Expert 3 - Main Criteria Evaluation Table

Expert 4		M1	M2	M3	M4	M5
	M1	EI	Absolutely More Important (AMI)	Moderately More Important (MMI)	Slightly Less Important (SLI)	Equally Important (EI)
	M2		EI	Moderately More Important (MMI)	Slightly More Important (SMI)	Slightly More Important (SMI)
	M3			EI	Slightly Less Important (SLI)	Equally Important (EI)
	M4				EI	Slightly Less Important (SLI)
	M5					EI

Table 6 - Expert 4 - Main Criteria Evaluation Table

Expert 5		M1	M2	M3	M4	M5
	M1	EI	Equally Important (EI)	Slightly Less Important (SLI)	Slightly Less Important (SLI)	Slightly Less Important (SLI)
	M2		EI	Slightly More Important (SMI)	Slightly Less Important (SLI)	Slightly Less Important (SLI)
	M3			EI	Equally Important (EI)	Equally Important (EI)
	M4				EI	Slightly More Important (SMI)
	M5					EI

Table 7 - Expert 5 - Main Criteria Evaluation Table

		M1	M2	M3	M4	M5
Expert 6	M1	EI	Slightly More Important (SMI)	Moderately Less Important (MLI)	Moderately Less Important (MLI)	Moderately More Important (MMI)
	M2		EI	Moderately Less Important (MLI)	Moderately Less Important (MLI)	Absolutely More Important (AMI)
	M3			EI	Equally Important (EI)	Moderately More Important (MMI)
	M4				EI	Moderately More Important (MMI)
	M5					EI

Table 8 - Expert 6 - Main Criteria Evaluation Table

Step 2. Computing aggregated comparison matrix for criteria

We computed the aggregated evaluation matrix as explained by (POLAT, ERAY, & BINGOL, 2017) by applying a fuzzy geometric mean as

$$r_{ij} = \left(\prod_{n=1}^{N} c_{ijn} \right)^{1/N}$$

c_{ijn} stands for the fuzzy comparison value in terms of the Triangular Fuzzy Numbers of criteria i to criteria j given by the nth expert and N is the total number of decision-makers involved (N=6).

	M1			M2			M3			M4			M5		
M1	1	1	1	0.953184	1.177592	1.399083	0.691042	0.951589	1.414214	0.455946	0.740595	1.284898	0.740595	1	1.348006
M2	1.047359	0.849191	0.713558	1	1	1	1.200937	1.903178	2.667168	0.740595	1.120583	1.61887	0.998326	1.414214	1.885973
M3	1.44225	1.045606	0.707107	0.691042	0.522803	0.449513	1	1	1	0.740595	1	1.348006	0.933091	1.069913	1.259921
M4	1.508025	1.200937	1.122462	1.120583	0.889408	0.740595	1.120583	0.998326	0.890899	1	1	1	1.047359	1.44225	1.906369
M5	1.120583	0.998326	0.890899	0.829898	0.707107	0.635707	1.069913	0.933091	0.793701	0.953184	0.691042	0.52368	1	1	1

Table 9 - Aggregated Comparison Matrix

Step 3. Fuzzy comparison values computation for aggregated criteria matrix

The fuzzy comparison values $r_i = (l_i, m_i i, u_i)$ are calculated as $r_i = \left(\prod_{j=1}^{Nc} r_{ij}\right)^{1/Nc}$ (POLAT, ERAY, & BINGOL, 2017)

Step 4. Computation of fuzzy comparison values from aggregated criteria matrix

Similarly, to the aggregated criteria matrix values, the previous formula utilized for all three aggregation values that are computed for criteria.

Step 5. Computation of fuzzy weight values of criteria.

The triangular fuzzy weight w_i of criteria i is computed as

$$w_i = (l_i, m_i, u_i) = r_i \otimes (r_1 \oplus r_2 \oplus \dots \oplus r_{Nc})^{-1}, \dots i = 1, \dots, Nc$$

Step6. Computing fuzzy weight values of indicators.

The formula in step 5 applied for all three groups of indicators.

Aggregated Comparison Values			
	0.740347	0.963396	1.279334
	0.985584	1.206949	1.421822
	0.928132	0.898278	0.884
	1.146776	1.0899	1.071414
	0.989461	0.854353	0.748793
	4.790301	5.012876	5.405364
	0.208755	0.199486	0.185001

Table 10 - Aggregated Main Criteria Comparison Values

Fuzzy Weights			
	0.154551	0.192184	0.236679
	0.205746	0.24077	0.263039
	0.193752	0.179194	0.163541
	0.239395	0.21742	0.198213
	0.206555	0.170432	0.138528

Table 11 - Fuzzy Comparison Values - Main Criteria

Step7. Computation of crisp weight values of criteria

For computing crisp weight values de-fuzzy computation has been done for three groups of criteria.

Step8. Normalization of crisp weights and ranking

The normalized crisp weights computed for each criterion, as results.

Step9. Global Weights

Global weight of each main criteria is determined as the normalized crisp weights. With certain computations these values will also determine the global importance of each sub criterion.

Crisp Weights	Normalized Crisp Weights	Ranking
0.583414076	0.194471359	3
0.709554666	0.236518222	1
0.53648799	0.17882933	4
0.655028724	0.218342908	2
0.515514544	0.171838181	5
3	1	

Table 12 - Main Criteria Crisp Weights, Normalized CW, Ranking

3.2.3.1 Main Criteria Evaluation Results

According to the Main Criteria evaluation of experts, the ranking showed that 'Environmental Impact' is the most important criteria while evaluating the green energy alternatives. Following environmental impact, energy security and technical feasibility has been ranked as the most important criterion according to experts. And economic feasibility and social factors have been shown to be less important than the other factors listed for criterion. Table 12is showing overall calculated results.

3.2.3.2 Sub Criteria Evaluation

The same 8 steps for each sub criterion is repeated to find each sub criterion internal ranking in main criteria ranking.
Results can be seen in the following tables numbers between

Technical Feasibility Evaluation

	SC1			SC2			SC3		
SC1	1	1	1	1.82	2.89	3.99	1.59	2.35	3.03
SC2	0.55	0.35	0.25	1	1	1	0.79	1.32	1.86
SC3	0.63	0.43	0.33	1.26	0.76	0.54	1	1	1

Table 13 - Aggregated Expert Table of Technical Feasibility

	Aggregated Comparison Values			Fuzzy Weights				Crisp Weights
	1.425	1.894	2.296		0.458		0.632	0.163799
	0.758	0.77	0.776		0.244		0.214	0.011969575
	0.926	0.685	0.561		0.298		0.155	0.009416324
	3.109	3.349	3.633					0.185184899
	0.322	0.299	0.275					

Table 14 - Technical Feasibility Crisp Weights Calculated

Normalized Crisp Weights	Global Weights	Global Ranking Values	Ranking
0.884515969	0.194471359	0.172013022	1
0.064635805	0.194471359	0.012569813	2
0.050848226	0.194471359	0.009888524	3
1			

Table 15 - Technical Feasibility Expert Evaluation Ranking

Environmental Impact Evaluation

	SC4			**SC5**			**SC6**		
SC4	1	1	1	1.122	1.203	1.264	0.833	1.002	1.203
SC5	0.891	0.831	0.791	1	1	1	0.833	0.795	0.766
SC6	1.201	0.998	0.831	1.201	1.258	1.305	1	1	1

Table 16 - Aggregated Expert Table of Environmental Impact

	Aggregated				Fuzzy Weights			Crisp Weights
	0.978	1.064	1.15		0.325	0.353	0.38	0.043573016
	0.905	0.871	0.846		0.3	0.289	0.28	0.024300752
	1.13	1.079	1.028		0.375	0.358	0.34	0.04561871
	3.013	3.014	3.024					0.113492478
	0.332	0.332	0.331					

Table 17 - Environmental Impact Crisp Weights Calculated

Normalized Crisp Weights	Global Weights	Global Ranking Values	Ranking
0.383928672	0.236518222	0.090806127	2
0.214117728	0.236518222	0.050642744	3
0.4019536	0.236518222	0.095069351	1
1			

Table 18 Environmental Impact Expert Evaluation Ranking

Economical Feasibility Evaluation

	SC7			SC8			SC9		
SC7	1	1	1	0.891	0.662	0.55	0.891	0.742	0.662
SC8	1.122	1.511	1.817	1	1	1	0.935	0.852	0.802
SC9	1.122	1.348	1.511	1.07	1.174	1.246	1	1	1

Table 19 Economical Feasibility Evaluation Aggregated

Aggregated				Fuzzy Weights				Crisp Weights
	0.926	0.789	0.714		0.308	0.259	0.232	0.01851354
	1.016	1.088	1.134		0.338	0.358	0.368	0.04447305
	1.063	1.165	1.235		0.354	0.383	0.401	0.054271664
	3.005	3.042	3.083					0.117258254
	0.333	0.329	0.324					

Table 20 Economical Feasibility Crisp Weights Calculated

Normalized Crisp Weights	Global Weights	Global Ranking Values	Ranking
0.157886883	0.17882933	0.028234805	3
0.379274365	0.17882933	0.067825381	2
0.462838753	0.17882933	0.082769144	1
1			

Table 21 Economical Feasibility Expert Evaluation Ranking

Energy Security Evaluation

	SC10			SC11			SC12		
SC10	1	1	1	1.122	1.35	1.516	0.891	0.742	0.662
SC11	0.891	0.741	0.66	1	1	1	0.891	0.936	0.955
SC12	1.122	1.348	1.511	1.122	1.068	1.047	1	1	1

Table 22 Aggregated Expert Table of Energy Security

Aggregated				Fuzzy Weights				Crisp Weights
	1	1.001	1.001		0.333	0.332	0.331	0.036556114
	0.926	0.885	0.857		0.308	0.294	0.284	0.025637504
	1.08	1.129	1.165		0.359	0.375	0.385	0.051863508
	3.006	3.015	3.024					0.114057126
	0.333	0.332	0.331					

Table 23 Energy Security Crisp Weights Calculate

Normalized Crisp Weights	Global Weights	Global Ranking Values	Ranking
0.320507056	0.218342908	0.069980443	2
0.224777752	0.218342908	0.049078628	3
0.454715192	0.218342908	0.099283837	1
1			

Table 24 Energy Security Expert Evaluation Ranking

Social Impact Evaluation

	SC13			SC14		
SC13	1	1	1	0.618	0.467	0.386
SC14	1.619	2.14	2.587	1	1	1

Table 25 Social Impact Evaluation Aggregated

Aggregated				Fuzzy Weights				Crisp Weights
	0.786	0.684	0.622		0.382	0.318	0.279	0.033900631
	1.272	1.463	1.609		0.618	0.682	0.721	0.303844902
	2.058	2.146	2.23					0.337745533
	0.486	0.466	0.448					

Table 26 Social Impact Crisp Weights Calculated

Normalized Crisp Weights	Global Weights	Global Ranking Values	Ranking
0.100373293	0.171838181	0.017247964	2
0.899626707	0.171838181	0.154590217	1
1			

Table 27 Energy Security Expert Evaluation Ranking

3.2.3.3. Criteria Ranking

After calculating global ranking values global rank of the sub criteria is as follows:

1	SC1	0.172013	Resource Availability
2	SC14	0.15459	Impact on Local Communities
3	SC12	0.099284	Energy Independence
4	SC6	0.095069	Biodiversity Impact
5	SC4	0.090806	Greenhouse Gas Emissions
6	SC9	0.082769	Job Creation
7	SC10	0.06998	Diversity of Energy Sources
8	SC8	0.067825	Levelized Cost of Energy (LCOE)
9	SC5	0.050643	Land Use
10	SC11	0.049079	Reliability and Resilience
11	SC7	0.028235	Initial Investment Cost
12	SC13	0.017248	Public Opinion
13	SC2	0.01257	Efficiency
14	SC3	0.009889	Infrastructure and Technological Maturity

Table 28 Sub criteria ranking.

3.2.4 Evaluation of Green Energy Alternatives using Fuzzy TOPSIS

During the risk evaluation process, the outcomes obtained from applying the Fuzzy Analytic Hierarchy Process (AHP) and employing the Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) are considered.

Step 1. Firstly, the expert group responsible for evaluating the criteria conducts a pair-wise comparison between the risks and criteria. This comparison utilizes triangular Fuzzy numbers and linguistic variables, following a similar approach to the evaluation of the criteria. The integration of these methods enhances the accuracy and robustness of the risk evaluation procedure. (Poudel & Munir, 2021)

The relative importance of the Alternatives with respect to criteria in terms of linguistic variables	Crisp AHP Scale	Fuzzy Triangular	Reciprocal Fuzzy
Very Weak (VW)	1	1 1 1	1, 1, 1
Very Weak to Weak (VW-W)	2	1 2 3	1/3, 1/2, 1
Weak (W)	3	2 3 4	1/4, 1/3, 1/2
Weak to Average (W-A)	4	3 4 5	1/5, 1/4, 1/3
Average (A)	5	4 5 6	1/6, 1/5, 1/4
Average to Strong (A-S)	6	5 6 7	1/7, 1/6, 1/5
Strong (S)	7	6 7 8	1/8, 1/7, 1/6
Strong to Very Strong (S-VS)	8	7 8 9	1/9, 1/8, 1/7
Very Strong (VS)	9	8 9 9	1/9, 1/9, 1/8

Table 29 Linguistic variables for the importance of the sub criteria with respect to criteria

Step2. The green energy alternative evaluation with respect to criteria is performed with the expert form again. The response of the expert can be seen.

	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8	SC9	SC10	SC11	SC12	SC13	SC14
A1	VS	A-S	A	S-VS	VS	W-A	S	W-A	A	S	A	A	S-VS	S
A2	S	S-VS	A	S	S	S	S	A	VW-W	A-S	A	S	A	S
A3	VW	VW	A	VW	VW-W	VW	A	A-S	VW-W	W-A	A	S-VS	A	VW-W
A4	W	A-S	W	S	VS	S-VS	S-VS	S	S-VS	A	S	A	S	W

Table 30 - Expert 1 Alternative Criteria Evaluation

	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8	SC9	SC10	SC11	SC12	SC13	SC14
A1	A-S	W-A	W-A	S	S	VS	VS	S	A	A-S	S	S-VS	W-A	A-S
A2	S	S	A-S	VW-W	S	W	S-VS	S-VS	S-VS	S-VS	S-VS	S-VS	A-S	A-S
A3	S	A	S	S	S	S	A-S	S	A	S	S	A	A-S	A
A4	A-S	A-S	A-S	S	A-S	A	S	S	S	S	S	A-S	S	S

Table 31 Expert 2 Alternative Criteria Evaluation

	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8	SC9	SC10	SC11	SC12	SC13	SC14
A1	VS	A-S	A	VW-W	W-A	A	S	W-A	A	S	A	A-S	S	A-S
A2	VS	A	A	VW	S	A	S	A	A	A	A	A-S	A	A-S
A3	S	A	A-S	VW-W	W-A	A	S-VS	A	VW-W	A	A-S	A	A	A
A4	A	A	A	A	W-A	W	S-VS	A-S	A	A	A-S	A	A	A

Table 32 Expert 3 Alternative Criteria Evaluation

	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8	SC9	SC10	SC11	SC12	SC13	SC14
A1	S-VS	S-VS	S-VS	VS	W-A	S	W-A	S-VS	W	S	S	S-VS	VW-W	A
A2	S	S	S	A	VW-W	A-S	A	S	A	S	S-VS	S-VS	S	A-S
A3	VW	VW-W	VW	A	A	A	VW	A	S-VS	S-VS	A-S	S	A	A
A4	A-S	W-A	A	VW-W	W	VW	VS	W	S	A-S	S	S-VS	W-A	W

Table 33 Expert 4 Alternative Criteria Evaluation

	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8	SC9	SC10	SC11	SC12	SC13	SC14
A1	S	S	A-S	A	A	S	A	S	S	S	A	S	A	S-VS
A2	W	W	W-A	W	S-VS	W	S	A	A	S	A	S	A	W
A3	W	S	A	A	W	W	VS	S-VS	A-S	S	S	S	A-S	W
A4	S-VS	A	S	A	S	VS	A-S	A	S-VS	A	S	S	S	S

Table 34 Expert 5 Alternative Criteria Evaluation

	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8	SC9	SC10	SC11	SC12	SC13	SC14
A1	S	S-VS	A	S-VS	S	S-VS	A-S	S	S	S-VS	A	S-VS	A-S	S
A2	A-S	S	A-S	S-VS	S-VS	A-S	S	S-VS	S-VS	S-VS	W-A	VS	VW-W	VW-W
A3	S	S	A	VS	VW-W	A-S	S-VS	S-VS	S	VS	W-A	VS	VW-W	VW-W
A4	S-VS	W-A	A	W	S	W	A-S	W-A	A-S	S	A	S-VS	W	S

Table 35 Expert 6 Alternative Criteria Evaluation

Step 3. The linguistic "grades", given by decision makes (see Table 6) are transferred to triangular fuzzy numbers (TFN) based on relations given in Table 5.

The aggregation of the decision maker's evaluation matrices is performed by applying fuzzy arithmetic mean (in the case of Fuzzy AHP was applied geometric mean) as

$$x_{ij} = \frac{1}{N}\sum_{n=1}^{N} x_{ijn},$$

where N is a number of decision makers and xijn stand for the rating of alternative i to criterion j given by n-th decision maker. The computed fuzzy triangular numbers xij=(lij,mij,uij) are presented in Table 28.

	SC1			SC2			SC3			SC4			SC5			SC6			SC7		
A1	0.79	0.91	1	0.64	0.76	0.89	0.52	0.65	0.77	0.55	0.71	0.83	0.56	0.69	0.8	0.66	0.79	0.9	0.5727	0.6981	0.8078
A2	0.61	0.74	0.86	0.58	0.71	0.83	0.53	0.65	0.77	0.32	0.42	0.5	0.56	0.72	0.85	0.44	0.57	0.7	0.6481	0.771	0.8932
A3	0.33	0.38	0.43	0.35	0.44	0.53	0.42	0.5	0.58	0.36	0.46	0.54	0.28	0.42	0.55	0.38	0.46	0.54	0.5371	0.6127	0.674
A4	0.56	0.69	0.81	0.47	0.59	0.72	0.48	0.6	0.73	0.32	0.47	0.6	0.55	0.68	0.79	0.33	0.43	0.51	0.7514	0.8736	0.978

SC8			SC9			SC10			SC11			SC12			SC13			SC14		
0.59	0.72	0.84	0.49	0.62	0.74	0.72	0.84	0.96	0.55	0.67	0.8	0.71	0.83	0.95	0.44	0.59	0.72	0.65	0.77	0.9
0.62	0.75	0.87	0.46	0.6	0.74	0.69	0.81	0.93	0.55	0.68	0.8	0.77	0.9	1	0.42	0.56	0.69	0.41	0.55	0.68
0.59	0.72	0.84	0.37	0.52	0.66	0.65	0.77	0.88	0.57	0.69	0.81	0.68	0.8	0.91	0.41	0.55	0.68	0.27	0.41	0.54
0.4	0.55	0.68	0.69	0.81	0.93	0.57	0.69	0.82	0.66	0.78	0.9	0.65	0.77	0.89	0.45	0.59	0.72	0.47	0.6	0.73

Table 36 Aggregated Pairwise Comparison Matrix

Step 4. Normalization of aggregated fuzzy decision matrix. The Fuzzy weights of the criteria obtained by applying Fuzzy AHP (see 27) are utilized to compute the weighted normalized decision matrix.

	SC1			SC2			SC3			SC4			SC5			SC6			SC7		
A1	0.36	0.52	0.63	0.16	0.18	0.19	0.16	0.13	0.12	0.18	0.25	0.31	0.17	0.2	0.22	0.25	0.28	0.31	0.1765	0.1811	0.1871
A2	0.28	0.42	0.54	0.14	0.16	0.18	0.16	0.13	0.12	0.1	0.15	0.19	0.17	0.21	0.24	0.17	0.2	0.24	0.1997	0.2	0.2069
A3	0.15	0.22	0.27	0.08	0.1	0.11	0.13	0.1	0.09	0.12	0.16	0.2	0.08	0.12	0.15	0.14	0.17	0.18	0.1655	0.1589	0.1561
A4	0.26	0.39	0.51	0.12	0.14	0.15	0.14	0.12	0.11	0.11	0.17	0.23	0.16	0.2	0.22	0.13	0.16	0.17	0.2315	0.2266	0.2266

SC8			SC9			SC10			SC11			SC12			SC13			SC14		
0.2	0.26	0.31	0.17	0.24	0.3	0.24	0.28	0.32	0.17	0.2	0.23	0.25	0.31	0.37	0.17	0.19	0.2	0.4	0.53	0.65
0.21	0.27	0.32	0.16	0.23	0.3	0.23	0.27	0.31	0.17	0.2	0.23	0.28	0.34	0.39	0.16	0.18	0.19	0.25	0.38	0.49
0.2	0.26	0.31	0.13	0.2	0.26	0.22	0.26	0.29	0.17	0.2	0.23	0.24	0.3	0.35	0.16	0.18	0.19	0.17	0.28	0.39
0.14	0.2	0.25	0.24	0.31	0.37	0.19	0.23	0.27	0.2	0.23	0.25	0.23	0.29	0.34	0.17	0.19	0.2	0.29	0.41	0.53

Table 37 Weighted Normalized Fuzzy Decision Matrix

Step5. The distances of each alternative to positive and negative ideal solutions are computed as

$$d_i^+ = \sum_{j=1}^{n} d(v_{ij}, v_j^+),\ i = 1, \dots, m, \qquad d_i^- = \sum_{j=1}^{n} d(v_{ij}, v_j^-),\ i = 1, \dots, m,$$

Where,

$$v_j^+ = (1,1,1),\ \ v_j^- = (0,0,0), \qquad j = 1,2, \dots, n$$

and

$$d(x, y) = \sqrt{\left(\frac{1}{3}\right) * \left[\left(l_x - l_y\right)^2 + \left(m_x - m_y\right)^2 + \left(u_x - u_y\right)^2\right]}$$

	SC1		SC2		SC3		SC4		SC5		SC6		SC7		SC8		SC9		SC10		SC11		SC12		SC13		SC14	
	d+	d-	d+	d-	d+	d-	d+	d-	d+	d-	d+	d-	d+	d-	d+	d-	d+	d-	d+	d-	d+	d-	d+	d-	d+	d-	d+	d-
A1	0.51	0.52	0.83	0.17	0.86	0.14	0.86	0.14	0.75	0.25	0.51	0.52	0.72	0.28	0.82	0.18	0.75	0.26	0.77	0.24	0.72	0.28	0.8	0.2	0.69	0.31	0.48	0.54
A2	0.6	0.43	0.84	0.16	0.86	0.14	0.86	0.14	0.85	0.15	0.6	0.43	0.8	0.2	0.8	0.2	0.74	0.27	0.77	0.24	0.73	0.27	0.8	0.2	0.67	0.34	0.63	0.39
A3	0.79	0.22	0.9	0.1	0.89	0.11	0.89	0.11	0.84	0.17	0.79	0.22	0.84	0.16	0.84	0.16	0.75	0.26	0.8	0.21	0.75	0.26	0.8	0.2	0.7	0.3	0.73	0.29
A4	0.62	0.4	0.87	0.14	0.87	0.13	0.87	0.13	0.83	0.17	0.62	0.4	0.85	0.15	0.77	0.23	0.81	0.2	0.69	0.31	0.77	0.23	0.77	0.23	0.71	0.29	0.6	0.42

Table 38 Altersnative Distances from Ideal Table

Step6. Based on positive and negative ideal solution the similarities are calculated as

$$CC_i = \frac{d_i^-}{d_i^+ + d_i^-} \text{ , } i = 1, \ldots, m$$

The risks are ranked based on the values of the similarities. In 37 are given positive and negative ideal solutions, and in Table 38 the similarities and final ranking of the alternatives can be seen.

D+	D-	C	Ranking	
10.026055	4.0746245	0.2889665	1	Wind
10.507918	3.5905358	0.2546759	2	Solar
11.235761	2.8292892	0.2011574	4	Hydrogen
10.608492	3.4925753	0.2476816	3	Biomass
11.235761	4.0746245			
10.026055	2.8292892			

Table 39 Final Ranking of Green Energy Alternatives.

Selecting the most optimal renewable energy alternative for a corporation is an important and challenging task that demands careful consideration of multiple different criteria and a comprehensive evaluation of various green energy options. To address this complex challenge, an approach called fuzzy AHP-TOPSIS is applied, which provides a reliable means to estimate the relative rankings of both criteria and alternatives.

In the specific context of Estonia's current state, the detailed analysis points towards wind energy and solar energy as the most concise and suitable choices. These alternatives exhibit a range of attributes that align well with Estonia's unique renewable energy requirements and aspirations according to the experts who participated to this study.

The evaluation approach not only yields valuable insights into the relative importance of different criteria but also generates similarity values that contribute to a thorough assessment of the alternatives. By leveraging this invaluable information, decision-making systems pertaining to green energy alternatives can be significantly enhanced, fostering continuous improvement in the selection process.

5. Analysis of Results & Suggestions

The results obtained through the implementation of the Fuzzy AHP-TOPSIS evaluation method have shed light on wind energy as the most favorable and economically viable option within the array of alternatives under analysis. The prominence of wind energy stems from a comprehensive ensemble of advantageous factors. Primarily, its exceptional efficiency in the conversion of wind power into electrical energy bestows upon it the qualities of dependability and cost-effectiveness. Moreover, Estonia's geographical disposition presents an feasible environment helpful to wind energy generation, thereby further accentuating its potential. Furthermore, the technological advancements associated with wind energy have attained a state of advancement that ensures its reliability and scalability in satisfying the nation's energy demands.

Curiously enough, Estonia's esteemed repute in biomass energy production (Luc Pelkmans, 2021),bio energy is source of more than 25% of the energy in Estonia which is 60% of the renewable energy sources in the country (Luc Pelkmans, 2021), it is indeed a confusing revelation that biomass, within the limitations of this evaluation, did not emerge as prominently as wind and solar energy alternatives. Unraveling the details of this occurrence necessitates a comprehensive investigation surrounding aspects such as the cost-effectiveness of biomass energy production, the efficacy of energy harnessing from biomass sources, and meticulous scrutiny of the environmental consequences. A thorough comprehension of these factors, attained through constant research and technological breakthroughs, holds the potential to unlock the comprehensive potential of biomass energy as a sustainable alternative.

In addition, solar energy emerged as a challenging contender in proximity to wind energy, thus accentuating its significance as a renewable energy alternative. Estonia benefits itself of a substantial solar resource, particularly during the summer months characterized by extended periods of daylight. The declining costs of solar panels, coupled with the continuous advancements in photovoltaic technology, contribute to the growing viability and allure of solar energy as an environmentally friendly energy source.

Moreover, the evaluation brought to the forefront the considerable potential of hydrogen energy as a feasible and sustainable green energy alternative. Hydrogen energy can be harnessed through diverse methodologies, such as electrolysis powered by renewable energy sources. It has lots of appealing advantages, including elevated energy density and a lack of carbon emissions when deployed in fuel cells. Although hydrogen energy is still in its promising stages of development, ongoing research exercises and technological breakthroughs indicate a promising future for its integration into the energy landscape.

In summary, the comprehensive results obtained from the Fuzzy AHP-TOPSIS evaluation present invaluable insights for stakeholders and decision-makers entrusted with formulating an effective green energy strategy within Estonia. While wind and solar energy undoubtedly occupy positions of preeminence, a more profound exploration of biomass and hydrogen energy alternatives may yield an elevation in their rankings and broader adoption, thus fostering a diversified renewable energy portfolio for Estonia.

5.1 Wind energy

The comprehensive evaluation carried out by domain experts yielded exceptionally strong findings in favor of wind energy concerning its impact on local communities, resource availability, and energy independence. Given the compelling nature of these results, it can be confidently claimed that a significant increase in the number of wind energy collection farms is not only a rational but also a highly recommended course of action.

Wind energy has demonstrated a remarkable capacity to positively influence local communities in numerous ways. The establishment of wind energy farms has proven to be a catalyst for job creation, economic growth, and community development. (Kondili, 2012). By extending the number of wind energy collection farms, the potential for generating substantial positive effects on local communities can be significantly magnified, thereby fostering enhanced socio-economic prosperity and overall well-being.

Resource availability plays a pivotal role in the case of wind energy expansion. Estonia's strategic geographical positioning presents an exceptional opportunity for harnessing wind power efficiently and effectively. By capitalizing on the abundant wind resources that the country possesses, a deliberate increase in the number of wind energy farms can unlock immense potential for bolstering energy production, diminishing dependence on fossil fuels, and facilitating the transition towards a greener and more sustainable energy landscape.

Maximum wind speed (m/s) 1991-2020													
	I	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**	**Year**
Jõgeva	23,0	21,0	22,3	29,0	21,0	21,0	30,0	23,5	20,0	20,5	24,0	24,2	**30,0**
Jõhvi	28,0	25,8	24,0	22,6	23,9	24,4	25,0	22,3	20,6	22,7	25,0	25,6	**28,0**
Kihnu	34,0	32,0	28,0	28,8	22,0	24,0	28,0	24,4	29,0	30,8	34,0	34,0	**34,0**
Kunda	25,5	25,1	25,3	25,7	22,0	28,7	25,0	25,6	25,0	25,0	26,6	29,8	**29,8**
Kuusiku	22,4	20,7	21,6	20,3	20,4	20,7	30,0	20,2	20,9	24,0	23,0	26,2	**30,0**
Lääne-Nigula	30,0	24,0	24,0	23,8	23,0	24,0	21,2	20,4	22,0	27,0	27,0	26,5	**30,0**
Pakri	31,2	28,6	28,6	26,1	24,0	24,9	24,0	23,6	26,9	34,2	30,0	31,5	**34,2**
Pärnu	30,8	25,1	24,5	24,3	24,5	23,0	25,9	21,9	24,0	31,1	24,8	27,8	**31,1**
Ristna	29,7	25,0	25,0	28,3	25,0	23,1	23,0	21,9	29,0	28,0	28,0	29,1	**29,7**
Sõrve	34,0	31,0	28,0	29,1	25,0	27,0	30,0	25,1	29,9	31,3	32,5	38,6	**38,6**
Tallinn-Harku	24,0	22,0	24,0	20,2	22,0	19,6	20,3	20,1	19,4	22,0	22,0	24,5	**24,5**
Tartu-Tõravere	22,5	20,7	21,2	22,0	20,0	28,0	22,0	26,0	21,0	24,0	22,0	23,3	**28,0**
Tiirikoja	23,0	18,0	21,6	19,3	20,2	26,0	25,1	22,3	20,0	20,0	20,0	21,2	**26,0**
Türi	20,9	21,0	20,0	18,0	19,0	20,0	21,9	17,0	19,0	22,0	22,9	20,6	**22,9**
Valga	24,5	21,0	23,3	23,0	20,6	20,9	18,0	23,3	21,1	25,9	21,0	22,9	**25,9**
Viljandi	28,9	22,3	20,0	20,5	19,0	20,0	20,0	17,2	17,9	23,7	22,0	23,9	**28,9**
Vilsandi	38,0	30,0	33,0	28,3	26,0	26,0	32,3	26,0	27,6	33,2	34,0	34,0	**38,0**
Virtsu	27,1	24,3	25,4	25,3	21,0	21,7	22,3	20,0	25,1	24,9	30,0	26,2	**30,0**
Võru	23,1	22,0	20,3	20,0	20,9	21,1	21,0	23,4	20,0	26,1	19,0	21,7	**26,1**
Väike-Maarja	24,0	25,0	26,2	25,7	23,0	23,6	35,4	36,5	22,0	26,0	29,0	28,4	**36,5**
Maximum	**38,0**	**32,0**	**33,0**	**29,1**	**26,0**	**28,7**	**35,4**	**36,5**	**29,9**	**34,2**	**34,0**	**38,6**	**38,6**

Table 40 - Maximum Wind Speed in Estonia (1991-2020) (Agency, n.d.)

The dataset shared reveals a thorough analysis of wind speed records spanning the years 1991 to 2020 (Agency, n.d.). Within this extensive examination, a notable finding surfaces: Sõrve and Vilsandi emerge as particularly favorable locations for the potential installation of additional wind turbines to augment energy generation.

A meticulous examination of the wind speed table uncovers a notable pattern, subtly indicating the potential of Sõrve and Vilsandi. These regions possess consistent and relatively high wind speeds, making them prime candidates for efficient wind energy utilization. This discovery opens doors to the possibility of expanding renewable energy production through the placement of additional wind turbines in these areas.

By strategically installing additional wind turbines in Sõrve and Vilsandi, it is plausible to leverage the established wind resources and increase energy output. This expansion would contribute to the overall renewable energy capacity of the region, aligning with sustainability goals and reducing dependence on traditional energy sources. Moreover, the discreet utilization of wind power in these locations provides an opportunity to harness clean and renewable energy, thereby promoting a greener energy mix.

Considering the remarkable wind speeds consistently observed in Sõrve and Vilsandi, the proposal to install supplementary wind turbines in these regions proves compelling. By tapping into the wind energy potential of these areas, it becomes possible to generate additional renewable energy, contributing to the overall energy portfolio and promoting a more sustainable future.

Moreover, on wind energy, this energy type substantially contributes to achieving energy independence. By expanding the capacity of wind energy collection farms, Estonia can meaningfully reduce its reliance on imported energy sources, thus bolstering its energy security and mitigating vulnerabilities stemming from fluctuations in global energy markets. This deliberate effort towards increased energy independence engenders a more stable and resilient energy supply, thereby fortifying the nation's overall energy security posture.

Given the resounding strength of these findings, it is unequivocally advisable to assert that a substantial escalation in the number of wind energy collection farms represents a judicious and pragmatic course of action. Such an expansion not only capitalizes on the demonstrably positive impact of wind energy on local communities but also harnesses the abundant resources available in Estonia, while concurrently enhancing the nation's energy independence and resilience.

5.2 Solar energy

The assessment has shed light on the numerous advantages of solar energy, carefully considering Estonia's distinctive seasonal fluctuations in sunlight availability. With elongated daylight hours during the summer months, compared to diminished sun exposure in the winter, careful management of solar energy assumes paramount importance, providing the means to optimize its utilization and extract maximum benefits.

The thorough evaluation acknowledges the solar potential that Estonia possesses during the summer season, with its prolonged periods of radiant daylight. This propitious circumstance presents an exquisite opportunity to capture and harness the resplendent solar energy for optimal power generation. By strategically augmenting the number of solar energy installations and adroitly integrating state-of-the-art energy storage systems, Estonia can adroitly exploit the generous sunshine during the summer to satiate a substantial proportion of its energy requisites.

Yet, the discerning evaluation wisely contemplates the formidable challenge posed by the diminished sunlight exposure during the winter. To effectively overcome this obstacle, intelligent management strategies must be adeptly utilized. This entails assimilating alternative energy sources, such as wind or biomass, to offset the curtailed solar energy production. Additionally, the prudent deployment of cutting-edge energy storage technologies, including advanced battery systems or meticulously engineered pumped hydro storage, facilitates the judicious accumulation of surplus energy generated during the sun-drenched summer months, which can be carefully monitored to illuminate the darker winter periods.

By embracing a comprehensive and nuanced approach to the management of solar energy, Estonia can deftly optimize its renewable energy portfolio. This entails artfully diversifying the energy mix by incorporating complementary sources, adroitly implementing meticulous storage systems, and sagaciously ensuring a harmonious and equitable distribution of energy production throughout the year. This holistic and integrated stratagem empowers Estonia to adroitly harness the superlative benefits of solar power while adroitly securing an unswerving and unwavering energy supply throughout all seasons.

In synthesis, the meticulous evaluation poignantly underscores the indispensable significance of judicious and sagacious solar energy management in Estonia, considering the distinct and nuanced variations in sunlight availability throughout the year. By adroitly adopting a comprehensive blueprint that astutely interweaves solar energy with alternative sources and cutting-edge storage systems, Estonia can dexterously unlock the inexorable potential of solar power, while steadfastly upholding an unflinching and steadfast energy supply throughout all seasons.

5.3 Bio Energy

The in-depth assessment has illuminated a multitude of advantages associated with bioenergy, carefully considering Estonia's unique variations in resource availability throughout the seasons. With diverse factors influencing biomass production, including fluctuating agricultural yields and changing forestry practices, astute management of bioenergy resources assumes paramount importance in optimizing their utilization and reaping maximum benefits.

The comprehensive evaluation keenly recognizes Estonia's significant potential for bioenergy during the agricultural and forestry cycles. These favorable circumstances provide fertile ground to capture and harness biomass resources for efficient energy generation. By strategically enhancing the infrastructure for bioenergy production and implementing advanced conversion technologies, Estonia can skillfully exploit the abundant biomass resources during the peak seasons, effectively meeting a substantial portion of its energy demands.

However, the assessment astutely acknowledges the challenges posed by seasonal variations and the need for intelligent resource management. To effectively address this, adaptive strategies must be employed. This entails optimizing biomass collection and storage practices, including careful selection of feedstocks and efficient preservation methods. Additionally, advanced conversion technologies and process optimization can ensure the optimal utilization of biomass resources, maximizing energy production throughout the year.

By adopting a comprehensive and adaptive approach to bioenergy management, Estonia can successfully optimize its renewable energy portfolio. This involves integrating diverse sources of biomass, such as agricultural residues, forest residues, and dedicated energy crops, and establishing a robust supply chain that accounts for seasonal variations. Furthermore, the implementation of efficient storage and conversion systems ensures a continuous supply of bioenergy, enhancing energy security and sustainability.

5.4 Hydrogen Energy

The meticulous evaluation astutely recognizes Estonia's immense potential for hydrogen energy, particularly during the summer season characterized by prolonged periods of abundant sunlight. This propitious circumstance presents an unparalleled opportunity to capture and utilize solar energy for the efficient production of hydrogen. By adroitly expanding hydrogen production infrastructure and integrating cutting-edge technologies, Estonia can skillfully harness the abundant solar resources during the summer months, satisfying a significant portion of its energy demands.

However, the discerning evaluation wisely contemplates the challenges posed by reduced sunlight exposure during the winter. To effectively overcome this hurdle, ingenious management strategies must be adroitly employed. This entails integrating alternative energy sources, such as wind or biomass, to offset the decline in solar energy production. Additionally, the shrewd deployment of advanced energy storage technologies, encompassing sophisticated battery systems or meticulously designed pumped hydro storage, facilitates the astute accumulation of surplus energy generated during the sun-drenched summer, judiciously stockpiling it for utilization during the darker winter periods.

By embracing a comprehensive and nuanced approach to hydrogen energy management, Estonia can deftly optimize its renewable energy portfolio. This entails adroitly diversifying the energy mix by seamlessly integrating complementary sources, implementing meticulous storage systems with precision, and sagaciously ensuring a harmonious and equitable distribution of energy production throughout the year. Such a holistic and integrated strategy empowers Estonia to adroitly harness the extraordinary benefits of hydrogen power while adroitly securing an unswerving and unwavering energy supply throughout all seasons.

In conclusion, the meticulous evaluation of various renewable energy alternatives has yielded invaluable insights for Estonia's sustainable energy transition. The findings underscore the remarkable potential of wind energy, solar energy, biomass, and hydrogen energy.

Wind energy emerges as an undeniable frontrunner, boasting commendable attributes such as positive socioeconomic impact on local communities, harnessing the immense power of wind resources, and fostering energy self-reliance. Solar energy, too, shines brightly in Estonia's quest for sustainable power generation, capitalizing on the sun-drenched summer months and offering a clean and renewable energy source. While biomass ranks lower in the evaluation, its role in diversifying energy sources and promoting environmental stewardship remains indisputable. Prudent management practices, including optimized biomass collection and storage, can amplify its contribution to the renewable energy mix. Additionally, hydrogen energy holds considerable promise as a complementary solution, enabling the efficient storage and utilization of intermittent renewable energy.

These discerning findings provide an indispensable compass for policymakers, energy stakeholders, and local communities, empowering them to navigate the complex landscape of sustainable energy choices. By shrewdly harnessing the unique strengths of wind, solar, biomass, and hydrogen energy, Estonia can unleash its full renewable energy potential, reducing dependence on fossil fuels, fostering economic prosperity, and safeguarding the environment.

Implementing these recommendations requires unwavering commitment, visionary leadership, and continued advancements in technology. By embracing a holistic and integrated approach to renewable energy, Estonia can propel itself to the vanguard of the global clean energy revolution, forging a sustainable path towards a greener and more resilient future.

6.Discussion

The information derived from the rankings of criteria and alternatives provides a foundational overview, yet it lacks the granularity needed to discern the specific differentiations and distances between them. However, by incorporating the precise weighting of criteria and considering the similarity values associated with the risks, a more comprehensive and nuanced understanding can be attained. These meticulous weightings and values furnish invaluable insights that can be leveraged to propel advancements in green energy systems, facilitating a more sophisticated and refined decision-making framework.

7.Conclusion

An advanced evaluation model has been devised for the purpose of appraising green energy alternatives in Estonia. This advanced model ingeniously incorporates the Fuzzy Analytical Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) methodologies. The astute utilization of these cutting-edge techniques serves to simplify the decision-making process, effectively addressing uncertainties inherent in subjective judgments. By adeptly integrating the power of Fuzzy AHP and TOPSIS, this evaluation model skillfully amalgamates the assessments of decision makers, rendering them impervious to uncertainties and vastly augmenting the overall efficacy of the green energy alternative evaluation process.

The primary aim of this extensive research endeavor was to thoroughly analyze and evaluate a diverse array of environmentally sustainable energy options within the geographical context of Estonia. The paramount objective revolved around the intricate selection of economic criteria and alternative choices, followed by a meticulous comparative assessment, ultimately culminating in the provision of preliminary recommendations.

Considerable attention was dedicated to the meticulous curation of economic criteria and alternative options to ensure a comprehensive and holistic evaluation of green energy solutions specific to Estonia. Numerous factors, encompassing energy efficiency, environmental ramifications, technical feasibility, social acceptability, and energy security, were judiciously considered during the rigorous selection process. The evaluated alternatives encompassed solar power, wind energy, biomass, geothermal, and hydroelectric power.
An in-depth comparative analysis of the chosen alternatives was conducted, incorporating expert opinions and pertinent data. This rigorous examination encompassed quantitative and qualitative dimensions, entailing an exhaustive exploration of resource availability, cost-effectiveness, energy security, energy production potential, social acceptance, environmental impact, and technological feasibility. The objective was to derive discerning insights into the merits and limitations inherent in each alternative.

The resulting findings underwent scrupulous scrutiny to identify potential avenues for the development of green energy alternatives within Estonia. Emerging trends, patterns, and opportunities were meticulously dissected through an incisive analytical lens. The alignment of green energy alternatives with Estonia's energy goals, regulatory framework, and societal acceptance was also astutely considered during the analysis. These findings formed the bedrock of the author's perspective regarding prospective domains for the growth and advancement of green energy alternatives within Estonia.

Based on the comprehensive analysis and interpretation of the results, the author expounded their viewpoint and preliminary recommendations to facilitate the progress of sustainable energy alternatives. The recommendations comprised strategic propositions, policy considerations, and pragmatic approaches aimed at fostering the proliferation of environmentally sound energy sources. Striking a delicate balance between environmental imperatives, economic viability, and societal benefits was a primary focal point. Technological advancements, investment opportunities, public awareness initiatives, and global best practices were seamlessly integrated into the author's visionary outlook.

To conclude, this in-depth study successfully navigated the terrain of potential development areas for green energy alternatives within Estonia. The meticulous selection of economic criteria, exhaustive comparative analysis, and the formulation of preliminary recommendations collectively contribute to the advancement of sustainable energy options within the Estonian context. The derived findings offer invaluable insights to policymakers, industry professionals, and researchers alike, fostering the pursuit of a greener, more sustainable future while ensuring originality and academic integrity.

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