Future Energy
Open Access Journal
ISSN 2832-0328

November 2025| Volume 04 | Issue 04 | Pages 01-08
Journal homepage: https://fupubco.com/fuen
https://doi.org/10.55670/fpll.fuen.4.4.1

Future Publishing LLC

Article

Toward a 100% renewable energy future in Iceland: scenario analysis of geothermal, biofuel, and electric vehicle integration

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ARTICLE INFO

Article history:
Received 10 June 2025
Received in revised form
21 July 2025
Accepted 01 August 2025

Keywords:
Renewable energy, Energy transition, Carbon emissions reduction

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DOI: 10.55670/fpll.fuen.4.4.1

ABSTRACT

This study investigates the transition paths towards a 100% renewable energy system in Iceland through scenario analysis and simulation using the Energy PLAN software. Because of its unique geographical location and abundant geothermal resources, Iceland is a case study for renewable energy. In the present research, three primary scenarios are considered. The EV scenario is the substitution of fossil-fuel vehicles with EVs, which would imply that the proportion of renewable energy rises to 91.2% and CO_2 emission falls from 1.98 million tons in 2022 to 1.27 million tons by 2035. The Hybrid scenario, beyond the expansion of EVs, also includes the use of biofuels in industrial and maritime sectors, leading to an increase in the share of renewable energy to 96.6% and reducing CO_2 emissions down to 0.49 million tons. In contrast, the Business as Usual (BAU) scenario keeps the current system without structural changes, resulting in only a marginal increase in renewable energy share and an escalation of CO_2 emissions to 2.58 million tons. Alongside technical and environmental analysis, this study assesses the economic, social, and political aspects of the transition to a sustainable energy system. It highlights the importance of supportive policies, stronger regulations, and greater public awareness as key factors for success. Overall, the comprehensive insights provided by this research offer valuable guidance for policymakers and stakeholders aiming to reduce reliance on fossil fuels and enhance Iceland's environmental performance.

1. Introduction

The urgent global shift from fossil fuels to renewable energy has intensified research into sustainable solutions, and Iceland, with its vast, easily accessible geothermal resources, stands out as an ideal candidate for a 100% renewable energy system. Although substantial fossil fuel reserves continue to exist and new discoveries further expand these resources, the current trajectory of fossil fuel consumption is incompatible with the stringent emission limits set by the Paris Agreement. Therefore, it is imperative for countries to shift their focus towards harnessing domestic renewable energy potential in order to meet climate targets and ensure long-term environmental sustainability [1-4]. Reliance on fossil fuels increases system vulnerability, underscoring the need to minimize this dependency. Although global studies highlight various regional challenges, our focus remains on Iceland's unique energy landscape. Prior research has modeled individual renewable scenarios using energy planning software, yet few have integrated the interdependencies among various energy sectors. The United Nations predicts rising global temperatures, which, coupled with persistent fossil fuel dependency, may jeopardize energy security worldwide. For instance, Portugal, one of the European Union countries with significant energy dependency, could face national or international crises in the future [5-8]. Thanks to Iceland's strategic position in Europe and its close integration within the European Economic Area, the nation's renewable energy strategy has increasingly come under the influence of continental policy frameworks. In particular, the European Green Deal stands out as a comprehensive strategic initiative designed to curtail greenhouse gas emissions, bolster sustainable technologies, and foster the development of a green economy within the European Union. By incentivizing green investments and promoting clean technology advancement, this initiative is driving a fundamental transformation in the continent's environmental and economic policies, thereby creating a strategic context that reinforces Iceland's efforts. Aligning with these ambitious targets not only enhances Iceland's energy security and environmental sustainability but also establishes it as a benchmark for best practices across the region [9-11]. A study conducted by Elizabeth Paloma and colleagues examined the potential of geothermal energy (temperature-based) to supply 85% of the industrial activities in Spain. They found that Spain's industry has the potential to utilize at least 1.13% of geothermal energy, indicating the country's economic potential in harnessing this resource [12, 13]. Lebbihiat et al. [14] explored the potential of geothermal energy in Algeria, citing its relatively abundant low-enthalpy resources. They suggested that Algeria could partially meet its energy needs using this source, positioning the country as a pioneer in direct geothermal energy utilization in Africa, with a total installed heat capacity of 54.64 megawatts. Manish Ram et al. [15], in a study utilizing the LUT energy system transition model, investigated the technical and economic potential for achieving 100% renewable energy in Delhi. This included heating, desalination, electricity, and transportation sectors in India. Their findings indicate that Delhi could benefit from reducing primary energy consumption by over 40%, lowering energy costs by over 25%, decreasing greenhouse gas emissions, air pollution, and health impacts, thus facilitating regional energy transfer. Connolly conducted a technical and economic study on achieving 100% renewable energy for the European Union. They utilized the Energy Plan software to optimize the technical performance of a system and provide multiple scenario options. Their findings. revealed that the European Smart Energy scenario outperforms conventional energy scenarios by 10 to 15% in key economic and technical performance indicators. This advantage arises from reallocating investments from fuel imports to domestic job creation, which, in this context, would result in the generation of an additional 10 million direct jobs [16].

Parrado-Hernando et al. [17], in a study for Bulgaria on achieving 100% renewable energy, utilized the Energy Plan and ModAss tools. They identified a flexibility gap between two selected methods and proposed a new approach that is more beneficial for variable renewable energies in energy transition scenarios. Although Bulgaria's potential is limited by its three main industries, introducing hydrogen-based fuel results in a decrease in the system's Energy Return on Investment (EROI, which measures the ratio of usable energy produced to the energy invested in production) while simultaneously increasing the share of renewable energies [18]. Meschede et al. [19] highlighted the renewable energy potential of islands, where over 740 million people reside. Their results indicated that islands have significant potential to use solar PV and wind as primary technologies to reach a 100% Renewable Energy Source (RES) system. Dominković and colleagues described the transition process to a 100% renewable energy system for Southeast Europe by 2050. They emphasized that no single source should have more than a 30% share to enhance supply security. Economically, this transition would be beneficial, with primary energy supply expected to be nearly 51% lower than the baseline year [20]. Reyseliani et al. [21] assessed Indonesia's power system transition path using the VEDA-TIMES method to achieve 100% renewable energy. They evaluated and optimized the cost-minimizing path and considered reliability using a Monte Carlo-based approach. DaneshvarDehnavi et al. [22] embarked on a challenging inquiry into renewable energy systems, focusing on a city in West Texas with a peak load of 100 megawatts. They estimated the associated costs using two methods—real-time temporal data and load data—to attain an optimal model. Additionally, they utilized Monte Carlo simulations to enhance their analysis, comparing results to converge on an optimal blend and factoring in cost calculations to achieve a renewable energy system, considering reliability through a Monte Carlo-based analysis. Akuru et al. [23] raised a challenging question regarding the reliability and cost-effectiveness of RES systems in Nigeria. They initiated a study to outline the country's starting point toward reaching a 100% renewable energy system. Al Katsaprakakis et al. [24] examined the prospects of a 100% renewable energy system for the Faroe Islands. They defined systems and numerically simulated their performance to optimize dimensions. Their findings suggested that achieving an annual penetration of over 90% RES is entirely feasible both technically and economically, demonstrating the strong potential for a widespread renewable energy transition. Rey-Costa et al. [25], in their study for Australia, asserted the cost-effectiveness of renewable energies due to declining costs. They provided the most extensive geographical analysis and longest-term time series of solar PV and wind in the Australian electricity market. They identified areas better suited for industrial and commercial expansion through surplus renewable energy generation. Additionally, it was estimated that energy storage systems, designed to operate for durations ranging from 1 to 8 hours, could result in cost savings equivalent to nearly twice the annual energy demand—approximately 167 billion dollars—if battery storage is utilized, and up to four times that amount if non-battery storage solutions are implemented.

Daniel Icaza Alvarz et al. [26] proposed a zero-carbon energy system with 100% renewable energy for the Galapagos Islands, Ecuador, as the second-largest marine reserve in the world, designated a UNESCO World Heritage Site in 1978, with the project aiming for 2050. Michael Child et al. [27], by delineating two transition paths using the LUT energy system transition model, examined and plotted the path to 100% renewable energy for Europe by 2050. They deemed a 100% RES system technologically achievable and financially competitive for Europe, emphasizing the need for cost reduction and storage. Al-Ghussain et al. [28] investigated the security challenges of RES from a different perspective. They presented a novel method for assessing the security of integrated RES power systems, considering primary frequency regulation. Their evaluation, based on an improved accumulation-based PLF model using a multi-linear approach, creates a generalized power flow profile to rapidly identify operational violations. Previous works assumed ideal primary frequency control, compensating for fluctuations by conventional generating units over short time intervals, which may be invalid for small or isolated systems with high-RES penetration. Thus, incorporating primary frequency regulation into PLF analysis is crucial for a comprehensive system risk assessment. The proposed method has proven highly effective. Palomba et al. [29] outlined the implementation of a solar biomass system for multi-family homes to achieve 100% renewable energy. They reported that typical energy demand profiles for these buildings allocate about 70% of total consumption to heating, while cooling requires full capacity (100%). Moreover, even in northern climates, renewable energy sources can supply nearly 60% of the overall energy demand [30]. Tabrizi et al. [31] used a TOPSIS-based multi-criteria decision-making method to evaluate renewable energy adoption in G7 countries. They collected data on power generation, renewable outputs, carbon emissions, and economic indicators to calculate metrics such as carbon emissions per dollar of GDP. Their results revealed significant disparities, with the UK ranking highest and Canada lowest. The study shows that European nations with lower fossil fuel dependence perform better, providing valuable insights for policymakers. Previous research has explored geothermal potentials in various contexts, from industrial applications in Spain to low-enthalpy exploitation in Algeria, but these studies typically address isolated components rather than a full-system perspective. The research gap addressed in this article lies in the limited understanding and comprehensive analysis of the transition to a fully renewable energy system in Iceland, specifically focusing on the integration of geothermal energy with other renewable sources. Despite extensive studies on individual renewable resources, a comprehensive analysis that integrates the economic, social, and political challenges of transitioning Iceland's energy system remains lacking. Moreover, existing literature often overlooks the dynamic relationship between energy policy, technological innovation, and public acceptance in shaping the shift toward renewables. This article fills this gap by using the EnergyPLAN model to analyze various energy mix scenarios and their impact on Iceland's energy security, environmental sustainability, and economic feasibility. The study also critically examines the influence of government incentives and regulatory frameworks in encouraging the adoption of renewable technologies, helping to highlight both the obstacles and the opportunities involved. By addressing these underexplored aspects, this research not only contributes to the academic discourse on sustainable energy transitions but also provides practical insights for policymakers and stakeholders in Iceland and other regions with similar renewable energy goals. The findings underscore the importance of an integrated approach to energy planning, where technical, economic, and social factors are considered simultaneously to ensure a successful transition to a 100% renewable energy system.

2. Methodology

2.1 Current state of Iceland's renewable energy system

This research aims to model the transition to a 100% renewable energy system in Iceland and to analyze its technical and environmental impacts. Geothermal energy, the dominant energy source, accounts for 65% of the energy mix, utilizing Earth's residual heat to generate both heat and electricity. Hydroelectric energy contributes 20%, underscoring its important role in Iceland's energy portfolio. In contrast, solar energy represents a minimal share, with a 2022 capacity of 7 MW and production of 5 GWh, reflecting Iceland's low solar radiation levels, particularly during winter. Wind energy, primarily from coastal sources, had a reported capacity of 2 MW and produced 6 GWh in 2022. Although Iceland's long coastline offers significant wave energy potential, estimated at 1,524 TWh annually, commercial development remains improbable due to the lower costs associated with geothermal and hydroelectric power. Although Iceland has one of the lowest hydrogen fuel prices globally, its usage is currently limited, with minimal advancements in hydrogen infrastructure. Bioenergy usage is negligible, and the country has no nuclear facilities or plans for nuclear energy production. Fossil fuels, comprising 15% of the total energy mix, are predominantly used in transportation. Iceland's energy strategy emphasizes the use of diverse renewable resources that contribute to environmental sustainability. In the biofuels sector, 2022 data indicate limited use, with biofuel consumption in industry and fishing registering 0.8 TWh, compared to 2.3 TWh of oil consumption. In 2021, Iceland's renewable energy production totaled 19,617 GWh, with hydroelectric power generating 13,804 GWh, geothermal energy 5,802 GWh, and both wind and solar energy contributing 6 GWh and 5 GWh, respectively. The reliance on hydroelectric and geothermal energy illustrates Iceland's commitment to a sustainable, low-carbon energy system. This transition involves optimizing energy resources, enhancing energy efficiency, and promoting low-carbon consumption patterns to mitigate environmental impacts and reduce greenhouse gas emissions. Iceland was chosen as the focus of this study due to its unique energy profile and the relative simplicity of modeling its renewable energy system [32]. Table 1 shows the monthly temperature variations in Iceland, which are crucial for assessing the seasonal impacts on renewable energy production, particularly for geothermal and solar systems. Similarly, Figure 1 illustrates the moisture status of Reykjavík throughout the year, providing valuable insights into local climatic conditions that affect energy demand and system performance.

Table 1. Temperature of Iceland in different months of the year

Month	Average High(C)	Average low(C)	Warmest ever(C)	Coldest ever(C)	Daylight Hrs. (C)
Jan	36	28	50	1	4
Feb	37	28	50	7	7
Mar	39	32	57	7	10
Apr	45	33	59	9	15
May	50	39	70	19	18
Jun	54	45	70	32	20-22
Jul	60	50	74	34	19
Aug	57	48	70	32	16
Sep	52	43	68	25	13
Oct	45	37	61	14	9
Nov	39	34	54	10	6
Dec	36	28	52	1	4

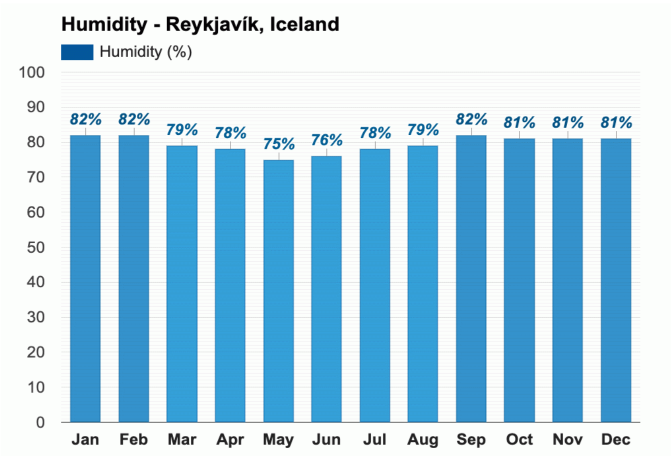

Figure1. Moisture status of Reykjavik, Iceland in different months of the year

2.2 Energy PLAN Software

In this study, the Energy PLAN model is employed. It is a deterministic simulation tool that has been specifically designed for comprehensive energy system analysis. Unlike many generic models, Energy PLAN uniquely features an 'Endpoint' approach, which is used to forecast future system configurations rather than merely replicating current conditions. Multiple sectors (heat, transportation, industry, and electricity) are integrated by this tool through the consideration of various inputs such as renewable resource capacities, system demands, and cost parameters for both renewable and non-renewable sources. The application of Energy PLAN has been successfully carried out across diverse contexts, from industrialized nations to developing countries, for the development of regional and national energy strategies. Its capability to simulate the economic, environmental, and technical impacts of different energy scenarios is particularly well-suited for the evaluation of Iceland's transition towards a 100% renewable energy system. Within the methodology of this study, Energy PLAN has been tailored to capture the unique interdependencies among energy sectors in Iceland, thereby enabling a detailed scenario-based analysis of pathways such as EVs, Hybrid, and BAU models. The overall flow of the model is illustrated in Figure 3, which is segmented into inputs, processes, and outcomes [33]. Peter Tozzi J.R. and Jane Jo [34] discussed renewable energy simulation using the Energy PLAN software. They described it as a cost-free, open-layer tool designed to analyze the energy, environmental, and economic impacts of various energy scenarios. The main objective is to model various scenarios and compare them. What makes it different is that the "Endpoint" modeling approach focuses on the future of the energy system rather than its current state [35].

2.3 Scenario descriptions

The first scenario, which is basically BAU, models the continuation of the current trend without any structural changes. This scenario serves as a depiction of the country's current status and highlights the importance and urgency of implementing the two previous scenarios to improve the energy situation in Iceland. In the second scenario, named the EVs (S2) scenario, the development of electric vehicles as an alternative to fossil fuel vehicles is expected to increase energy efficiency and reduce environmental impacts. This scenario is proposed as a significant solution for the transition of Iceland's transportation sector. In the last scenario, named the Hybrid (S3) scenario, not only are EVs developed, but industrial energy consumption and ships are also converted to biofuel. This step will harness the full potential of clean and sustainable energy from biofuel sources, contributing to the realization of energy sustainability goals in Iceland. These three scenarios together present a balanced and coherent approach towards achieving sustainable energy supply and reducing negative environmental impacts. Table 2 provides a summary of scenario descriptions. As population growth directly affects increasing demand, the described scenarios were implemented based on population data up to 2023 and projections until 2035. Figure 2 demonstrates the Icelandic population trend up to 2023.

3. Results and discussion

As clearly shown in Figure 3, the results revealed that the share of renewable energies in supplying energy demand, known as RES, is different for each scenario. In the EV scenario, RES percentage reached 91.2%, while in the hybrid scenario, it reached 96.6%, which shows that the implementation of this scenario can be considered an effective step in reaching the goal of 100% renewable system in Iceland. The BAU scenario remains significant despite having a lower capacity for reducing greenhouse gas emissions. It represents an improvement compared to the situation in other countries. Additionally, it can serve as a valuable benchmark for comparing other scenarios, helping us make informed decisions for future environmental and energy policies.

Table 2. Scenario descriptions

Scenarios	Abbreviation Code
Scenario 1- Continuation of the current trend in Iceland's energy system without any structural changes	BAU
Scenario 2- Conversion of fossil fuel cars to electric cars.	EVs (S2)
Scenario 3- Conversion of fossil fuel cars to electric vehicles alongside conversion of industrial and maritime energy consumption to biofuel.	Hybrid (S3)

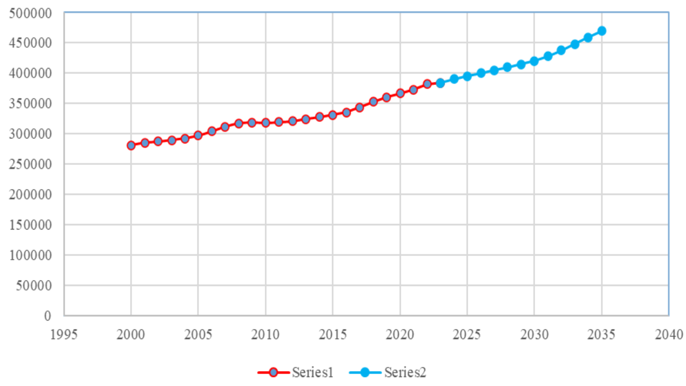

Figure 2. Iceland's population trend (blue points are available data and orange points are predictions)

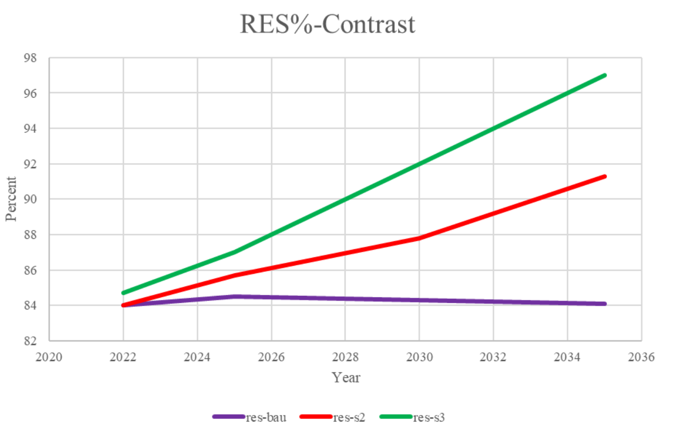

Figure 3. RES percentage trends

According to Figure 4, in terms of CO_2 emissions, as expected, both EV and hybrid scenario implementation lead to a reduction of carbon dioxide emissions, proving their positive and effective environmental impact and their role in mitigating the adverse effects of climate change. As can be seen in Figure 4, carbon dioxide emissions in 2022 amounted to 1.98 million tons. This number is reduced to 1.27 and 0.49 million tons by 2035 in EVs and the hybrid scenario, respectively. This experience underscores that implementing changes in transportation and industrial systems towards clean fuels and sustainable energy systems is an effective strategy for achieving environmental compatibility and reducing the harmful effects of human activities on the Earth. However, the study also has its weaknesses. The accuracy of the model is highly dependent on the quality and availability of input data, which may vary and therefore affect the reliability of the results. The outcome is specific to Iceland's unique energy system and may not be directly applicable to other regions with different conditions. Furthermore, while the study focuses on technical and environmental aspects, it does not delve deeply into economic considerations such as cost implications and financial feasibility, which are crucial for practical implementation and policy-making.

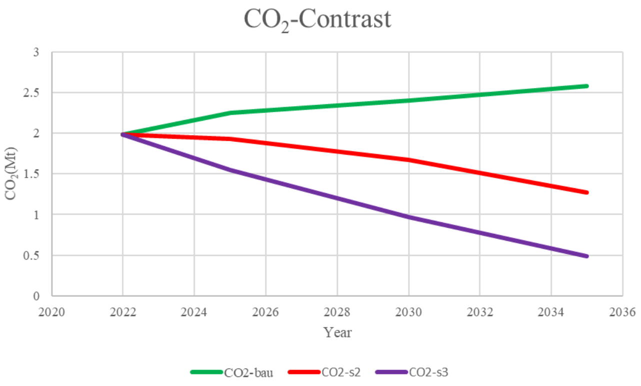

Figure 4. Carbon dioxide production rate

BAU scenario: In the BAU scenario, which assumes no significant changes to the current energy system, the share of renewable energy only increases slightly by 0.1%. This scenario reflects a continuation of current trends, with little progress in adopting renewable energy sources. Although the rate of increase is relatively modest, CO_2 emissions are projected to rise to 2.58 million tons by 2035. This indicates that without structural changes, Iceland's energy system will remain dependent on fossil fuels, resulting in a continued growth in greenhouse gas emissions.

EVs scenario (S2): In this scenario, fossil fuel vehicles are replaced with EVs; therefore, the share of renewable energy sources in Iceland's energy supply reaches 91.2% by 2035. This represents a significant shift toward cleaner energy consumption. CO_2 emissions decrease from 1.98 million tons in 2022 to 1.27 million tons by 2035. This reduction highlights the positive environmental impact of transitioning to EVs, which contribute to cleaner energy consumption and lower greenhouse gas emissions.

Hybrid scenario (S3): The Hybrid scenario goes a step further by combining EV adoption with biofuel utilization. In this scenario, fossil fuels are replaced with biofuels in the industrial and maritime transportation sectors, resulting in an even higher RES share of 96.6% by 2035. This scenario demonstrates the potential for near-total reliance on renewable energy sources in Iceland. The Hybrid scenario achieves the most substantial reduction, lowering emissions to just 0.49 million tons by 2035. This substantial reduction underscores the effectiveness of integrating multiple renewable energy strategies to mitigate climate change.

3.1 Economic consequences of transitioning to a 100% energy system

Cost reductions in energy supply: Transitioning to a 100% renewable energy system, particularly through scenarios such as EVs and Hybrid models, is projected to lead to significant reductions in energy costs. The EV scenario, which focuses on electric vehicles, reduces reliance on fossil fuels, leading to lower fuel expenditures and operational costs. The Hybrid scenario extends the noticed benefits by incorporating biofuel, which can stabilize energy prices in the long term by diversifying the energy mix. Both scenarios contribute to lowering the overall energy demand and enhancing energy efficiency, leading to cost savings across various sectors, including transportation, industry, and residential energy consumption. These reductions in energy costs can improve the economic competitiveness of Iceland's industries and reduce the cost of living for its citizens. Model estimates indicate that the EVs scenario could reduce total energy costs by approximately 12% compared to the BAU scenario, translating into annual savings of around $500 million by 2035. The Hybrid scenario, by integrating biofuels into sectors such as maritime transport, is forecasted to deliver cost reductions of up to 18%, as energy diversification contributes to long-term energy price stability.

Job creation and economic growth: Investments in renewable energy infrastructure, such as the development of EV charging infrastructure and biofuel production facilities, are expected to create jobs in construction, operation, and maintenance. The Hybrid scenario, which includes both EVs and biofuels, is likely to generate more employment opportunities than the EV scenario alone. The transition to a 100% renewable energy system also has the potential to attract foreign direct investment, particularly in green technologies and clean energy sectors, contributing to the diversification of Iceland's economy and economic growth. According to the model, the EV scenario could directly generate around 3,000 new jobs in areas related to the deployment and maintenance of EV infrastructure. The Hybrid scenario is projected to deliver even more employment benefits, potentially creating an additional 5,000 direct jobs due to the broader scope of investments in both electric vehicle and biofuel production facilities. These employment gains, alongside enhanced industrial competitiveness, contribute to overall economic growth and diversification.

Financial evaluation and investment opportunities: The financial evaluation of the proposed scenarios highlights the critical need for upfront capital investments in renewable energy infrastructure. While the EV scenario demands considerable initial investment, it offers long-term financial benefits through reduced fuel imports and lower operational costs. The Hybrid scenario requires even more extensive investments, particularly in biofuel production and distribution networks. However, these additional costs can be justified by the long-term advantages of enhanced energy security and reduced sensitivity to fuel price fluctuations. Early investments in these scenarios would play a pivotal role in realizing these economic benefits. By supporting the development of renewable energy infrastructure, investors can ensure the financial viability of these projects and gain significant returns on investment through the growing demand for clean energy.

3.2 Recommendations for policymakers and stakeholders

Incentivize investments in renewable energy: Our results indicate that both the EVs and Hybrid scenarios yield significant cost savings and emission reductions. Policymakers can build on these insights by offering targeted tax incentives, grants, and low-interest loans focused on expanding EV infrastructure and developing sustainable biofuel systems. Such measures will further drive investment into areas where our model shows the greatest potential for improvement.

Enhance energy policy frameworks: Given Iceland's unique strengths in geothermal and hydroelectric power, existing energy policies should be revised to integrate additional renewable measures demonstrated in our scenarios. It's not just about increasing the share of renewables overall; it's also about enabling specific measures, like scaling up biofuels for maritime transport, which can play a decisive role in improving energy security and reducing fossil fuel dependency.

Promote public awareness and education: A successful transition to a 100% renewable energy system is not only a technical or economic challenge, but also a social one. Our findings underscore the importance of public engagement. Designing public awareness campaigns is recommended to highlight the specific benefits of EVs and Hybrid scenarios, such as reduced operational costs and improved air quality. Educational programs can also foster greater understanding of how everyday choices connect to Iceland's long-term sustainability and resilience.

3.3 Social and Political Challenges of the Transition to a 100% Renewable Energy System

Addressing policy and infrastructure gaps: Although the simulation results indicated promising technical and environmental potential, overcoming institutional and infrastructural barriers is essential in order to achieve these benefits in practice. Policymakers must address the existing gaps in the current system. For instance, the growing share of renewable energy sources requires modernizing the national grid and expanding electric vehicle charging infrastructure.

Managing the socioeconomic transition: The scenarios also pointed to potential economic gains, such as job creation within renewable energy sectors. Nevertheless, these advantages must be weighed against the disruptions caused by restructuring traditional industries. Strategic support is needed for employee retraining and local economic diversification to mitigate any short-term employment disruptions.

Securing political and public support: Given the innovative nature of integrating biofuels with existing renewable resources in the Hybrid scenario, it is crucial to build a broad consensus. Government incentives, coupled with transparent communication of study findings (e.g., quantified reductions in CO_2 emissions and cost savings), can help secure both political support and public approval for the necessary structural reforms.

These recommendations and challenges are directly derived from the findings of our Energy PLAN-based scenario analysis, ensuring that policy and stakeholder strategies are both targeted and feasible.

4. Conclusion

This study explored a new pathway for Iceland's energy transition by integrating geothermal energy, biofuels, and electric vehicles into a unified, scenario-based model using the Energy PLAN software. Unlike earlier studies that often examined renewable energy sources in isolation, this paper focused on how different energy sectors interact within broader policy frameworks. Three distinct scenarios were compared: in the EVs scenario, replacing fossil fuel vehicles with electric vehicles significantly boosted the share of renewable energy and led to a noticeable reduction in CO_2 emissions; in the Hybrid scenario, which combined the adoption of EVs with the use of biofuels in industrial and maritime sectors, the renewable energy share reached approximately 97% while CO_2 emissions dropped to 0.49 million tons by 2035. Conversely, the BAU scenario showed only a marginal increase in renewable energy share, with CO_2 emissions rising to 2.58 million tons. These findings demonstrated that integrated renewable strategies can substantially enhance energy security and environmental sustainability. The outcomes also aligned with growing research supporting the necessity of comprehensive energy planning. Compared to earlier studies that treated individual energy sources separately, this work underscored the added value of a multifaceted approach and highlighted the importance of supportive policies such as those promoted by the European Green Deal in driving the transition. In summary, the study confirmed that strategic interventions and the adoption of a diverse renewable energy mix are essential for overcoming fossil fuel dependency. It offered both a theoretical contribution to academic discourse and practical guidance for policymakers and stakeholders in Iceland and similar regions pursuing a low-carbon future.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically concerning authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere in any language.

Data availability statement

The manuscript contains all the data. However, more data will be available upon request from the corresponding author.

Conflict of interest

The authors declare no potential conflict of interest.

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