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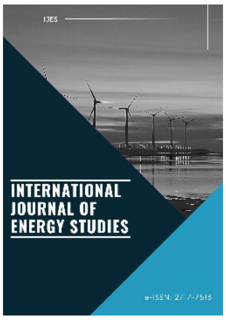

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A Fuzzy-based model proposal for forecasting greenhouse gas-free supply chain potential

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Highlights
- Renewable energy certificates are used for reducing greenhouse gas emission.
- Greenhouse gas-free supply chain potential can be forecasted based on REC.
- Because of insufficient data, fuzzy is more useful than machine learning.
- This study proposes fuzzy models for forecasting green supply chain potential.

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ABSTRACT

Various greenhouse gas emission control approaches, such as filtration, require costly audits and are not suitable for creating foresight to scale gains across the supply chain. Thus, these practices are not suitable for building effective policies to reduce greenhouse gas emissions. This study proposes an approach to forecast greenhouse gas-free supply chain potential based on the producible renewable energy certificate amount to be able to build consistent, realistic, effective, and applicable policies to reduce emissions and promote renewable energy production. The greenhouse gas-free supply chain potential of countries and states can be measured and tracked through their total energy consumption certified with renewable energy certificates. By proportioning this value to the total energy consumption of the supply chain, the extent to which the green transformation has been achieved can be measured and scaled. The proposed model is built on fuzzy logic since renewable energy certificates contain uncertainties, and there is not enough data to make machine learning-supported forecasts because it is a developing field and an innovative business. The developed model is applied to the example of Türkiye, and the practical greenhouse gas-free supply chain potential of Türkiye is forecasted as 30.9 million megawatts (equivalent to 221 thousand ten-year trees) for 2024. Even in possible adverse events in the market and climatic conditions, it is not expected to decrease below 22.7 million megawatts. By considering these calculations, more realistic and more applicable obligatory energy policies can be produced without bringing additional audit burdens to the industrialists across the country.

Keywords: Renewable energy certificate, Green supply chain, Greenhouse gas emission, Electricity trading, Fuzzy logic

1. INTRODUCTION

Green supply chain (GSC) is an extended supply chain (SC) network that aims to reduce the environmental damage of manufactured products throughout their life cycles [1]. While there is a structure in which environmental concepts are prioritized in the GSC, there is a structure in which cost and time are at the forefront of the traditional SC [2]. GSC covers all processes from the first stage of production to the last stage [3]. In GSC, it is aimed to carry out all kinds of processes in production without harming the environment and to benefit from waste [4]. Companies that adopt GSC aim to reduce the negative effects harming nature and increase their profitability and productivity by considering the concept of green [5]. There is increasing interest in GSC among many practitioners and researchers due to the rapid rise of negatives such as emissions, pollution, solid wastes, and toxic materials that cause environmental degradation. A GSC can reduce the impact of industrial activities on nature and living things without compromising cost, quality, performance, and energy use efficiency [6]. Focusing on renewable energy (RE), green logistics, green production, and green products contributes to businesses increasing their SC activities [7].

The increase in energy consumption brings air, water, and soil pollution, greenhouse gas (GHG) emissions, and many other problems. The reduction of GHG emissions is a crucial goal in GSC applications, particularly for manufacturing companies. However, traditional approaches like filtration are inadequate for effectively controlling and scaling emission reductions due to diverse manufacturing processes. These methods also require costly audits, making them unsuitable for creating foresight across the SC. They also do not give the insight to scale the overall achievement overall the country. RE emerges as a promising solution to combat the increase in GHG emissions, especially in the manufacturing industry, which is responsible for a significant portion of carbon dioxide (CO_2) emissions. Conventional energy sources not only contribute to emissions but also pose environmental risks and depletion concerns. Recognizing the growing global demand for energy and the need for sustainable solutions, countries are increasingly adopting policies to promote RE. These policies, if integrated into GSC strategies, can offer substantial support in accelerating the transformation towards RE resources (RERs).

Renewable Energy Certificate (REC) is one of the latest mechanisms used to eliminate or reduce the GHG emissions. RECs are instruments that represent the quantity of electricity produced from RE sources [8]. REC mechanism aims to reduce CO_2 and other GHG emissions and contribute to the growth of the share of RE [8] [9]. RECs can be generated from solar energy (SE), wind energy (WE), hydropower energy (HE), geothermal energy (GE), and biomass energy (BE) [9]. RECs correspond to the electricity in MWh (megawatts per hour) units produced by RERs [10]. RECs contain information not only about the energy source but also about energy properties. Consumers with REC serves reducing GHG emissions by using energy [11]. RECs offer significant potential in developing efficient energy policies to support GSC and mitigate GHG emissions. They serve as valuable instruments in reducing CO_2 and other GHG emissions associated with electricity production from RERs. In addition to the benefits that REC mechanisms provide, it is foreseen that the motivation it provides to energy producers will have a locomotive effect encouraging the increase of the share of RESs in energy production. Thus, sustainable energy transformation will be accelerated. Industrialists and large companies are increasingly demanding RECs, even pressuring their suppliers to adopt certified energy. This growing prevalence of RECs in industries contributes to the measurement of GHG-free SC potential, making it a reliable and practical approach in tackling the GHG emission challenge.

This study proposes a fuzzy logic-based approach to forecast the GHG-free SC potential of countries and states using producible RECs. The goal is to establish consistent, realistic, effective, and applicable policies for reducing GHG emissions and promoting RE production. The model utilizes the total MW energy consumption certified with RECs to measure and track the GHG-free SC potential, which can be scaled to assess the progress of the green transformation. The proposed model is particularly suitable for RECs, given their role in addressing not only air, water, and soil pollution but also GHG emissions. By leveraging the GHG-free SC potential, countries can develop more applicable and effective energy policies while supporting long-term planning and reducing certification and audit costs for industries. The generic nature of the model is applicable to any country or state, enabling the basis for future energy policies. As RE and REC remain developing fields with uncertainties and limited data for machine learning-based forecasts, a fuzzy logic-based model offers a reliable forecasting tool for this context. The proposed model is applied to the example of Türkiye by using the demands of industrial establishments and the expected statistical increase in REC capacities. Currently, REC planning and trading operations are managed on an annual basis worldwide. As a future projection, a modified version of the model is developed by considering the expected potential in the scenario where REC planning and trading are done monthly. This model is also applied to the case of Türkiye to find the monthly-basis GHG-free SC potential. It is expected that this study will contribute to the determination of Türkiye’s REC policy and the planning of SCs of domestic and foreign companies that implement GSCs. The rest of the paper has been arranged as follows: literature review is presented in Section

2, a fuzzy based model to forecast the GHG-free SC potential of the countries is proposed in Section 3 and applied to Türkiye case in Section 4. Results are discussed in Section 5, and concluding remarks and future research directions are given in Section 6.

2. LITERATURE REVIEW

One of the most important issues in the world in recent times is environmental sustainability. In this context, GSC practices have gained great importance in terms of reducing the damages, such as soil and air pollution caused by the industry to the environment. Common GSC practices can be listed as increasing energy efficiency, reducing waste, recycling [12], Waste management [13], Green purchasing [14], Green procurement [15], Reverse logistics [16], Green logistics [2], Green product [17], Green supplier selection [18], Eco-design [19], etc.

Many studies have been done in the literature for increasing the efficiency of GSC. Sheu et al. [20] created an optimization-based multi-objective linear programming (MOLP) model to solve logistics operation problems in the GSC by optimizing integrated logistics and reverse logistics operations. This proposed model improved the total net profit by 21.1%. Kainuma & Tawara [21] extended the scope of the SC by including recycling and reuse. They also proposed the multiple utility method theory to evaluate the SC. Walton et al. [22] found that GSC-related studies can be beneficial in reducing costs and providing better service to customers in the furniture industry. Wang et al. [23] proposed a MOLP model for GSC network design to minimize the environmental impact and the total cost by considering the minimization of the cost and the carbon emission overall the SC. Improvements in network capacity and the increase in the supply facilities reduced the total cost and carbon emission [23]. Kafa et al. [24] proposed a mathematical model based on economic, environmental, and social perspectives to evaluate the sustainability performance of green practices in the SC. There are many studies evaluating GSC management practices [25] [26] [27] and GSC management performance [28] [29], green supplier performance [30], and GSC risks [31] using fuzzy decision-making approaches. As a GSC management practice, Köseoğlu [32] focused on the green supplier selection problem by proposing intuitionistic multiplicative TODIM method based on intuitionistic multiplicative number.

The manufacturing industry is responsible for almost half of CO_2 emissions because of energy usage [33]. In the GSC concept, the energy requirements should be met by RE sources since the production of electricity from conventional sources causes GHG emissions. The integration of SC with RE greatly assists in tackling global warming, and possible global energy crisis. As an emergent concept, in RE supply chains (RESC), RE production also takes place within an SC including informational, financial, and physical flows. Some studies such as [34] focus on the performance improvement of RESC to provide better management of SC costs to make RE more economic and competitive. Even if the initial investment is currently higher for RE than conventional energy sources, it is expected to decrease in the long term as manufacturers' widespread generation of RE [35]. Wang et al. [36] measured RE/non-RE consumption in global SCs and determined the "green-degrees" of SCs. When the green-degrees are analyzed with the characteristics of SCs, it is deduced that energy awareness, top management commitment, and energy auditing are the key factors for the successful development of RESCs [36]. Fernando et al. [35] investigated the effects of energy management practices on RESC initiatives on manufacturing companies in Malaysia and found that if knowledge about energy efficiency is insufficient, energy may not be managed effectively, and opportunities such as converting waste into energy may be missed.

Most of the studies about GSC and GHG emissions present conclusions about possible energy policies. The widely agreed viewpoint is that RE-related policies should be made. Many researchers are directly interested in RE policies, which are essential for a smooth transition to green energy sources [37] [38] [39] [40]. As a specific example, Zhang & Kong [41] concluded that RE policies support the total factor productivity of energy companies after the investigation about the RE policies. Gulagi et al. [42] analyzed current RE policies and different energy policies for Bangladesh and observed that emission costs accelerate the green transition. Khan et al. [43] confirmed that energy efficiency and RE have a positive impact on green economic growth and emphasized that management plays a major role in the implementation of RE and energy efficiency technologies. Unfortunately, as mentioned by Xu et al. [44], despite the presence of numerous energy restriction policies, how to ensure these policies play a better role is still a topic that requires in-depth discussion. Additionally, there is a lack of relevant research on the role of GSC in promoting enterprise-energy transformation.As one of the recent and developing approaches to combat GHG emissions, REC is a promising approach for building effective RE policies. In the literature, there are some studies on RECs from various perspectives. Gupta & Purohit [45] evaluated the effectiveness of REC mechanisms in India by considering cost competitiveness, decentralized distributed generation, and RE portfolio diversity. Irfan [46] examined the relationship between electricity and REC markets in India using an autoregressive distributed lag

(ARDL) modeling by using price, trade volume, electricity trade volume, and wholesale electricity price of solar as variables. Girish et al. [10] discussed REC trading in India, policies promoting RE, the obligation to purchase renewables, the role of energy exchanges in REC trading, and possible policy considerations for the future. Hulshof et al. [47] investigated the customer churn rate, certification rate, expiry performance of certificate expiry dates, and price variability of the REC markets of 20 European countries using a Guarantee of Origin (GO) between 2001-2016 and concluded that the certification rate in 2015 increased compared to 2001, but there was no change in other variables. Adamczyk & Graczyk [48] evaluated the REC system implemented in Poland since its accession to the European Union. REC certificates have also started to be bought and sold in Türkiye, but they are not widely used yet. There are both domestic and foreign certification bodies in Türkiye. Özcan et al. [9] analyzed the RECs used in the world, evaluated the REC system in Türkiye, and calculated Türkiye's REC potential according to electricity consumption data. They concluded that REC was produced from 0.72% of Türkiye's current potential. The literature shows that although REC is a mechanism promoting RE, it will not become widespread quickly unless it is supported by energy policies.

3. THE PROPOSED METHODOLOGY

As a component of GSC studies, GHG emissions of the companies should be decreased or amortized but it is difficult to control and follow up. Most of the approaches such as filtering do not give the insight to scale the overall achievement because the processes of the manufacturing systems have great diversity. RE plays an important role in solving the GHG emission increase. REC is one of the latest mechanisms used to eliminate or reduce the GHG emission problem. RECs are instruments that represent the qualities of electricity produced from energy sources and reduce CO_2 and other GHG emissions. The prevalence of REC has a high impact and potential to contribute to GSC. RECs are demanded by industrialists. Large industrialists may force their suppliers to obtain RECs as well. Thus, it is possible to measure the GHG free SC potential via the REC. In fact, it can be said to be a consistent and practical approach to measuring this potential. This study proposes an approach to forecasting states' and countries' GHG-free SC potential based on potentially producible REC amount to be able to build consistent, realistic, effective, and applicable policies to reduce GHG emissions and promote RE production. Currently, it is popular to use machine learning approaches to make forecasts. However, RE and REC are developing fields so there is no sufficient data for conducting such a mechanism. However, the proposed model is built on fuzzy logic since REC contains uncertainties and there is not enough data to make machine learning-supported forecasts because is a developing field and an innovative business. Actually, when the literature is analyzed, it is seen that too many studies use fuzzy logic-based methodologies in the RE field such as [49] [50] [51] [52].

The proposed model is applied within a procedural framework shown in Figure 1 The procedure consists of two phases. It is possible to consider the work done in these phases as (i) preliminary preparation, and (ii) calculation. In the preliminary phase, data are collected from energy platforms. The collected data are analyzed and the fuzzy set parameters to be used are decided. In the last step of the first phase, the contract loss ratio, industry growth ratio, and green electricity production capacity increase ratio model parameters are determined. GHG-free SC potentials for the next years are calculated on a monthly and annual basis with the input data obtained using the calculation models given in the following sub-sections. To test the accuracy of the results, data from previous years are estimated and the MAPE value is calculated. In the next step, sensitivity analysis is performed to be able to make qualified managerial and policy inferences.

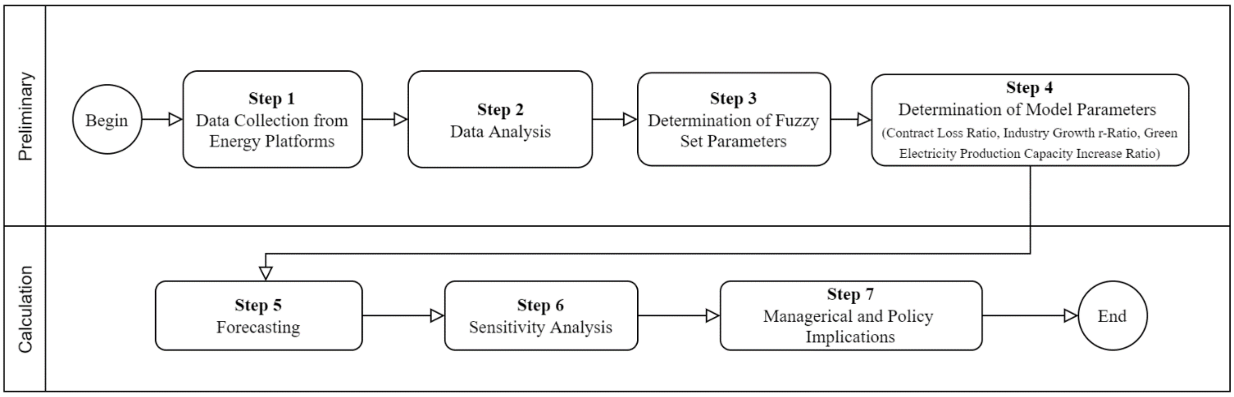

Figure 1. Execution procedure for the proposed forecasting model

3.1. The Potential based on Available REC Trading Scheme

The proposed fuzzy-based model uses three parameters and two decisions variables to calculate the theoretical and practical GHG-free SC potentials. The model is given below:

Indices:

$j \in \{1,2,\ldots,12\}$: months

$n \in \mathbb{Z}^* = \{0\} \cup \mathbb{Z}^+$: future years

Parameters:

$\tilde{r}$: fuzzy annual green electricity production capacity increase ratio

$\tilde{\imath}$: fuzzy annual industry growth ratio

$\tilde{s}$: fuzzy contract loss ratio because of the certificate cost

Decision variables:

$\tilde{x}_j$: fuzzy green electricity production capacity for month j in year 0.

$\tilde{d}_j$: fuzzy electricity demand for month j in year 0.

Output variables:

$\tilde{T}_n^{yearly-basis}$: theoretical yearly-basis fuzzy GHG-free SC potential for n years after now.

$\tilde{P}_n^{yearly-basis}$: practical yearly-basis fuzzy GHG-free SC potential for n years after now.

Model:

$$\tilde{T}_n^{yearly-basis} = \min\left\{(1+\tilde{r})^n \times \sum_j \tilde{x}_j, (1+\tilde{\imath})^n \sum_j \tilde{d}_j\right\} \tag{1}$$

$$\tilde{P}_n^{yearly-basis} = (1-\tilde{s}) \times \tilde{T}_n^{yearly-basis} \tag{2}$$

3.2. The Potential based on Monthly Planning as a Future Projection

Performing RE certification on an annual basis is an incomplete approach in terms of controlling environmental impacts. As a future projection, it is foreseen that this certification process can be reduced to monthly periods since the production of RE changes on a monthly basis with seasonal effects, but the energy demand does not vary as much as the RE production on a monthly basis. Although the buy-sell match that can be obtained in the bottom total is certified on an annual basis, if the certification is done on a monthly basis, there will be a change in the total amount of certificates. In the monthly planning approach, a scaling of RE capacities is made on a monthly basis using market data, and a calculation is made for the parts of it that can match the demand on a monthly basis. Thus, a new capacity value is obtained. This obtained capacity is a more realistic value for reducing environmental impacts and for certification to provide an effective benefit for nature. In addition, it is an important statistic in terms of demonstrating the sustainable capacity of the country regarding REC certification and indirectly a more realistic statistic in terms of showing the GSC potential.

The proposed monthly-basis model has some additional parameters, and the main equation is updated accordingly:

Parameters:

$\tilde{r}$: fuzzy monthly green electricity production capacity increase ratio

$\tilde{\imath}$: fuzzy monthly industry growth ratio

Additional output variables:

$\tilde{T}_n^{monthly-basis}$: theoretical monthly-basis fuzzy GHG-free SC potential for n years after now.

$\tilde{P}_n^{monthly-basis}$: practical monthly-basis fuzzy GHG-free SC potential for n years after now.

Model:

$$\tilde{T}_n^{monthly-basis} = \sum_j \min\{((1+\tilde{r})^n \times \tilde{x}_j), ((1+\tilde{\imath})^n \times \tilde{d}_j)\} \tag{3}$$

$$\tilde{P}_n^{monthly-basis} = (1-\tilde{s}) \times \tilde{T}_n^{monthly-basis} \tag{4}$$

4. CASE STUDY

In this section, the proposed forecasting model is applied to the Türkiye case by using the demands of industrial establishments to find the monthly-basis GHG-free SC potential.

4.1. Renewable Energy in Türkiye

Although Türkiye is in a very convenient geographical location in terms of RERs, it is a foreign-dependent country in energy since almost more than half of the energy in Türkiye is imported [53] [54]. In Figure 7, production rates based on resources for 2022 are given. The most significant growth in production in 2022 is seen in natural gas, hydropower, imported coal, and lignite production. According to Figure 2, it is seen that traditional fossil fuels are produced more than RERs to meet Türkiye's energy demand. However, it can be interpreted that the share of hydroelectricity in production is higher than other RERs. Figure 3 shows the changes in power based on HE, WE, SE, BE, and GE over the last 11 years [55].

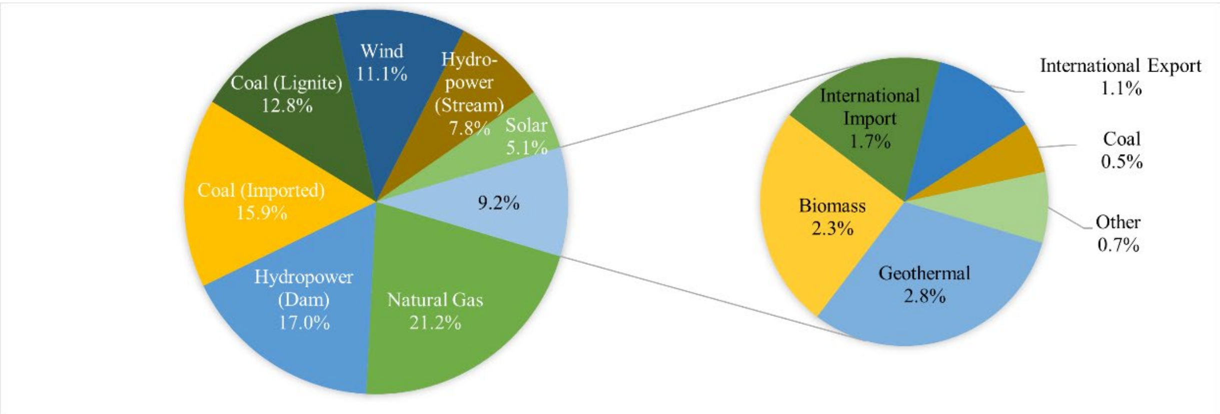

Figure 2. Resource-based electricity production rates in Türkiye in 2022 [56]

Türkiye has various RE sources and aims to increase its WE and SE by at least 1000 MW per year in the coming years [54]. Türkiye has also a high potential in terms of SE thanks to its geographical location [55]. Since Türkiye is located on an active tectonic belt, it is in a very good position when compared to other countries in terms of GE. It is the first country in Europe in terms of GE potential and the 4th country in the world in terms of installed power [55]. Türkiye is one of the countries using I-REC standards. A domestic certification foundation also issues certificates namely REC-G.

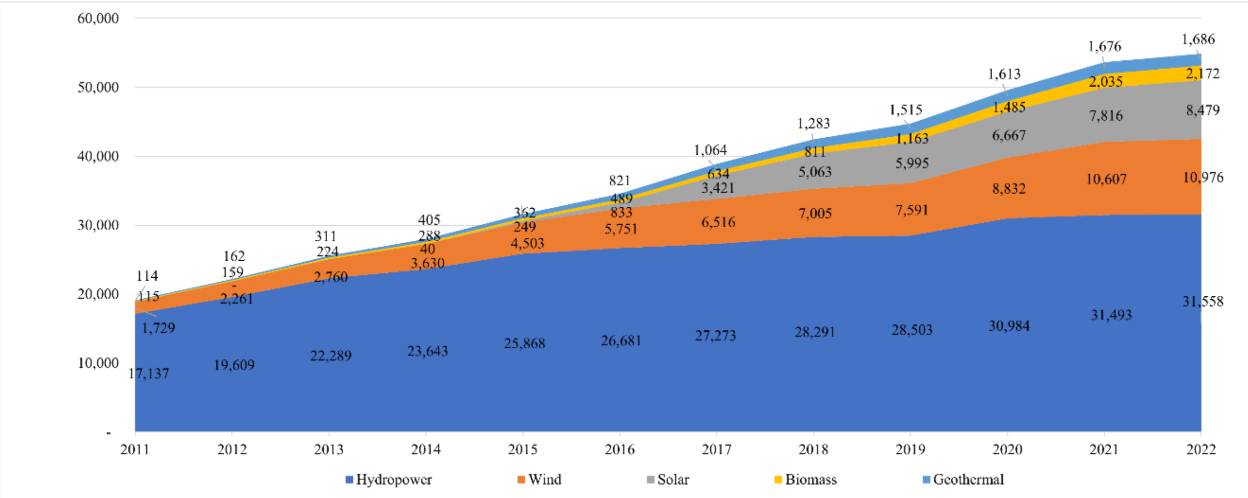

Figure 3. Installed power based on RERs [55]

4.2. Forecasted Greenhouse Gas-Free Supply Chain Potential of Türkiye based on REC

Data collected from the EXIST transparency platform [57] and Foton [58] were used for the application. Data was analyzed and it was decided that the fuzzy information can be modeled as a Triangular Fuzzy Set.

Contract loss ratio is calculated by combining the data collected from both I-REC and REC-G systems. In the I-REC system, some of the certificates are issued to 2022 while the production is made in the previous year. If the contract loss ratio is calculated by using all the issued certificates, it is found as 77%. On the other hand, it is calculated as 85% by ignoring the quantity produced in the previous year. In the current scenario, there is no apparent reason that require the use of other fuzzy set shapes such as trapezoid. In order to not make the calculations complex unnecessarily, the triangular fuzzy set is decided by considering this situation. Triangle form would be the most appropriate approach for the current scenario. Of course, different future findings may require the use of different fuzzy set shapes. The proposed model can also be used with different cluster shapes, in which case arithmetic operations will need to be performed in accordance with that set shape. By using the input data given in Table 1, the GHG-free SC potentials for the next five years are calculated as in Table 2 according to the yearly-basis model given in Eqs. (1-2). According to the results of the yearly-basis model, practical GHG-free SC potential is forecasted between 21 and 34 million MWh, and the most probable value is found as 27 million MWh for 2023. The accuracy of the forecasts decreases while the period is increasing. The practical GHG-free SC is forecasted between 26 and 63 million MWh with the most probable value 42 million MWh for 2027. The utilized capacity of RE sources changes on a monthly basis with seasonal effects while the energy demand is fluctuating very less depending on the seasons. In the monthly planning approach, the RE capacities matched with the demand on a monthly basis, and different GHG-free SC potentials are obtained according to the yearly-basis model. The forecasted potentials for Türkiye are given in Table 3. Results show that the most probable values of the forecasted GHG-free SC potentials are approximately 4.9% less than the yearly-basis model. The lower bounds of the forecasts are 2.6% less and the upper bounds of the forecasts are 7% less than the lower and upper bounds of the yearly-basis model, respectively. The potential is forecasted between 20 and 32 million MWh with the most probable value 26 million MWh for 2023. It is forecasted between 25 and 58 million MWh for 2027.

Table 1. Input data in triangular fuzzy set form

	Yearly-basis	Monthly-basis
$\tilde{r}$	$\langle 0.055,\ 0.109,\ 0.162 \rangle$	$\langle 0.0044,\ 0.0087,\ 0.0126 \rangle$
$\tilde{\iota}$	$\langle -0.006,\ 0.024,\ 0.089 \rangle$	$\langle -0.0005,\ 0.002,\ 0.0071 \rangle$
$\tilde{s}$	$\langle 0.77,\ 0.81,\ 0.85 \rangle$	$\langle 0.77,\ 0.81,\ 0.85 \rangle$
Month (j)	$x_j\ (MWh)$	$d_j\ (MWh)$
1	9’751’335.73*	26’769’770.65
2	9’700’923.88	24’159’138.22
3	13’632’657.17	26’786’641.90
4	13’927’311.77	24’475’916.15
5	13’647’510.45	23’979’859.69
6	12’657’071.72	25’712’148.12
7	13’006’907.09	27’398’690.91
8	11’141’042.66	29’896’238.98
9	9’217’761.55	25’863’031.15
10	9’066’848.03	23’705’364.07
11	8’377’563.24	23’242’726.53

12	8’061’973.48	25’054’734.79
Total	132’188’906.77	307’044’261.16

*: The character ‘ is used as thousands separator to avoid confusion with notation marks

Table 2. Forecasted potentials in triangular fuzzy set form for the next five years in yearly-basis model

Year	$T_n^{yearly-basis}(MWh)$	$P_n^{yearly-basis}(MWh)$
2023	⟨139′459′296.64, 146′597′497.61, 153′603′509.67⟩	⟨21′469′190.62, 27′819′893.65, 34′652′222.78⟩
2024	⟨147′129′557.96, 162′576′624.85, 178′487′278.23⟩	⟨22′649′996.1, 30′852′262.05, 40′265′882.87⟩
2025	⟨155′221′683.65, 180′297′476.96, 207′402′217.31⟩	⟨23′895′745.89, 34′215′158.62, 46′788′955.9⟩
2026	⟨163′758′876.25, 199′949′901.94, 241′001′376.51⟩	⟨25′210′011.91, 37′944′610.91, 54′368′766.75⟩
2027	⟨172′765′614.44, 22′1744′441.26, 280′043′599.5⟩	⟨26′596′562.57, 42′080′573.49, 63′176′506.96⟩

Table 3. Forecasted potentials in triangular fuzzy set form for the next five years in monthly-basis model

Year	$T_n^{monthly-basis}(MWh)$	$P_n^{monthly-basis}(MWh)$
2023	⟨135′878′944.19, 139′438′063.81, 142′874′261.69⟩	⟨20′918′009.94, 26′461′243.67, 32′231′755.36⟩
2024	⟨143′352′286.12, 154′636′812.76, 166′019′892.08⟩	⟨22′068′500.49, 29′345′519.23, 37′453′299.73⟩
2025	⟨151′236′661.85, 171′492′225.35, 192′915′114.6⟩	⟨23′282′268.02, 32′544′180.82, 43′520′734.28⟩
2026	⟨159′554′678.26, 190′184′877.92, 224′167′363.17⟩	⟨24′562′792.76, 36′091′496.53, 50′571′093.23⟩
2027	⟨168′330′185.56, 210′915′029.61, 260′482′476⟩	⟨25′913′746.36, 40′025′469.65, 58′763′610.34⟩

According to the United States Environmental Protection Agency [59], 0.477 tons of CO_2 emission is prevented per 1 MWh of energy provided by RESs. The specified amount of CO_2 emission can be absorbed by 7,153 ten-year-old trees. In other words, 7,153 trees are saved by using 1 MWh RE. When these data are scaled with the forecasted values, it is expected that approximately 189,277 (between 149,627 and 230,554) trees will be saved in Türkiye in 2023 by GSCs.

In order to validate the results, the model has been used for forecasting the data of the previous years. Both I-REC and REC-G mechanisms have been introduced in recent years in Türkiye. Foton [58] shares data for I-REC as of 2020 and EXIST [57] shares data for REC-G as of 2021. To provide a consistent analysis, the GHG-free SC potentials for 2021 and 2022 have been forecasted as shown in Table 4. The mean absolute percentage error (MAPE) has been reached as 2.9%. The actual value has been covered by the triangular fuzzy forecasts. Forecast quality for 2022 is noticeably better than 2021. This may be due to the fact that the REC mechanisms are very new in 2021.

Table 4. Deviations of the forecasts for previous years

Year	Actual (MWh)	Forecast (MWh)	Is Actual Value Covered by Fuzzy Forecast?	Percentage Deviation
2021	21,409,236	$\langle 19'289'046.2,\ 22'619'988.2,\ 25'663'674.7\rangle$	Yes	$\langle -9.9\%,\ 5.7\%,\ 19.9\%\rangle$
2022	20,347,104	$\langle 18'283'456.1,\ 20'396'743.2,\ 22'085'778.6\rangle$	Yes	$\langle -10.1\%,\ 0.2\%,\ 8.5\%\rangle$
			MAPE	$\langle 10.0\%,\ 2.9\%,\ 14.2\%\rangle$

4.3. Sensitivity Analysis

The forecasts are obtained assuming that current REC policies and directions will continue. However, it is predicted that the interest and sensitivity towards RE will increase in the near future. Such a tendency can reduce the contract loss ratio in the proposed models. A reduction in the contract loss ratio will lead to increase in the forecasted GHG-free SC potentials. To explore the relationship between the forecast values and the contract loss ratio, a sensitivity analysis has been made. Several contract loss ratio values have been tested and the results are presented in Table 5:

Table 5. Sensitivity analysis based on contract loss ratio in yearly-basis model

Contract Loss Ratio	Year	$P_n^{yearly-basis}$ (MWh)
$\langle 0.75, 0.8, 0.85\rangle$	2023	$\langle \mathbf{20'918'894.5},\ 29'319'499.52,\ \mathbf{38'400'877.42}\rangle$
	2024	$\langle 22'069'433.69,\ 32'515'324.97,\ 44'621'819.56\rangle$
	2025	$\langle 23'283'252.55,\ 36'059'495.39,\ 51'850'554.33\rangle$
	2026	$\langle 24'563'831.44,\ 39'989'980.39,\ 60'250'344.13\rangle$
	2027	$\langle 25'914'842.17,\ 44'348'888.25,\ 70'010'899.88\rangle$
$\langle 0.5, 0.55, 0.6\rangle$	2023	$\langle 55'783'718.66,\ 65'968'873.92,\ 76'801'754.83\rangle$
	2024	$\langle 58'851'823.18,\ 73'159'481.18,\ 89'243'639.12\rangle$
	2025	$\langle 62'088'673.46,\ 81'133'864.63,\ 103'701'108.65\rangle$
	2026	$\langle 65'503'550.5,\ 89'977'455.87,\ 120'500'688.26\rangle$
	2027	$\langle 69'106'245.78,\ 99'784'998.56,\ 140'021'799.75\rangle$
$\langle 0.25, 0.3, 0.35\rangle$	2023	$\langle 90'648'542.82,\ 102'618'248.33,\ 115'202'632.25\rangle$
	2024	$\langle 95'634'212.67,\ 113'803'637.39,\ 133'865'458.67\rangle$
	2025	$\langle 100'894'094.37,\ 126'208'233.87,\ 155'551'662.98\rangle$

	2026	⟨106′443′269.56, 139′964′931.36, 180′751′032.38⟩
	2027	⟨112′297′649.39, 155′221′108.88, 210′032′699.63⟩
⟨0, 0.05,0.1⟩	2023	⟨125′513′366.98, 139′267′622.73, 153′603′509.67⟩
	2024	⟨132′416′602.16, 154′447′793.6, 178′487′278.23⟩
	2025	⟨139′699′515.28, 171′282′603.11, 207′402′217.31⟩
	2026	⟨147′382′988.62, 189′952′406.85, 241′001′376.51⟩
	2027	⟨155′489′053, 210′657′219.19, 280′043′599.5⟩
0.8	2023	⟨**27′891′859.33**, 29′319′499.52, **30′720′701.93**⟩
	2024	⟨29′425′911.59, 32′515′324.97, 35′697′455.65⟩
	2025	⟨31′044′336.73, 36′059′495.39, 41′480′443.46⟩
	2026	⟨32′751′775.25, 39′989′980.39, 48′200′275.3⟩
	2027	⟨34′553′122.89, 44′348′888.25, 56′008′719.9⟩

When the contract loss ratio decreased to <0%, 5%, 10%>, the GHG-free SC potential can be increased to 125-153 million MWh interval for 2023, and to 155-280 million MHW range for 2027. Actually, decreasing the contract loss ratioto nearly zero in 5 years is not a realistic expectation due to reasons such as certification cost, and lack of motivation of companies to request certification. Here, a more realistic expectation might be to lower it to the 50-60% range. In this case, the GHG-free SC potential expectation is found as 99 million MWh for 2027. The upper and lower limits are calculated as 69 and 140 million MWh. The saved tree count is found as approximately 713,762 for this forecast (with upper and lower limits as 494,317 and 1,001,576). The results show that the precision of the forecasts decreases as the forecast horizon increases. This is due to the use of a fuzzy modeling approach. The precision of the results will increase if the fuzziness of some of the model parameters is removed. For example, if the fuzziness of the "contract loss ratio" is removed in the first scenario and the value is changed from <0.75, 0.8, 0.85> to 0.8, the gap between the upper and lower bounds of the forecasts gets smaller. For 2023, the lower bound increases from 20.9 million MWh to 27.8 million MWh, and the upper bound decreases from 38.4 million MWh to 30.7 million MWh. As the forecasting horizon gets longer, the gap reduces dramatically. For 2027, the gap decreases by %51 when the fuzziness of the contract loss ratio is removed by changing the value from <0.75, 0.8, 0.85> to 0.8. This finding shows that more sophisticated measurements of model parameters, like the contract loss ratio, will help to increase the quality of the forecasts of the proposed model.

5. RESULTS AND DISCUSSION

The study utilizes REC platforms to calculate the contract loss ratio, yielding 77% when considering all issued certificates and 85% when excluding the quantity produced in the previous year. Using the triangular fuzzy set to address this situation, the yearly-basis model forecasts a practical GHG-free SC potential of 21-34 million MWh for 2023. The accuracy of forecasts decreases with an extended period, projecting a potentioal of 26-63 million MWh with the most probable value at 42 million MWh for 2027. Monthly planning accounts for seasonal effects on RE capacities and results in a most probable GHG-free SC potential 4.9% lower than the yearly-basis model. The forecasts indicate that about 189 thousand trees will be saved in Türkiye in 2023 through GSCs. The model's validation exhibits a mean absolute percentage error of 2.9%, with better forecast quality for 2022 compared to 2021, likely due to the newness of REC mechanisms in 2021. The forecast assumes the continuation of current REC policies and direction, but increasing interest and sensitivity towards RE may lead to a decrease in the contract loss ratio and subsequently increase the forecasted GHG-free SC potentials. The sensitivity analysis indicates that if the contract loss ratio is lowered to the 50-60% range, the potential expectation for 2027 is 99 million MWh. However, decreasing the contract loss ratio to nearly zero in five years is not a realistic expectation. The precision of the forecasts decreases with a longer forecast horizon due to the fuzzy modeling approach, and removing fuzziness from certain model parameters may improve the forecast quality.

An analysis has been conducted on the applicability of the proposed methodology to other countries. It is believed that the method can be used to formulate policies in both developed and developing countries, though it is not applicable to underdeveloped countries. The proposed methodology offers the potential to create more realistic and applicable obligatory energy policies without imposing additional audit burdens on industrialists. By proportioning the GHG-free SC potential of countries to their total energy consumption, the progress of the green transformation can be measured and scaled. This enables the establishment of more realistic numeric targets to incentivize green investments. Governments can easily audit and track investments through manageable numerical reports, while domestic certification institutions can plan their activities accordingly. Moreover, industrial management can effectively manage budgets and track target achievement ratios. Additionally, the proposed approach-based policies may act as a catalyst for a change in energy perspectives.

The introduced methodology is promising for promoting green transition and obligating green investments. This approach, based on REC mechanisms, provides a forecast model to measure GHG-free SC potential to use as a basis while building effective energy policies. For example, when it can be predicted how much green transformation the industry can afford, it becomes easier to determine the consumption amounts for which compulsory laws will be applied. Similarly, it becomes easier to decide which amounts should be considered for incentive regulations. In this way, the government will be able to implement sanctions consistently without losing its authority and without causing industrialists to feel offended or bored. On the other hand, the applicability of the proposed model is limited to countries with reliable and transparent energy statistics, excluding underdeveloped nations.

The proposed fuzzy models offer some advantages over other forecasting methods, especially in the context of managing uncertainties and limited data availability in the renewable energy sector. Fuzzy logic is inherently designed to handle uncertainty and imprecision, making it particularly suitable for emerging fields like renewable energy, where data may be sparse or uncertain. These models can provide meaningful forecasts even with incomplete data sets by using expert knowledge to define fuzzy rules and membership functions, unlike traditional statistical methods such as regression analysis or time-series forecasting, which often require large amounts of high-quality data to produce accurate predictions. In situations with limited data or significant variability, traditional models may struggle to provide reliable outputs. Fuzzy models are highly flexible and can be easily adjusted to incorporate new data or changing conditions. This adaptability allows for continuous refinement and improvement of the model as more data becomes available or as market conditions evolve. While machine learning models, such as neural networks, can also handle complex and nonlinear relationships, they typically require extensive training data and computational resources. Fuzzy models, on the other hand, can be implemented with less data and adjusted more intuitively. This flexibility is a significant advantage in a rapidly evolving field like renewable energy. Another major benefit of fuzzy models is their interpretability. The rules and membership functions used in fuzzy models are often more transparent and understandable to stakeholders compared to the "black-box" nature of many machine learning models. For instance, models like deep learning or support vector machines can be highly accurate but are often criticized for their lack of transparency. The decisions made by these models can be difficult to interpret and explain, which is a crucial aspect for policy-making and strategic planning. The proposed fuzzy models are particularly well-suited for developing realistic and applicable energy policies. Their ability to incorporate expert judgment and handle uncertainty makes them valuable for setting regulatory standards and planning long-term policies in RE. While traditional optimization models (e.g., linear programming) are excellent for specific, well-defined problems, they may not effectively capture the broader uncertainties and dynamic changes in the renewable energy sector.

Although the findings are specific to Türkiye, the general analysis, discussions, and implications can be adaptable to other developing countries facing similar energy-related challenges. The suggestions for building policies using REC mechanisms to manage green energy transitions are relevant for other developing countries, with country-specific calculations for specific policy numbers.

The proposed fuzzy models for forecasting GHG-free supply chain potential demonstrate a commendable approach to handling the inherent uncertainties and variability in renewable energy and REC markets. The models leverage fuzzy logic to provide more adaptable and nuanced predictions compared to traditional statistical methods. However, the reliability of these models is contingent upon the accuracy and comprehensiveness of the input data, as well as the expert-defined parameters within the fuzzy logic system. Given the evolving nature of the renewable energy sector and the limited historical data, there is a notable challenge in validating these models comprehensively. The stability of the fuzzy models hinges on their ability to produce consistent outputs under varying input conditions. Sensitivity analyses indicate that the models can maintain stability if the input parameters are within expected ranges, demonstrating robustness against minor fluctuations. However, significant deviations in key parameters such as industry growth ratio or green electricity production capacity could lead to substantial variations in outputs, reflecting the complex dynamics of the renewable energy market. Thus, while the models are stable under controlled conditions, their performance under extreme or unforeseen scenarios remains a critical area for ongoing assessment and improvement.

6. CONCLUSION

Several methods are used for decreasing or amortizing GHG emissions in industry. However, most of the traditional approaches do not give the insight to scale the overall achievement in RE transformation because the processes of the manufacturing systems have great diversity. The tendency towards RE sources has increased all over the world but the transition to RE is a difficult and long process that requires time and capital. All countries are at the beginning of this transformation and are developing various policies to accelerate it.

This study proposes a model to forecast and scale the GSC potential of the countries based on REC mechanisms in order to form the basis of future energy policies. The REC mechanism is suitable for a such forecast since it is one of the latest mechanisms used to reduce not only the air, water, and soil pollution problems but also the GHG emission problem. The progress of the green transformation can be measured and scaled by proportioning GHG-free SC potential measured through their total MW energy consumption certified with REC to the total energy consumption of the SC. Thus, it is thought that more applicable, and more effective energy policies can be built based on the GHG-free SC potential of countries. In this way, it can be possible to support the long-term planning of domestic certification institutions and reduce the certification, and audit costs of the industry. REC is a developing field and an innovative business so REC-related issues contain uncertainties and there is not enough data to make machine learning-supported forecasts. For this reason, a fuzzy logic-based model has been developed for forecasting. The proposed model is generic so it can be applied to any country or state to forecast the GHG-free SC potential. Currently, REC certification is carried out on an annual basis for both the producer and the consumer side. However, while the production capacity of RE varies depending on the seasons, such seasonality is not observed in the consumption of the industry. For this reason, the current annual certification scheme is not sufficient for a sustainable environment. It is foreseen that this certification process will start to be done on a monthly basis in the future. For this reason, the proposed forecasting model has been extended for the monthly-basis certification scenario as well. In the monthly-basis setup, GHG free SC potential values are calculated lower than in the annual-based model. Although, Türkiye is also a country that still provides most of its energy from conventional sources, it has a high potential to successfully complete the RE transformation. The developed model is applied to the Türkiye example. The practical GHG-free SC potential of Türkiye is forecasted as 22.7 million MW for 2024 in the worst case considering possible adverse events in the market and climatic conditions. The expected most probable GSC potential is forecasted as 30.9 million MW for 2024 and it is expected to increase between 10-11% annually for the following years. When this data is combined with the calculation method suggested by EPA [59], it is expected that approximately 220 thousand ten-year trees will be saved in Türkiye in 2024 by SCs. GHG-free SC potential can be increased up to 73.2 million MW for 2024 practically by following the right policies to promote REC and the theoretical upper limit for this increase is

154.5 million MW (equivalent to 1.1 million trees). When forecasts are made according to the monthly-basis model, the potential for 2024 decreases to 22.1 million MW in the worst-case scenario and to 29.4 million MW in the most probable case. These findings can be guiding for determining the RE policies of countries and making supplier management decisions of companies.

As a future study, novel approaches can be developed to calculate the contract loss ratio in the proposed model with more sophisticated methods or the model can be integrated with advanced RE forecasting methods to improve the output quality. In addition, detailed policies can be designed and implemented based on the proposed forecasting model. Policies can also be designed based on the calculated GHG-Free SC potentials to encourage REC production.

NOMENCLATURE

BE: Biomass energy
CO_2: Carbon dioxide
GE: Geothermal energy
GHG: Greenhouse gas
GSC: Green supply chain
HE: Hydropower energy
MW: Megawatt
MWh: Megawatts per hour
RESC: Renewable energy supply chain
RER: Renewable energy resource
SC: Suppy chain
SE: Solar energy
WE: Wind energy

DECLARATION OF ETHICAL STANDARDS

The authors of the paper submitted declare that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

Gürkan Işık: Performed conception and design of the study and commented on and edited subsequent versions of the manuscript, read and approved the final manuscript.

Miraç Tuba Çelik: Performed material preparation, data collection and analysis were performed and the first draft of the manuscript and commented on and edited subsequent versions of the manuscript, read and approved the final manuscript.

CONFLICT OF INTEREST

Authors declare no competing interests that are directly or indirectly related to this study.

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