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Estimation of greenhouse gas emissions using linear and logarithmic models: A scenario-based approach for Turkiye's 2030 vision

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A R T I C L E I N F O

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A B S T R A C T

Turkiye pledged to considerably reduce its greenhouse gas (GHG) emissions by the year 2030 as a part of its commitment under the Paris Agreement. The problem with analyzing mitigation of greenhouse gas emissions requires generation of accurate, reliable and consistent emission forecasts. This study aimed to accurately forecast Turkiye's total CO_2 emissions per capita and per capita CO_2 emissions from energy industries, industrial processes and agricultural sectors till 2030 using linear and logarithmic models based on increasing and decreasing scenarios. Turkiye's total CO_2 emissions per capita in 2030 could reach to 7.6 and 7.7 tons of CO_2, with total emissions of about 635 and 643 million tons (Mt) based on linear and logarithmic models, respectively. Linear modeling results showed that per capita CO_2 emissions from Turkiye's energy industries, industrial processes and agricultural sectors could reach to 5.3, 0.9 and 0.9 tons in 2030, respectively, while logarithmic modeling results yielded that per capita CO_2 emissions from Turkiye's energy industries, industrial processes and agricultural sectors could be 5.5, 1.1 and 0.9 tons in 2030, respectively. The accuracy of fit for linear and logarithmic models was assessed by calculating root mean square error (RMSE $<$ 0.2036) and mean absolute percentage error (MAPE $<$ 12.3347) values which showed that the models fitted well with the timeline data. In conclusion, Turkiye's greenhouse gas emissions can be reduced if utilization of renewable energy sources in the country's energy portfolio is increased, and the shares of energy intensive processes in the industrial and agricultural sectors are reduced.

1. Introduction

Renewables are important components of the global energy mix [1,2]. Yet, as of 2023, majority of global energy demand is still supplied from fossil fuels, and it is expected that the share of fossil fuels in the global energy mix will continue to rise in the years to come [3,4]. When fossil fuels are utilized for power generation, significant amounts of greenhouse gases (GHG's) such as nitrous oxide (NO_2), methane (CH_4), carbon dioxide (CO_2) and fluorinated gases are released into the atmosphere [5,6]. Increasing concentrations of these gases accelerate global warming and adversely affect climate change [7,8]. Climate change is currently the most serious threat facing humanity, and it is expected that its effects will get worse in the upcoming years [9]. Changes in seasonal climate and the impacts of extreme weather events are already negatively affecting financial and social well-being of different countries [10]. The Intergovernmental Panel on Climate Change (IPCC) predicted that global average temperatures would rise nearly 1.5 °C until 2030 [11]. Scientists agree that temperature rise above this limit could have irreversible and catastrophic effects on the environment [12,13]. Therefore, many countries aim to reduce their GHG emissions by 45 % until 2030 (in reference to 2010), and probably achieve a net zero emissions level by 2050 [11,14].

Turkiye is a developing country with a growing population. In 2021, Turkiye's population was nearly 84.9 million, and the annual population growth rate was about 1.3 % [15]. The Turkish economy grew almost 11.0 % in the same year, and it generated nearly 2.6 % of the global gross domestic product (GDP) based on purchasing power parity per capita (PPP) [16,17]. Turkiye's growth reached to the highest rate among Group of Twenty countries in 2021 as COVID-19 related measures were gradually lessened, and governments around the globe loosened monetary policy [18]. Turkiye's GDP and GHG emissions followed similar increasing trends [19,20]. It is known that any reduction in GDP will have a direct effect on GHG emissions [21]. Yet, the effects of GDP change on Turkiye's GHG emissions are not well examined.

Turkiye's energy demand has been growing alongside its economy and population. The country's annual electricity consumption reached

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to 332.9 GWh in 2021 [22]. For a very long time, fossil fuels supplied a big chunk of Turkiye's energy demand [23]. Extensive utilization of fossil fuels for power generation unfortunately skyrocketed the country's GHG emissions. In early 2010s, the Turkish government made a bold decision to increase the share of renewables in the country's energy portfolio [24]. As of today, this strong will still prevails, and the share of renewables in the country's electricity generation reached to almost 33.5 % in 2020 [25,26]. Different renewable energy sources are utilized in Turkiye's energy mix [27]. In 2021, nearly 7.0 % of Turkiye's total energy was supplied from hydropower, solar, geothermal and wind energy [28]. In 2019, Turkiye's installed hydropower, solar, geothermal and wind energy capacities reached to 30,983, 6667, 1613 and 8832 MW, respectively [29,30]. Previously, the share of renewable energy sources in Turkiye's electricity generation was expected to rise 32 % in 2030 [31]. However, given the potential and achievement of the 2023 targets, it is believed that the 2030 goals should be updated and revised to at least 50 % generation [32].

There are two major drivers of Turkiye's renewable energy program. The first one is to reduce Turkiye's imported energy costs, and the other one is to reduce the country's GHG emissions. Evaluating past decarbonization efforts is critical in determining Turkiye's potential for reducing emissions, and the choice of a suitable method for this assessment is crucial [21]. So far, Turkiye reduced its dependence on imported fossil fuels for power generation, and hence, decreased its energy expenditures by increasing its renewable energy capacity. However, Turkiye is still far away from reducing its GHG emissions. Turkiye signed the Paris Agreement in 2016 to decrease its GHG emissions by 21 % until 2030 based on a business as usual (BaU) scenario [33]. Achieving carbon neutrality by 2050s is vital for achieving the Paris Agreement targets [34]. The climate goal set out in the Paris Agreement may not be achievable without immediate and significant decarbonization in all emission sectors [35]. Yet, Turkiye's GHG emissions increased two folds between 1990 and 2020, and it is projected to rise in the years to come [32]. Therefore, urgent action must be taken to reduce the country's GHG emissions.

It is expected that increasing renewable energy capacity with a motivation would eventually decrease Turkiye's GHG emissions. Yet, energy sector is and probably will be the primary source for Turkiye's GHG emissions [36]. Industrial processes and agricultural sectors also generate significant amounts of GHG's. As a result, controlling and reducing GHG generation from Turkiye's energy, industrial processes and agricultural sectors will have an important role in mitigating Turkiye's emissions and fulfil the 2030 and 2050 emissions targets.

This study stands out from previous studies in several aspects. Primarily, detailed review of the literature clearly showed that there are few publications on Turkiye's total GHG emissions per capita, and the results of these published forecasts are not consistent with each other. Background information showed that there is no forecasting study analyzing GHG emissions from Turkiye's energy industries, industrial processes and agricultural sectors per capita based on decreasing and increasing scenarios for sectoral emissions. This knowledge gap must urgently be filled with appropriate scientific information. Secondly, there are limited numbers of forecasting studies that use up to date GHG emissions data. In contrast to previous studies, current data were used in this study to forecast Turkiye's GHG emissions per capita. Thirdly, this research focused on GHG emissions per capita because individual carbon footprints is the hot topic of recent publications concerning GHG emissions. Turkiye's economy is developing, and the GHG emissions per capita are not as high as those of the developed countries, suggesting that small lifestyle changes might have knock-on reduction effects. Thus, academics and policy makers urgently require sound forecasts on this topic to assess and design Turkiye's macroeconomic and macro-energy futures in a sustainable manner. That's why, a sound forecasting model for Turkiye's GHG emissions is urgently required. Therefore, the aim and contribution of this study to the existing literature is to generate per capita forecasts of Turkiye's GHG emissions from energy, industrial processes, and agricultural sectors till 2030 using different models based on different scenarios.

The remainder of this study is organized as follows: Section 2 illustrates the literature review on GHG emissions from Turkiye's different sectors including data and forecasts. Section 3 presents data and methodology. Section 4 explains the main results, including forecasting results for CO_2 emissions from Turkiye's energy industries, industrial processes and agricultural sectors till 2030, and results of decreasing and increasing CO_2 emissions scenarios for Turkiye till 2030. Section 5 summarizes the key findings and future studies.

2. Literature review on GHG emissions from Turkiye's different sectors including data and forecasts

Most of the forecasting studies in the literature focused on GHG emissions from Turkiye's energy sector. Hamzacebi and Karakurt [37] forecasted CO_2 emissions from energy industries of Turkiye till 2025 using data from 1965 to 2012 using the grey prediction method, and they found that CO_2 emissions from Turkiye's energy industries would increase to 496 Mt in 2025.

Kone and Buke [38] conjectured CO_2 emissions from energy industries of Turkiye till 2030 using data between 1991 and 2008 via a linear extrapolation, and they calculated that Turkiye's GHG emissions from energy industries would rise to 268.9 Mt in 2030. Aydin [39] predicted CO_2 emissions from Turkiye's energy industries till 2025 using data between 1971 and 2010 via linear regression, and calculated that CO_2 emissions from Turkiye's energy industries would rise to 335.4 Mt in 2025. Ayvaz et al. [40] estimated CO_2 emissions from energy industries of Turkiye between 2015 and 2030 using data between 1965 and 2014 utilizing the grey prediction method, and they estimated that CO_2 emissions from Turkiye's energy industries would rise to 607.9 Mt in 2030. Es and Hamzacebi [41] forecasted CO_2 emissions from Turkiye's energy industries between 2023 and 2030 using the grey prediction method by considering Turkiye's emissions reduction targets, and data between 1990 and 2017. They found that Turkiye's CO_2 emissions in 2030 will reach to 678.9 Mt based on the BaU scenario or 611.4 Mt based on the emission reduction scenario. Sahin [42] forecasted GHG emissions from Turkiye's energy industries between 2017 and 2025 using the grey prediction method with data between 1990 and 2016, and estimated that Turkiye's GHG emissions from energy industries would reach to 585.2 Mt in 2025.

There are some studies that forecast CO_2 emissions from other industries besides energy industries. Sozen et al. [43] estimated GHG emissions from Turkiye's energy, industrial production and transportation sectors between 2008 and 2020 using an artificial neural network, and they estimated that Turkiye's total GHG emissions would reach to 450 Mt of CO_2 equivalent in 2020. Ozer et al. [44] estimated CO_2 emissions resulting from electricity utilization and generations from Turkiye's transport, residential, agriculture, commercial, industry and service sectors between 2006 and 2030 using a long-term energy alternatives planning method, and they calculated that Turkiye's CO_2 emissions from electricity generation would reach to 425.0 Mt of CO_2 in 2030. Ates [45] forecasted CO_2 emissions from Turkiye's steel and iron industries in 2025 by using long-range energy alternatives planning (LEAP) software based on BaU, slow-speed energy, accelerating energy and cleaner production scenarios as 34.9, 32.5, 24.6 and 14.5 Mt of CO_2, respectively.

There a few studies on forecasting Turkiye's total GHG emissions per capita, and none of them are subdivided to energy industries, industrial processes and agricultural sectors. Shaheen et al. [46] estimated CO_2 emissions from Turkiye's agricultural, forestry and fishing sectors using a fractional grey prediction method with data between 1971 and 2014, and they found that Turkiye's CO_2 emissions per capita would reach to nearly 6.8 tons in 2030. Zhao and Du [47] estimated Turkiye's CO_2 emissions in 2012 as 4.0 tons per capita using a qualitative flexible method. The implications that can be referred from the current study are

Table 1
Sectoral CO_2 emissions (Mt) between 2000 and 2020 [49].

Year	Total	Energy industries	Industrial processes	Agricultural sector	Other
2000	299.0	216.0	26.3	42.3	14.3
2001	279.8	199.2	25.9	39.9	14.8
2002	285.7	205.9	26.9	37.6	15.2
2003	304.9	220.4	28.3	40.6	15.6
2004	314.5	226.3	30.8	41.3	16.1
2005	337.0	244.4	33.7	42.4	16.4
2006	358.0	260.5	36.7	43.9	16.8
2007	391.3	291.5	39.3	43.4	17.1
2008	387.9	288.3	41.1	41.3	17.2
2009	395.1	292.9	43.0	42.0	17.2
2010	398.7	287.8	49.0	44.4	17.4
2011	428.5	309.9	53.9	46.9	17.8
2012	448.0	321.6	56.2	52.7	17.6
2013	440.0	308.3	59.2	55.9	16.7
2014	459.4	326.8	59.9	56.2	16.5
2015	474.5	342.0	59.2	56.1	17.1
2016	500.8	361.7	63.5	58.9	16.7
2017	528.3	382.4	66.4	63.3	16.3
2018	524.0	374.1	68.0	65.3	16.6
2019	508.1	365.4	58.6	68.0	16.1
2020	523.9	367.6	66.8	73.2	16.4

Table 2
Turkiye's population (million people) projection between 2021 and 2030 [50].

Year	Population
2021	84.9
2022	85.9
2023	86.9
2024	87.9
2025	88.9
2026	89.8
2027	90.7
2028	91.6
2029	92.5
2030	93.3

to generate sound forecasts and inclusive models for estimating greenhouse gas emissions from Turkiye's energy industries, industrial processes and agricultural sectors for mid-long periods.

3. Data and methodology

3.1. Data: GHG emissions from Turkiye's energy industries, industrial processes and agricultural sectors

Turkiye's electricity consumption increased nearly 175 % between 1990 and 2020 [48]. A big portion of Turkiye's energy demand was supplied from fossil fuels [48]. Thus, Turkiye's total CO_2 emissions increased nearly 2.5 times during this period [49]. In 2020, Turkiye's total GHG emissions was estimated as 523.9 Mt of CO_2 equivalent. This is equal to an increase of 175 % in CO_2 emissions between 2000 and 2020. CO_2 emissions from Turkiye's energy industries, industrial processes and agricultural sectors are given in Table 1 [49]. As a remark, in Table 1 and throughout this study, sectoral CO_2 equivalent emissions refer to the total amount of GHG's emitted by energy industries, industrial processes and agricultural sectors, expressed as CO_2 equivalent. This measurement takes into account not only CO_2, but also different GHG's such as CH_4, NO_2 and fluorinated gases by converting them into the CO_2 equivalent based on their global warming potential. Fluorinated gases include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF_6). Nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOC), ammonia (NH_3), carbon monoxide (CO) and sulfur dioxide (SO_2), which contribute to the indirect greenhouse gas effect, were not included in calculations [49].

Turkiye's energy industries have the largest share in the country's CO_2 emissions, which accounts for nearly 70 % of the total emissions. Emissions from energy sector mostly originate from fossil fuel combustion for heat and power generation. Emissions from livestock and their manure, utilization of synthetic fertilizers and urea applications are the major contributors of GHG emissions from Turkiye's agricultural sectors, and they are equal to nearly 14 % of the country's total CO_2 emissions. Emissions from industrial processes and product use follow the emissions from agricultural sectors, and they account for nearly 12.7 % of the country's total emissions. Emissions from Turkiye's industrial processes and product use include streams coming from the chemical industry, mineral products, non-energy fuel, metal production and solvent utilization [49].

Population and population growth are the key parameters that are used to forecast nationwide CO_2 emissions. In the literature, there are few forecasts based on per capita emissions [46,47]. These forecasts are inconsistent, and they do not include current GHG emissions data (2021 and onwards). The novelty of this study lied on the fact that per capita models were generated based on population growth data published by the Turkish Statistical Institute (TurkStat). Population projections between 2021 and 2030 given in Table 2 were also obtained from TurkStat and used in associated calculations [49,50].

3.2. Methodology used to forecast GHG emissions from Turkiye's energy industries, industrial processes and agricultural sectors till 2030

3.2.1. Linear model

Turkiye's CO_2 emissions from energy industries, industrial processes and agricultural sectors between 2021 and 2030 were forecasted using the data given in Table 1 with the following methodology. First, per capita CO_2 emissions between 2000 and 2020 were calculated. Turkiye's CO_2 emissions per capita were estimated by using linear models given in Eqs. (1) through (4) for a period between 2021 and 2030 using the population projections given in Table 2.

In Eqs. (1) through (4), t is year, which is $\geq$ 2021, c_1, c_2, c_3, c_4, c_5, c_6, c_7 and c_8 are arbitrary constants calculated using the statistical functions provided by Microsoft Excel 2016, and $\varepsilon(t)$ is a random error term in year t. Eq. (1) was used to forecast Turkiye's total CO_2 emissions per capita between 2021 and 2030.

$$TCE_{pc1}(t) = c_1 \cdot t + c_2 + \varepsilon(t) \tag{1}$$

In Eq. (1), $TCE_{pc1}(t)$ is total CO_2 emissions per capita in year t in tons. Using statistical methods, c_1 and c_2 were calculated as 0.1 and −206.6, respectively. The mathematical model fitted almost flawlessly to the timeline data with $R^2 > 0.9125$. Forecasts for Turkiye's total CO_2 emissions per capita till 2030 generated by using Eq. (1) are shown in Fig. 1a. Here, it must be emphasized that in Figs. 1 and 2 the results of this study are given alongside with timeline data. Therefore, these figures are shown in Section 4 of this study.

Eq. (2) was used to forecast Turkiye's per capita CO_2 emissions from energy industries between 2021 and 2030.

$$ECE_{pc1}(t) = c_3 \cdot t + c_4 + \varepsilon(t) \tag{2}$$

In Eq. (2), $ECE_{pc1}(t)$ is CO_2 emissions from energy industries per capita in year t in tons. Calculated values for c_3 and c_4 were 0.1 and −142.1, respectively. The mathematical model fitted well to the data with $R^2 > 0.8537$. Forecasts for Turkiye's per capita CO_2 emissions from energy industries till 2030 generated by using Eq. (2) are presented in Fig. 1b.

Eq. (3) was used to forecast Turkiye's per capita CO_2 emissions from industrial processes between 2021 and 2030.

$$ICE_{pc1}(t) = c_5 \cdot t + c_6 + \varepsilon(t) \tag{3}$$

In Eq. (3), $ICE_{pc1}(t)$ is CO_2 emissions from industrial processes per

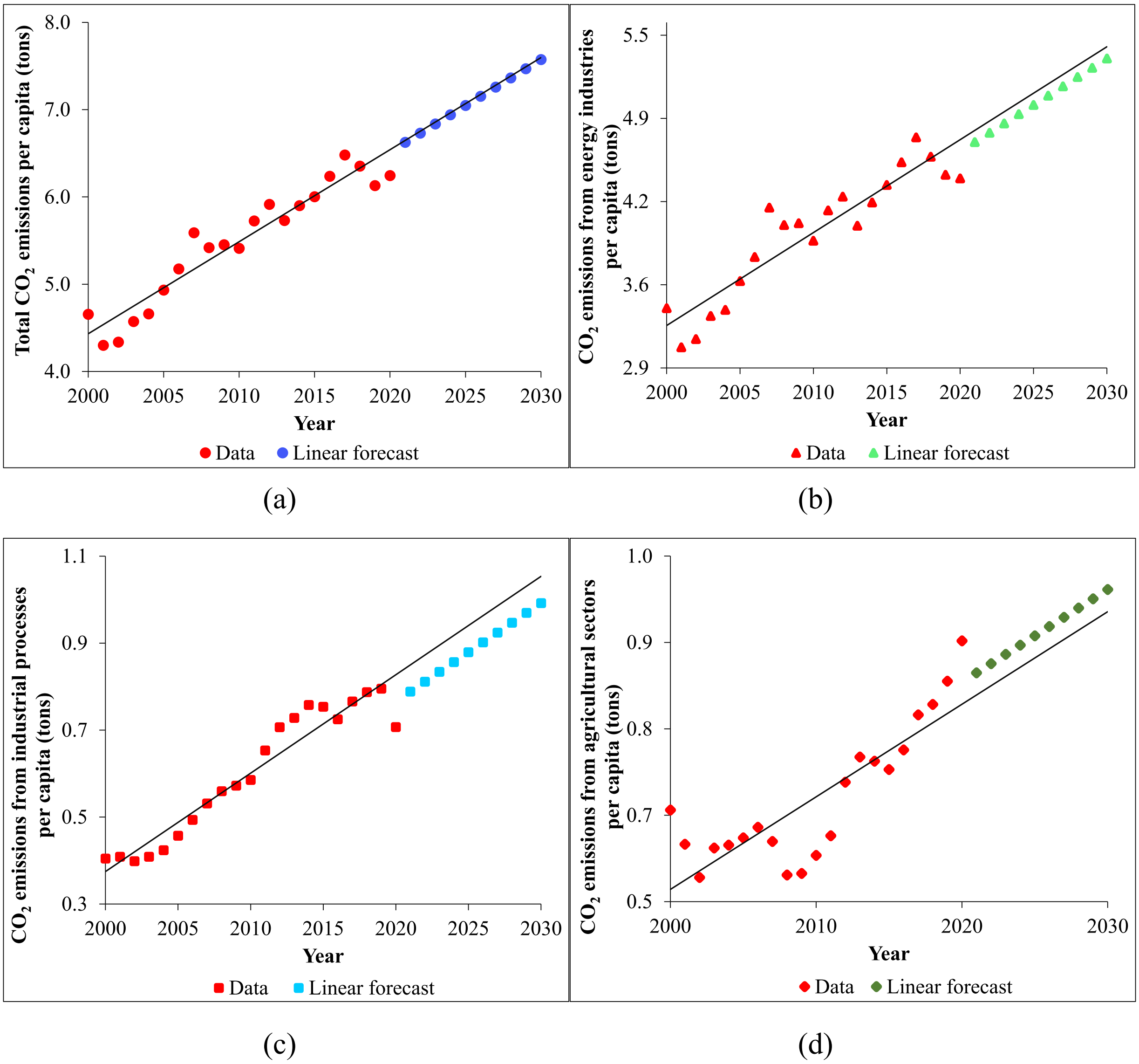


Fig. 1. Timeline data between 2000 and 2020 and (a) Linear forecasts for total CO_2 emissions per capita between 2021 and 2030, (b) Linear forecasts for CO_2 emissions from energy industries per capita between 2021 and 2030, (c) Linear forecasts for total CO_2 emissions from industrial processes and industrial use per capita between 2021 and 2030, and (d) Linear forecasts for total CO_2 emissions from agricultural sectors per capita between 2021 and 2030.

capita in year t in tons. Calculated values for c_5 and c_6 were 0.1 and −44.9, respectively. The mathematical model fitted almost seamlessly to the data with $R^2 > 0.9192$. Forecasts for Turkiye's per capita CO_2 emissions from industrial processes till 2030 generated by using Eq. (3) are given in Fig. 1c.

Eq. (4) was used to forecast Turkiye's per capita CO_2 emissions from agricultural sectors between 2021 and 2030.

$$ACE_{pc1}(t) = c_7 \cdot t + c_8 + \varepsilon(t) \tag{4}$$

In Eq. (4), $ACE_{pc1}(t)$ is CO_2 emissions from agricultural sectors per capita in year t in tons. Calculated values for c_7 and c_8 were 0.1 and −23.0, respectively. The mathematical model fitted adequately to the data with $R^2 > 0.6993$. Forecasts for Turkiye's per capita CO_2 emissions from agricultural sectors till 2030 generated by using Eq. (4) are presented in Fig. 1d.

3.2.2. Logarithmic model

Turkiye's per capita CO_2 emissions from different sectors were also estimated by using logarithmic models given in Eqs. (5) through (8) for a period between 2021 and 2030 using the population projections given in Table 2. In Eqs. (5) through (8), t is year, which is ≥ 2021, c_9, c_{10}, c_{11}, c_{12}, c_{13}, c_{14}, c_{15} and c_{16} are arbitrary constants calculated using statistical functions provided by Microsoft Excel 2016, and $\varepsilon(t)$ is a random error term in year t. Eq. (5) was used to forecast Turkiye's total CO_2 emissions per capita between 2021 and 2030.

$$TCE_{pc2}(t) = c_9 \cdot \ln(t) + c_{10} + \varepsilon(t) \tag{5}$$

In Eq. (5), $TCE_{pc2}(t)$ is total CO_2 emissions per capita in year t in tons. Using mathematical and statistical methods, c_9 and c_{10} were calculated as 212.1 and −1607.9, respectively. The mathematical model fitted very well to the data with $R^2 > 0.9129$. Forecasts for Turkiye's total per capita CO_2 emissions till 2030 generated by using Eq. (5) are shown in Fig. 2a.

Eq. (6) was used to forecast Turkiye's per capita CO_2 emissions from energy industries between 2021 and 2030.

$$ECE_{pc2}(t) = c_{11} \cdot \ln(t) + c_{12} + \varepsilon(t) \tag{6}$$

In Eq. (6), $ECE_{pc2}(t)$ is CO_2 emissions from energy industries per

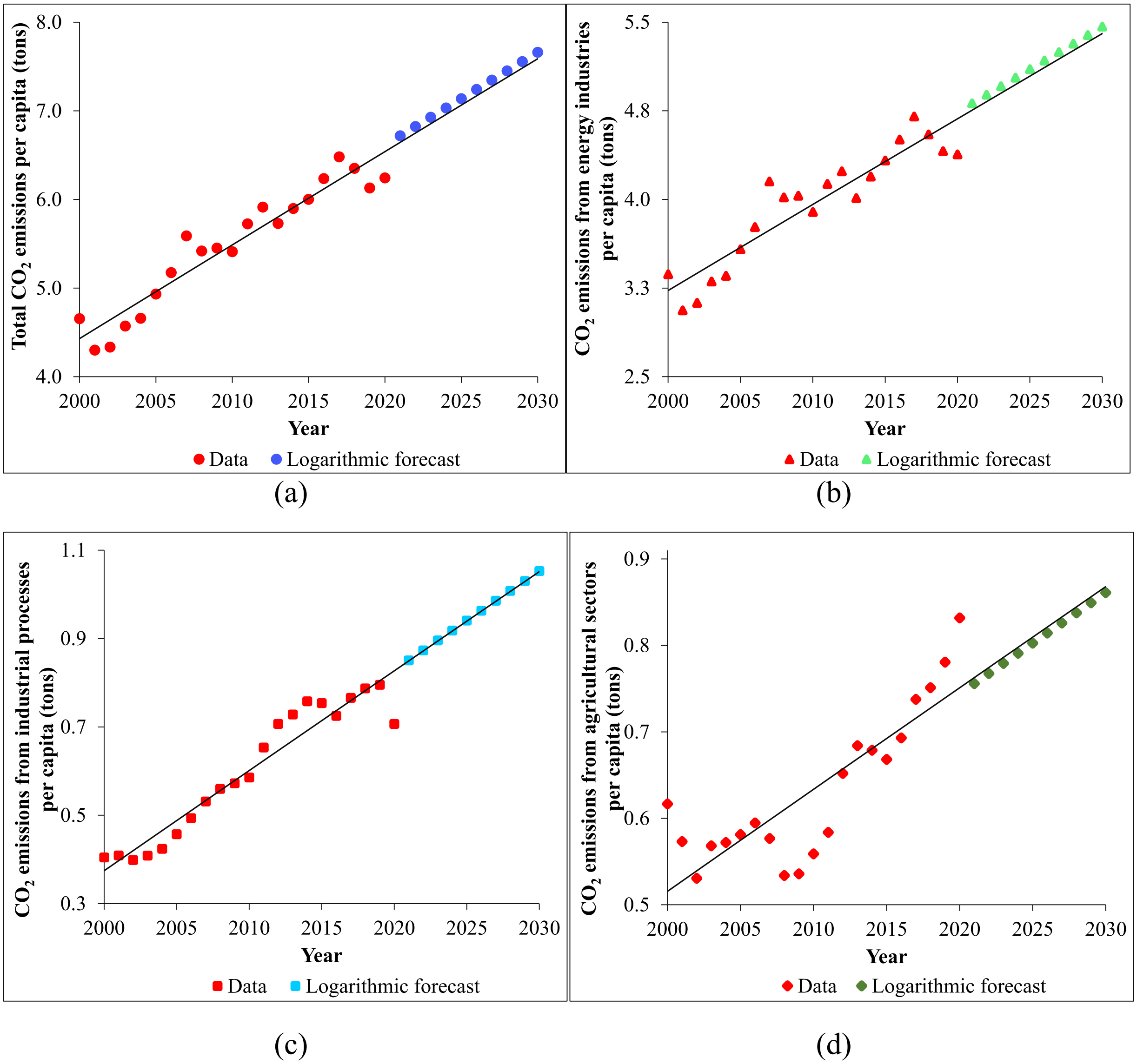


Fig. 2. Timeline data between 2000 and 2020 and (a) Logarithmic forecasts for total CO_2 emissions per capita between 2021 and 2030, (b) Logarithmic forecasts for CO_2 emissions from energy industries per capita between 2021 and 2030, (c) Logarithmic forecasts for CO_2 emissions from industrial processes and industrial use per capita between 2021 and 2030, and (d) Logarithmic forecasts for CO_2 emissions from agricultural sectors per capita between 2021 and 2030.

capita in year t in tons. Calculated values for c_{11} and c_{12} were 146.1 and −1106.9, respectively. The mathematical model fitted well to the data with $R^2 > 0.8541$. Forecasts for Turkiye's per capita CO_2 emissions from energy industries till 2030 generated by using Eq. (6) are presented in Fig. 2b.

Eq. (7) was used to forecast Turkiye's per capita CO_2 emissions from industrial processes between 2021 and 2030.

$$ICE_{pc2}(t) = c_{13} \cdot \ln(t) + c_{14} + \varepsilon(t) \quad (7)$$

In Eq. (7), $ICE_{pc2}(t)$ is CO_2 emissions from industrial processes per capita in year t in tons. Calculated values for c_{13} and c_{14} were 45.5 and −345.4, respectively. The mathematical model fitted extremely well to the data with $R^2 > 0.9195$. Forecasts for Turkiye's per capita CO_2 emissions from industrial processes till 2030 generated by using Eq. (7) are given in Fig. 2c.

Eq. (8) was used to forecast Turkiye's per capita CO_2 emissions from agricultural sectors between 2021 and 2030.

$$ACE_{pc2}(t) = c_{15} \cdot \ln(t) + c_{16} + \varepsilon(t) \quad (8)$$

In Eq. (8), $ACE_{pc2}(t)$ is CO_2 emissions from agricultural sectors per capita in year t in tons. Calculated values for c_{15} and c_{16} were 23.7 and −179.4, respectively. The mathematical model fitted adequately to the data with $R^2 > 0.6982$. Forecasts for Turkiye's per capita CO_2 emissions from agricultural sectors till 2030 generated by using Eq. (8) are presented in Fig. 2d.

The aforementioned methodology was used to calculate Turkiye's total CO_2 emissions, and the emissions from industrial processes, energy industries and agricultural sectors between the years 2021 and 2030. Results obtained by using the models given in Eqs. (1) through (8), and the data given in Tables 1 and 2 are analyzed and discussed in Section 4.

3.3. Generation of decreasing and increasing CO_2 emissions scenarios for Turkiye till 2030

CO_2 emission from a process is related to the method of generation and the amount of raw material utilized during its production. In any process, the production must meet the demand. For this reason, GHG emission projections are sensitive to demand, and the assumptions on

Table 3
RMSE and MAPE values of forecasting models of CO_2 emissions per capita.

Model	Forecasting model	RMSE	MAPE (%)
Linear	Eq. (1)	0.1990	3.0704
	Eq. (2)	0.2036	4.2883
	Eq. (3)	0.0733	11.0965
	Eq. (4)	0.0543	6.6964
Logarithmic	Eq. (5)	0.0954	1.7699
	Eq. (6)	0.1496	3.9203
	Eq. (7)	0.0622	12.3347
	Eq. (8)	0.0345	4.9687

which this demand is based on. Considering the uncertainties in any model, sensitivity analysis should be carried out with appropriate assumptions that cover a rise in demand for the increasing scenario and a reduction in demand for the decreasing scenario. According to a recent report, it is estimated that Turkiye's electricity demand in 2030 will reach to 359,252, 395,918 and 453,590 GWh based on the low, medium and high demand scenarios, respectively, where the scenarios were generated from adapted general policies, and they do not constitute a fixed and definite trajectory for the coming decade [51].

In the current study, GHG emissions from Turkiye's different sectors were generated using decreasing and increasing scenarios for a period between 2021 and 2030. The models used annual changes of CO_2 emissions per capita based on timeline data between 2000 and 2020. Per capita emissions from Turkiye's energy industries, industrial processes and agricultural sectors between 2000 and 2020 were calculated using CO_2 emissions and population data. Factors of ±0.1, ±0.5, ±1.0, ±2.0 and ±5.0 % were used to generate decreasing and increasing scenarios for Turkiye's CO_2 emissions till 2030. These values were used to represent the annual change in the timeline data. The timeline data were also linearly extrapolated (solid lines in Figs. 1 and 2) to show continuation in the trend, which can be used a reference guideline to compare the models generated in this study.

Renewable energy technologies are becoming more important each day because of increased global concern on sustainability. Thus, researchers all around the world focus on exploring energy saving potentials of renewable energy sources as sustainable alternatives to fossil fuels [27]. A decreasing CO_2 emissions scenario was developed to estimate potential emissions till 2030 based on increasing share of renewable energy sources in Turkiye's energy mix. This model was generated by considering Turkiye's pre and post 2023 energy targets [27]. This scenario was created to show the possibility of GHG emissions savings by extensive utilization of renewable energy sources. Reductions should be implemented to sectors other than the energy sector. A decreasing scenario based on the annual change of CO_2 emissions per capita was generated using the timeline data between 2000 and 2020. Then, emissions from Turkiye's energy industries, industrial processes, agricultural sectors and aggregate were estimated using reduction factors of 0.1, 0.5, 1.0, 2.0 and 5.0 % till 2030.

3.4. Accuracy of the modeling results

Differences between actual and forecasted values can be obtained using different statistical evaluations. In this study, performance of forecasting results was assessed by semi-empirical models based on the analogy suggested by Lee and Tong [52]. The accuracy of fit was assessed using mean absolute percentage error (MAPE) and root mean square error (RMSE). MAPE statistically defines the accuracy of the predicted values with the raw data, and RMSE compares the predicted values with raw time series data. MAPE and RMSE are defined in Eqs. (9) and (10), where A_t is the past data sequence in the year t, F_t is the predicted data sequence in the year t, and n is the number of the predicted values.

$$\mathrm{MAPE} = \frac{1}{n}\sum_{t=1}^{n}\left|\frac{A_t - F_t}{A_t}\right| \times 100\% \tag{9}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{t=1}^{n}(A_t - F_t)^2} \tag{10}$$

The scale criteria of MAPE were proposed by Lewis in 1982 where MAPE ≤ 10 %, 10 % ⟨ MAPE ≤ 20 %, 20 % < MAPE ≤ 50 % and MAPE ⟩ 50 % correspond to high accurate forecast, good forecast, reasonable forecast and inaccurate forecast, respectively [53,54]. The accuracy of forecast was evaluated based on the estimation of error. Thus, better forecasts had smaller RMSE and MAPE values [55].

4. Results and discussion

4.1. Forecasting results for CO_2 emissions from Turkiye's energy industries, industrial processes and agricultural sectors till 2030

Turkiye is a fast-growing economy with increasing energy demand [56]. Turkiye's energy use per capita considerably increased in the last ten years [1]. Linear modeling results obtained in this study showed that per capita CO_2 emissions from Turkiye's energy industries, industrial processes and agricultural sectors would reach to 5.3, 0.9 and 0.9 tons in 2030 (Fig. 1), respectively. On the other hand, logarithmic modeling results showed that per capita CO_2 emissions from Turkiye's energy industries, industrial processes and agricultural sectors would reach to 5.5, 1.1 and 0.9 tons in 2030 (Fig. 2), respectively. Turkiye's total CO_2

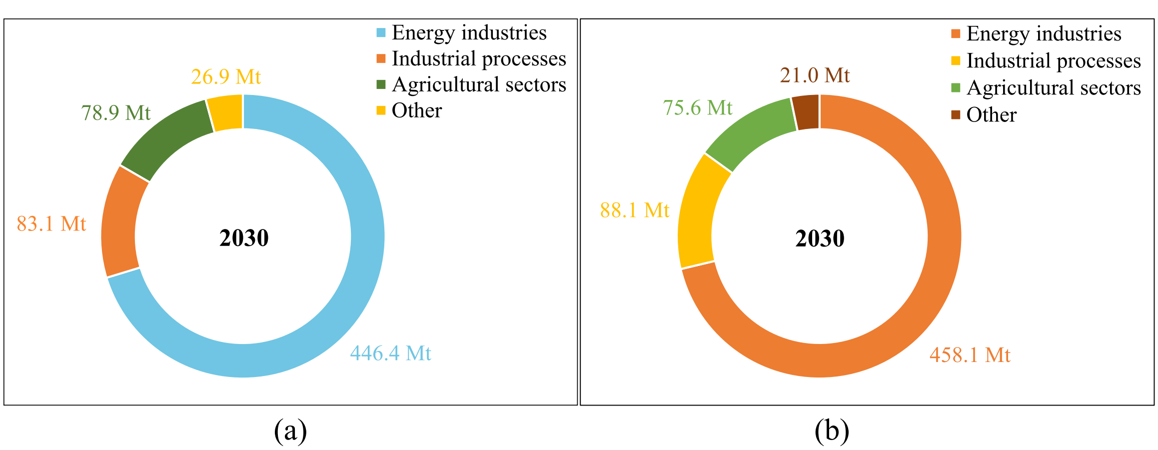
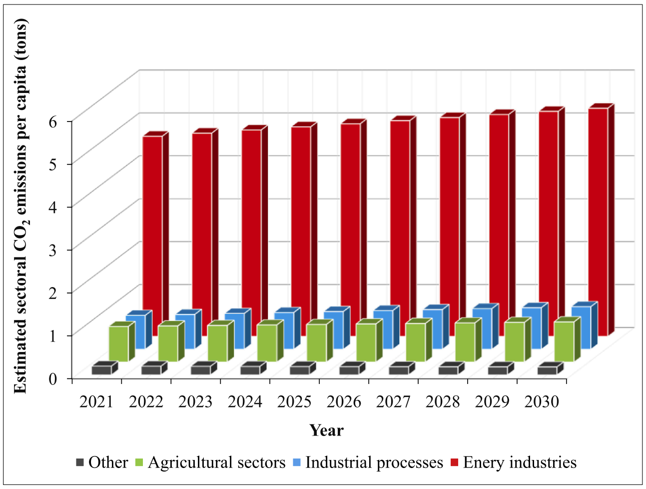
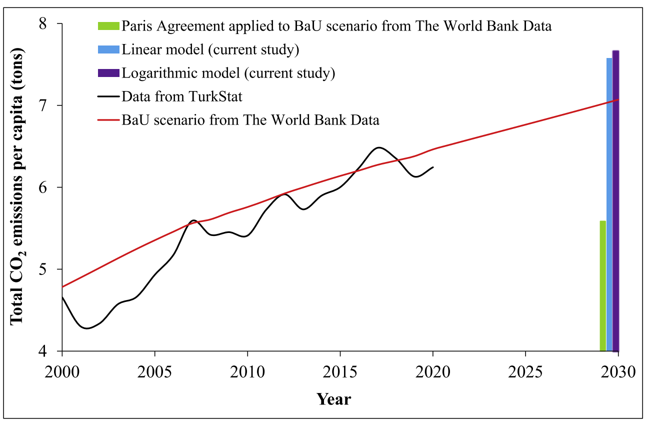


Fig. 3. (a) Linear forecasts for total CO_2 emissions, and CO_2 emissions from energy industries, industrial processes and agricultural sectors in 2030, and (b) Logarithmic forecasts for total CO_2 emissions, and CO_2 emissions from energy industries, industrial processes and agricultural sectors in 2030.



(a)



(b)

Fig. 4. (a) Linear forecasts for total CO_2 emissions per capita and CO_2 emissions from energy industries, industrial processes and agricultural sectors between 2021 and 2030, and (b) Timeline data between 2000 and 2020, and forecasts for total CO_2 emissions per capita based on Paris agreement, linear modeling, logarithmic modeling and BaU scenario.

emission per capita in 2030 was estimated to reach 7.6 (Fig. 1a) and 7.7 tons (Fig. 2a) based on the linear and logarithmic models, respectively. These would be slightly lower than the previous total GHG emissions estimates of 7.8–9.5 tons per capita for the year 2030 [50,57,58].

The transformation of the Turkiye's energy system must also fulfill the requirements of the Paris Agreement. In the context of limiting global warming under the Paris Agreement, several countries have also investigated their carbon neutral pathways within these goals [59,60]. Fossil fuels supplied 87 % of Turkiye's energy demand [61]. However, in the last couple of years, Turkiye's energy industries had started to change in environmentally promising ways. As the time progresses, the share of renewables in Turkiye's energy portfolio will reach to a critical value and even surpass that of fossil fuels. Renewable sources will dominate Turkiye's electricity generation capacity by 2030 [32].

Under the Paris Agreement up to 21 % reduction in GHG emissions from the BAU level by the year 2030 will enable Turkiye to step on low-carbon development pathways compatible with the long-term objective of limiting the increase in global temperature below 2 °C. The implementation of plans and policies outlined in this Nationally Determined Contribution (NDC) for the energy sector involves ambitious targets aimed at diversifying and enhancing the sustainability of Turkiye's electricity production. By 2030, the plan includes increasing the capacity of electricity production from solar power to 33 GW and wind power to 18 GW [62]. Furthermore, utilizing full hydroelectric potential and commissioning of a nuclear power plant by 2030 are strategic measures to secure a robust and diversified energy mix [58]. The gap between observed emissions and the reductions needed to meet locally agreed climate objectives is assuring. Therefore, it is envisaged that the emissions from the country's energy sector would start to decelerate in the years to come. This fact is also shown in the results given in Figs. 1b and 2b.

It is critical to comprehend the insights and information gaps of stakeholders involved in functions that are affected by or address climate change to implement effective climate change policies [63]. In 2009, several support mechanisms, such as energy efficiency projects and voluntary agreements, were introduced to support industrial enterprises in their efforts to reduce energy losses and inefficiencies [64]. Turkiye's growing renewable energy utilization will clearly reduce the country's GHG emissions from industry and related applications between 2021 and 2030, as shown by the linear and logarithmic modeling results given in Figs. 1c and 2c, respectively. The results showed that emissions reduction from the industrial processes would be the highest.

Agriculture accounted for 73.2 Mt of Turkiye's total GHG emissions in 2020, and 60 % of CH_4 and 80 % of N_2O emissions came from the agricultural sectors where livestock produced almost half of the GHG's emitted from Turkiye's agricultural sectors [49]. GHG emissions from the agricultural sectors surprisingly increased in 2020 because livestock was subsidized and some farmers received a diesel payment and $411 million worth of cattle were imported in the same year [25]. In the agricultural sector, Turkiye's NDC outlines targeted measures to enhance sustainability and reduce environmental impact. The commitment includes fuel savings through land consolidation in agricultural areas, promoting more efficient land use. Additionally, the rehabilitation of grazing lands is prioritized to ensure sustainable livestock management practices. To address environmental concerns, the plan emphasizes controlled use of fertilizers and the implementation of modern agricultural practices that prioritize ecological balance. Furthermore, support for minimum tillage methods demonstrates Turkiye's dedication to fostering sustainable and environmentally conscious agricultural practices. These initiatives collectively reflect a holistic approach aimed at promoting resource efficiency and resilience within the agricultural sector [62]. Yet, estimates for analyzing the impacts of government policies on CO_2 emissions from the agricultural sectors and other sources are limited. Smart agriculture has just started to be considered and financed by businesses and organizations [65]. However, this will not be enough for short term reduction of CO_2 emissions from Turkiye's agricultural sectors as revealed by the linear and logarithmic modeling results presented in Figs. 1d and 2d, respectively. It is suggested that implementing the optimization of the animal waste management procedures, utilization of manure for power generation through anaerobic treatment and the further reduction of the use of fertilizers [9,60] could foster more sustainable and resilient agricultural sector addressing environmental concerns and contributing to climate change mitigation efforts in Turkiye.

The accuracy of fit for linear and logarithmic models was assessed by calculating RMSE and MAPE values where smaller RMSE and MAPE values showed that the models fitted well with the timeline data (Table 3).

CO_2 emissions from Turkiye's energy industries, industrial processes and agricultural sectors in 2030 estimated using linear and logarithmic models are shown in Fig. 3a and 3b, respectively. The aggregate CO_2 emissions of Turkiye in 2030 were forecasted as 635.1 Mt (linear model) and 642.7 Mt (logarithmic model). These forecasted values are in good agreement with the other forecasted results reported in the literature [37,38,40,42,66].

As a result of the estimations based on the linear modeling used in this study (Fig. 4a), total CO_2 emissions per capita based on BaU scenario are projected to reach 7.1 tons whereas it would be 5.6 tons to fulfill the requirements of the Paris Agreement in 2030 (Fig. 4b). It is envisaged that Turkiye might not fulfill the requirements of the Paris Agreement in

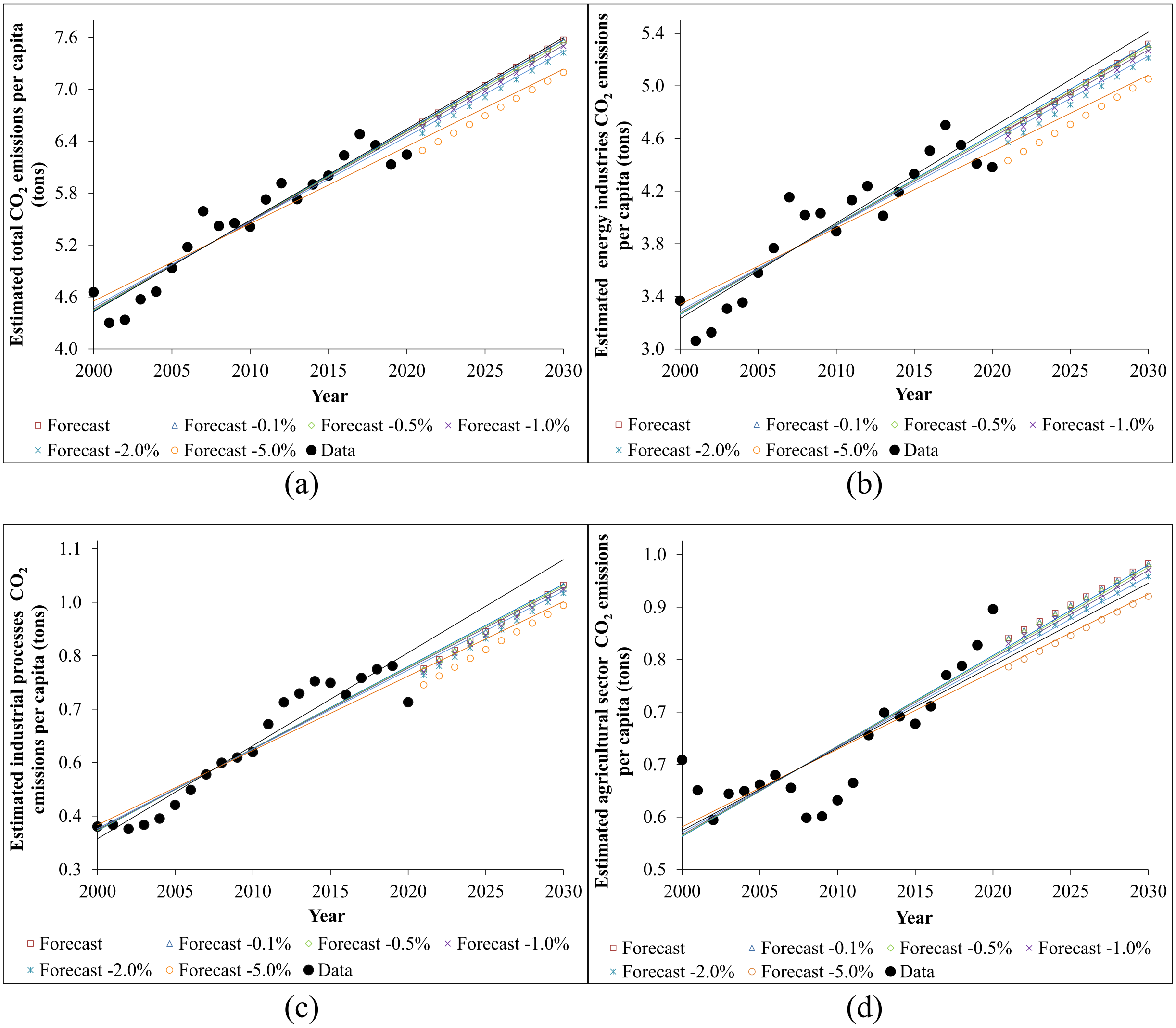


Fig. 5. Timeline data between 2000 and 2020 and (a) Linear forecasts for total CO_2 emissions per capita between 2021 and 2030 based on decreasing scenario, (b) Linear forecasts for CO_2 emissions from energy industries per capita between 2021 and 2030 based on decreasing scenario, (c) Linear forecasts for CO_2 emissions from industrial processes and industrial use per capita between 2021 and 2030 based on decreasing scenario, and (d) Linear forecasts for CO_2 emissions from agricultural sectors per capita between 2021 and 2030 based on decreasing scenario.

2030. Turkiye's CO_2 emission from the energy industries in 2030 was calculated as 5.3 tons per capita (Fig. 4a) or nearly 500 Mt (Fig. 3). It is evident that the main source of Turkiye's GHG emissions is the energy sector. This finding is in agreement with some of the recent studies [18, 67]. Therefore, Turkiye should use renewable energy sources, increase energy efficiency, and carefully plan its future investments. In order to reduce emissions, large industries and local authorities, must first determine their carbon footprints and develop reduction strategies. A good way forward could be the implementation of carbon tax and emission trading systems [1]. Lastly, development of new technologies should be supported by local authorities and private sector.

4.2. Results of decreasing and increasing CO_2 emissions scenarios for Turkiye till 2030

Turkiye's population is estimated to be nearly 93.3 million in 2030 [50]. Turkiye's CO_2 emissions increased considerably between 2000 and 2020. Turkiye's GHG emissions per capita followed an increasing linear trend until 2020 which would probably continue till 2030 (Fig. 1). Yet, continuation of this increasing trend would be highly problematic for Turkiye when the environmental targets of Turkiye are considered. The majority of previous studies focuses on GHG emission reduction scenarios [37]. However, any reduction is causally related to the policy planning and mass action. If the government and private sector could not reduce Turkiye's GHG emissions, an increasing trend would be imminent. Thus, policy planners and researchers urgently need models with increasing trends to precisely analyze Turkiye's energy and economic future to accurately develop investment policies.

In the current study, increasing and decreasing linear (Eqs. (1) through (4)) and logarithmic (Eqs. (5) through (8)) models were generated for estimating total CO_2 emissions per capita and per capita CO_2 emissions from Turkiye's energy industries, industrial processes and agricultural sectors using annual decrements and increments of 0.1, 0.5, 1.0, 2.0 and 5.0 % till 2030. The results of these forecasts are reported in Figs. 5 through 8 where solid black lines showed the continuation of timeline series with direct linear and logarithmic extrapolations.

Energy sector will keep on being the main source for Turkiye's GHG emissions in the upcoming years. Developing policies focusing on CO_2 emissions savings from energy sector would be beneficial both at local and global levels. In the decreasing scenario, priority was given to the increasing share of renewable energy sources. Modeling studies showed

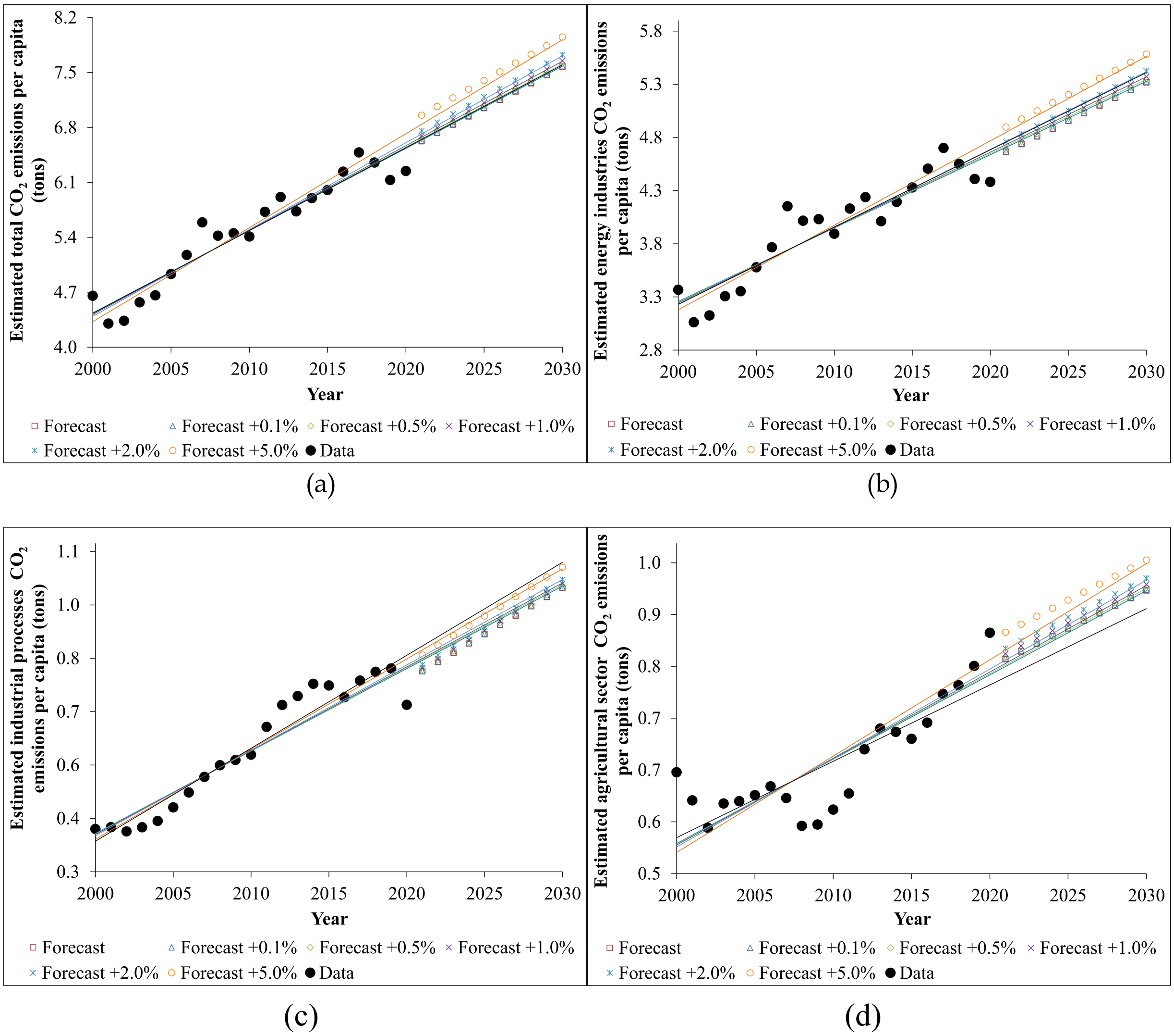


Fig. 6. Timeline data between 2000 and 2020 and (a) Linear forecasts for total CO_2 emissions per capita between 2021 and 2030 based on increasing scenario, (b) Linear forecasts for CO_2 emissions from energy industries per capita between 2021 and 2030 based on increasing scenario, (c) Linear forecasts for CO_2 emissions from industrial processes and industrial use per capita between 2021 and 2030 based on increasing scenario, and (d) Linear forecasts for CO_2 emissions from agricultural sectors per capita between 2021 and 2030 based on increasing scenario.

that Turkiye's total CO_2 emissions per capita in 2030 would change between 7.0 and 7.6 tons if the decreasing scenarios prevail (Figs. 5 and 7). As a fresh breadth to previous studies, analytical results obtained in this study could be validated by other researchers in the future, thus paving a new path towards the assessment of Turkiye's and other countries GHG emissions reduction targets.

The reduction in GHG emissions during 2019 and 2020 was notably attributed to a decrease in the consumption of fossil fuels compared to previous years [68]. During COVID-19 pandemic, increased government spending in many countries for promoting a return to normal economic activity has been initiated. COVID-19 affected most of the industrial activities, and environmental emissions dropped [68]. Yet, this reduction in industrial activities was compensated by speeding up other economic activities. As a result, considering the potential recovery from COVID-19, an increasing scenario for Turkiye's CO_2 emissions is also possible. Modeling studies showed that Turkiye's total CO_2 emissions per capita in 2030 would change between 7.6 and 8.0 tons if the increasing scenarios prevail (Figs. 6 and 8).

Quantification of the effect of climate change mitigation actions is very useful for policy design and assessing policy effectiveness [69]. The current research on forecasting GHG emissions in Turkiye for the year 2030 acknowledges certain limitations, and efforts to chart a path for future work aimed at addressing these gaps. Recognizing the complexity of modeling and predicting emissions, the study has some inherent limitations, such as data availability, the intricacies of predictive models and the dynamic nature of the factors influencing emissions. Turkiye has recently taken steps to diversify its electricity generation from different renewable energy sources. In addition, a nuclear power plant is expected to be completed till 2030 with the possibility of ground laying for an additional one. When these nuclear power plants are started to operate, it is projected that Turkiye will meet approximately 15 % of its total electricity demand from nuclear energy plants in the upcoming years. In the future, researchers who will generate forecasts for GHG emissions of Turkiye should provide a long-term horizon to the NDC by considering these new investments. Mitigation actions aimed at reducing emissions can have several co-benefits that contribute to a broader positive impact. Some of the co-benefits that may be considered in the forecasting include the followings: improved public health, enhanced environmental quality, climate change mitigation, economic benefits due to reduced healthcare costs, increased labor productivity, preservation of

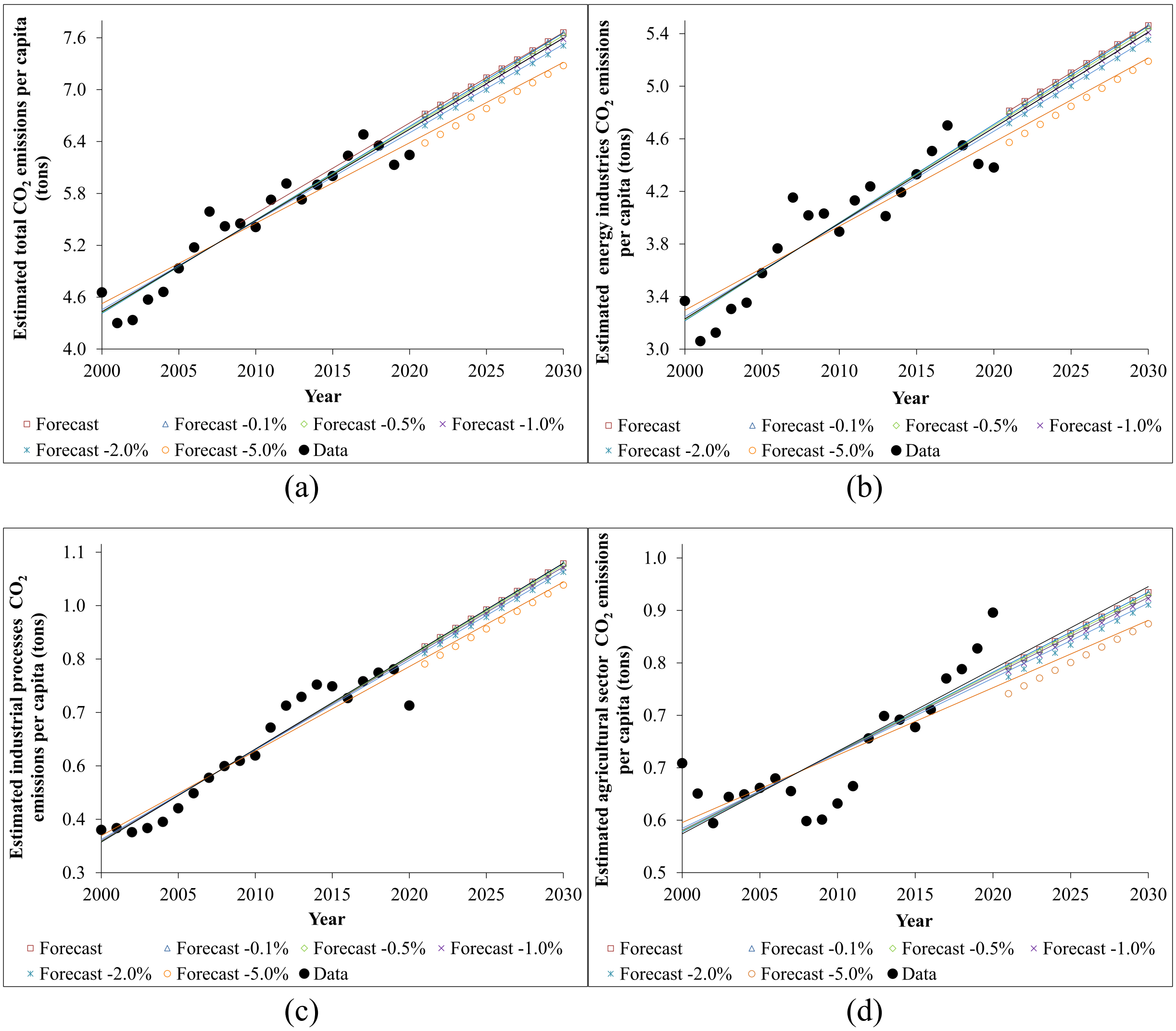


Fig. 7. Timeline data between 2000 and 2020 and (a) Logarithmic forecasts for total CO_2 emissions per capita between 2021 and 2030 based on decreasing scenario, (b) Logarithmic forecasts for CO_2 emissions from energy industries per capita between 2021 and 2030 based on decreasing scenario, (c) Logarithmic forecasts for CO_2 emissions from industrial processes and industrial use per capita between 2021 and 2030 based on decreasing scenario, and (d) Logarithmic forecasts for CO_2 emissions from agricultural sectors per capita between 2021 and 2030 based on decreasing scenario.

natural resources, improvements in energy efficiency, social equity, investments in cleaner technologies and renewable energy sources, and improving the quality of life for communities, making them more appealing [70]. Therefore, future research should also focus on co-benefits of mitigation actions with air-pollution.

5. Conclusion

Forecasting results showed that (i) Turkiye's total CO_2 emissions per capita could reach 7.6 and 7.7 tons in 2030 based on the linear and logarithmic models, respectively, and (ii) Turkiye's total emissions in 2030 could be nearly 635 and 643 Mt based on the linear and logarithmic models, respectively. Turkiye's total CO_2 emissions per capita and per capita CO_2 emissions from Turkiye's energy industries, industrial processes and agricultural sectors were also forecasted till 2030 using linear and logarithmic models based on different decreasing and increasing scenarios. Forecasts for Turkiye's total CO_2 emissions per capita in 2030 using the linear model yielded 7.2 and 7.9 tons while the logarithmic model gave estimates of 7.3 and 8.0 tons corresponding to the decreasing and increasing scenarios, respectively. Total CO_2 emissions per capita based on BaU scenario were projected to reach 7.1 tons whereas it would be 5.6 tons to fulfill the requirements of the Paris Agreement in 2030. Thus, forecasts generated in this study showed that Turkiye would not meet the Paris Agreement emissions reduction target of 21 % in 2030. It is strongly suggested that policy makers should use the results of this study to identify potential shortcomings in current mitigation strategies and probably strengthen and refine them into closer alignment with the overarching goals of the Paris Agreement. The current study fills a gap by offering models to forecast sectoral based GHG emissions per capita because individual carbon footprints in Turkiye can serve as a benchmark for future studies. Further studies are suggested to develop long term projections to reach a net zero emissions target for Turkiye in 2050 by considering regular updates to reflect changing conditions. The models generated in this study could also be used to estimate GHG emissions of other developing countries. As a final suggestion, in order to reduce local and global GHG emissions, the share of energy-intensive processes should be reduced, and associated emissions from subsectors should be clearly addressed by considering the use of sustainable technologies.

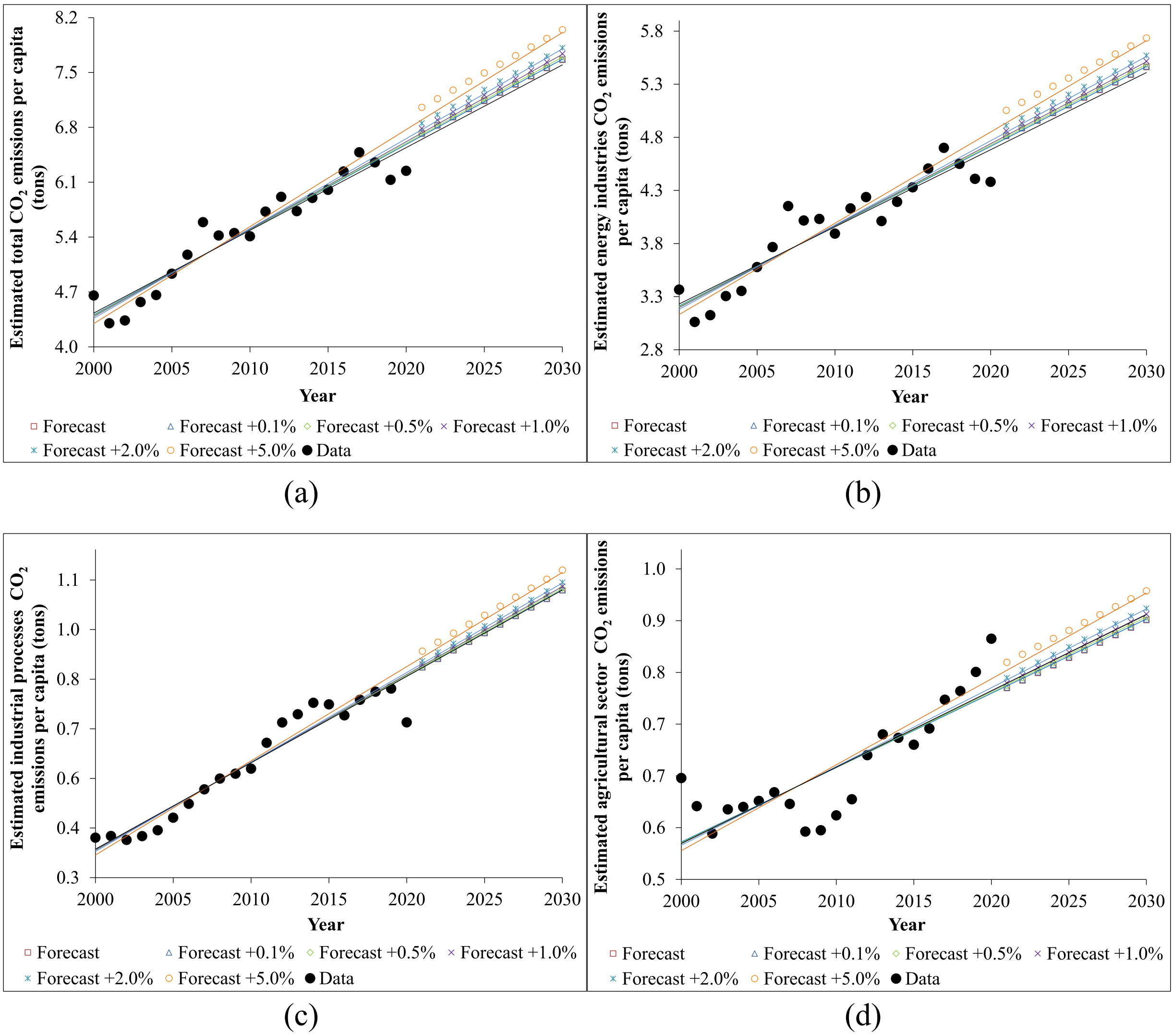


Fig. 8. Timeline data between 2000 and 2020 and (a) Logarithmic forecasts for total CO_2 emissions per capita between 2021 and 2030 based on increasing scenario, (b) Logarithmic forecasts for CO_2 emissions from energy industries per capita between 2021 and 2030 based on increasing scenario, (c) Logarithmic forecasts for CO_2 emissions from industrial processes and industrial use per capita between 2021 and 2030 based on increasing scenario, and (d) Logarithmic forecasts for CO_2 emissions from agricultural sectors per capita between 2021 and 2030 based on increasing scenario.

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CRediT authorship contribution statement

Murat Ozdemir: Methodology, Writing – original draft, Writing – review & editing, Supervision. **Seray Pehlivan:** Investigation, Formal analysis, Visualization. **Mehmet Melikoglu:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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