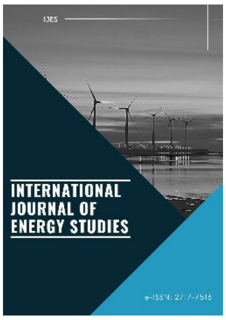
INTERNATIONAL JOURNAL OF ENERGY STUDIES

e-ISSN: 2717-7513 (ONLINE); homepage: https://dergipark.org.tr/en/pub/ijes



Research Article
Int J Energy Studies 2025; 10(2): 569-594
DOI: 10.58559/ijes.1572361

Received	:	24 Oct 2024
Revised	:	22 Apr 2025
Accepted	:	22 Apr 2025

Türkiye's net zero plan: Mathematical analysis of emission and mitigation approaches

Mujeeb Babatunde Adetayo [a*]
[a]Department of Chemical Engineering, Engineering Faculty, Marmara University, Istanbul, Turkey, ORCID Number: 0000000177077864
*(*Corresponding Author: mujeebadetayo@marun.edu.tr)*

Highlights

- Türkiye's CO_2 emission is envisaged to peak in 2032
- Enhancing Türkiye's energy plan is necessary to achieve the net zero goal
- Growth pace of renewables cannot solely deliver Türkiye's 2053 net zero target
- Fossil impact factor reduction approach offers substantial emission mitigation
- The smart emission mitigation approach is most effective for Türkiye's energy system

You can cite this article as: Adetayo MB**.** Türkiye's net zero plan: Mathematical analysis of emission and mitigation approaches**.** Int J Energy Studies 2025; 10(2): 569-594.

ABSTRACT

Türkiye's 2022 energy plan on net zero studies Türkiye's envisaged energy utilization based on energy resources, but excludes the associated emissions. This study has filled this gap and the calculations are based on primary energy consumption. Also, historical data-based forecasts have been carried out for comparison. Existing emission reduction methods investigated are the single process mitigation (SpM) which includes energy substitution (ES) and impact factor reduction (IFR), and the smart mitigation (SM) which combines both SpM methods. Unlike previous studies, the carbon capture efficiency parameter (C_{eff}) has also been introduced. Four case studies were considered: business as usual-based energy plan (Eplan_BAU), energy plan (Eplan), business as usual-based projection (Proj_BAU), and projection (Proj). The Eplan and Proj data give a cumulative and average annual energy consumption of 122.75 EJ and 7.67 EJ, and 151.39 EJ and 9.46 EJ respectively from 2020 to 2035, and the Eplan emission peaks by 2032. Relative to Proj_BAU, Proj and Eplan_BAU, the Eplan gives an emission reduction of 24.45%, 18.54% and 6.82% respectively. Also, the energy substitution and impact factor reduction mitigation approaches give emission reduction of ranges 13.46-56.10**%** and 12.55-62.74% respectively relative to Eplan. All in all, the SM gives the highest emission reduction.

Keywords: Türkiye, Energy plan, Net zero emission, Energy consumption, Emission mitigation

1. INTRODUCTION

Türkiye has made a commitment of the year 2053 for its net zero emission transition [1]. In order to achieve this, it has placed abrupt emission mitigation as a major goal in its energy policy [2]. In addition to that, Türkiye's 2022 national energy plan which covers the period up to 2035 was specifically developed towards accomplishing the target [1]. These actions are necessary because of the fossil fuel dominance in Türkiye's energy system, accounting for more than 80% of energy supply and consumption [3]. According to Inal et al. (2021), Türkiye's dependence on oil and natural gas is 93% and 99% respectively. The oil and natural gas utilization is dominated by the high emission intensive sectors: power and transport [2]. It is known that motor vehicles powered by fossil fuels and used in transportation cause air pollution in cities. They are also one of the most important sources of carbon emissions that cause climate change [4]. For example, in Türkiye, the transport sector was the second largest emitting in 2020 with 21.53% of the total emissions, followed by industry (19.89%), and residential (9.81%) [5]. These, coupled with the country's strong economic and population growth, as well as increasing energy demand, have led to steady greenhouse gas (GHG) emission expansion. According to the International Energy Agency (2023), Türkiye's CO_2 emission registered 86% growth in 2022 from 2000 levels and accounted for 1.19% of the global emission. The emission intensity of Türkiye's energy system also reflected in the British Petroleum's (BP) statistical energy review. Relative to other European countries, the year 2022 BP review showed that Türkiye's primary energy consumption was 6.4 EJ, placing the country in the fourth position after Germany, France and the United Kingdom. However, based on CO_2 emission, Türkiye ranked second with the total emission of about 400 $MtCO_2$ [6]. The impact of these carbon emissions is not limited to environmental challenges, but also has the potential of affecting Türkiye's economic activities. Moreover, the Mediterranean basin characterized by semi-arid and arid regions in which Türkiye is located further exposes the country to problems related to emission-induced climate change [7]. To mitigate these challenges and additionally meet the 2053 net zero goal, Türkiye's 2022 national energy plan was drafted, and it studies the country's envisaged energy utilization based on energy resources. To further strengthen and corroborate the outcome of the plan, this study is based on calculating the associated emissions and focuses on the primary energy consumption. In addition to that, historical data-based energy and emission forecasts have been carried out for comparison with the plan to determine its impact reduction potential. The extent of emission mitigation obtainable through existing mitigation approaches [8] has also been investigated. Moreover, the carbon capture efficiency parameter (C_{eff})

has also been introduced in this work. Impact and mitigation studies are very essential for effective net zero emission planning, and therefore makes this study very necessary.

Furthermore, meeting Türkiye's net zero emission transition target has high potential on mitigating the country's agricultural-related challenges and remains a permanent solution to the European Union's Green Deal impacts on the country's economy. The Green Deal policy is aimed at reducing carbon leakage risks and fostering fair competition with respect to products exported into the European Union (EU) region [9] and can have devastating effect on Türkiye's exporting activities [10]. This is because Türkiye's emission intensity, especially of electricity grid, is higher than most of other countries exporting to the EU [11]. As a result, numerous studies have been carried out on the Green Deal [12] and how its negative impacts on Türkiye's economy can be mitigated [13]. As for agriculture, the potential challenges that could result from the emission induced climate change [14] and its impacts on the sector have also been extensively studied [15]. Generally, efforts to minimize potential emissions and agricultural waste that contribute to climate change will ensure efficient use of industrial resources and significant savings in commonly consumed resources such as water and energy. In order to make cleaner production and environmentally friendly technology more effective, the use of emission reduction techniques together with recycling or industrial ecology (symbiosis) techniques is also being considered within the framework of the Green Deal [16]. These techniques are inspired by the circular-based characteristics of the natural ecosystems which help to reduce negative impacts. In addition to industrial ecology (symbiosis), other effective concepts are industrial metabolism [17], cradle-to-cradle design [18], and techno-ecological synergy [19]. The concept of zero waste is another very effective method of emission mitigation. Zero emission is an extension of eco-efficiency and aims to provide maximal economic value with zero adverse ecological impact, thereby decoupling the economy and ecology relationship [18]. The method can be said to be one of the most effective emission mitigation approaches in that the wastes or emissions are not even produced in the first place. Where waste or emissions are inevitable, the clean technologies are sustainable measures that can be used. Some of these technologies include carbon capture, utilization and storage (CCUS), as well as clean coal technologies (CCTs) which include coal bed methane (CBM), integrated gasification combined cycle (IGCC), circulating fluidized bed (CFB), and coal liquefaction (CL) [20]. Additionally, sustainable exploration methods like polymer flooding can as well be used for fossil fuel recovery if seen very necessary [21].

Türkiye has had a long history in terms of efforts towards mitigating emission and achieving energy sustainability. The country joined the United Nations Framework Convention on Climate

Change (UNFCCC) in May 2004 [22]. It also set up its National Greenhouse Gas Inventory in 2006 [15] and ratified the Kyoto Protocol in 2009 [22]. It has also been a member of the International Energy Agency (IEA) since 1974 [2]. Several plans have previously been created to overcome the environmental emission challenges in Türkiye. Examples are the Green Deal Action Plan [24], Türkiye's 11th Development Plan [25], and the Türkiye's national climate change plan which is embodied in the National Climate Change Strategy and whose implementing plan is known as the National Climate Change Action Plan (NCCAP) 2011-2023 [2].

There are numerous studies that have been carried out on Türkiye's energy system. Some of these studies are based on life cycle assessment (LCA) and limited to energy sources, while others are limited to sectors [26]. For example, Atilgan and Azapagic's (2016) study was limited to the electricity sector and uses life cycle approach to evaluate the environmental impacts of Türkiye's renewable electricity [27]. Kursun's (2022) study was based on life cycle assessment of Türkiye's solar power [28]. Cekinir et al. (2022) also investigated Türkiye's energy system based on its energy projection for 2050 [29]. There are also studies on the decarbonization of Türkiye's energy system using different methods. For example, Acar et al.'s (2022) study on Türkiye's emission mitigation investigated the approach of green financing [30]. Teimourzadeh et al.'s (2023) emission mitigation approach is based on gradual closure of the fossil fuel energy plants [31]. Güllü et al.'s (2023) work also focussed on the electricity sector and is based on renewable energy utilization in place of fossil fuels [32]. Additionally, using circularity approaches of energy framework material recycling and CO_2 utilization, Adetayo and Kursun (2024) investigated the extent of emission mitigation obtainable from Türkiye's electricity sector and its extended impact on the Green Deal. The present study explores the same CO_2 utilization approach, but with modifications. One of the most recent studies that specifically focuses on Türkiye's net zero emission transition is Türkiye's 2022 national energy plan [1] on which this work is based. Türkiye's 2022 national energy plan was carried out by the country's Ministry of Environment and Natural Resources (MENR) based on the electricity and natural gas market law. As previously mentioned, the report covers the period up to 2035 and is based on means of achieving Türkiye's 2053 net zero emission target [1]. The plan proposes Türkiye's envisaged energy utilization based on different energy resources as summarized in Table 1, and uses the mitigation strategy of domestic energy utilization among others.

Table 1. Projected percentage primary energy consumption by source based on Türkiye's 2022 national energy plan [1].

Year	Solid fuel (%)	Oil (%)	Gas (%)	Fossil (Total, %)	Nuclear (%)	Renewables (%)

2020	27.6	28.7	27	83.3	0	16.7
2035	21.4	26.5	22.5	70.4	5.9	23.7

However, knowledge of the emission intensity associated with the plan is not only critical in assessing its overall performance, but also important in determining the emission reduction rate obtainable when compared with the business as usual (BAU) trend; i.e., historical data-based forecast. This is therefore a major goal of this study and the research output will serve as guide towards subsequent planning processes. Apart from intensifying the use of local energy sources, there is also the need to determine the extent of emission mitigation obtainable from established methods. For this reason, this study aims to calculate the emissions associated with Türkiye's envisaged energy utilization with respect to the primary energy consumption, carry out a historical data-based primary energy and emission forecast for effective comparison and assessment, and investigate the extent of emission mitigation obtainable from the use of existing sustainable mitigation measures. The novelty of this study lies in the fact that it explores the fundamental emission equations to formulate different impact mitigation strategies to the emission challenges. Through this, the potential of some mitigation methods like the single process mitigation (SpM) approach which includes energy substitution (ES) and impact factor reduction (IFR), and the smart mitigation (SM) approach which combines both SpM methods has been investigated. Even though this study is based on existing mitigation approaches [8], necessary modifications have been used where necessary. Also, the mathematical description and analysis explored give scientific basis to why certain mitigation methods are being used and how their efficacy can be improved from the scientific point of view. All these reflect the originality of this study.

2. METHODOLOGY

In this study, the calculations have been carried out using parameters such as the historical and projected energy consumption, as well as the fractional share and impact factor of Türkiye's energy sources. The energy sources include lignite (L), hard coal (HC), natural gas (NG), geothermal (GT), solar (S), hydro (reservoir) (HR), wind (W), waste (Wst) and hydro (stream) (HS). The data were sourced from the International Energy Agency reports [33] and Türkiye's 2022 national energy plan [1]. The calculations were carried out using models which are based on derived mathematical formulas. Being the impact category that is most related to climate change, the results obtained from this study have been analyzed based on the global warming potential (GWP). In the first stage of the study, the limited primary energy consumption data from the energy plan was modelled and scaled up. Historical data-based primary energy consumption forecast was also carried out. The results from both data sources were thereafter analyzed. In the second stage, the impacts associated with both the up-scaled and forecasted data were calculated and analyzed. The third stage is based on emission mitigation approaches. The flow chart of the study pattern is shown in Figure 1. The impact factor of the energy sources is a very important parameter in impact calculations. Impact factors are numbers which represent emission intensities and are attributed to specific impact categories known as impact potentials. For Türkiye's energy system, Table 4 shows the different energy sources as well as their GWP impact factors.

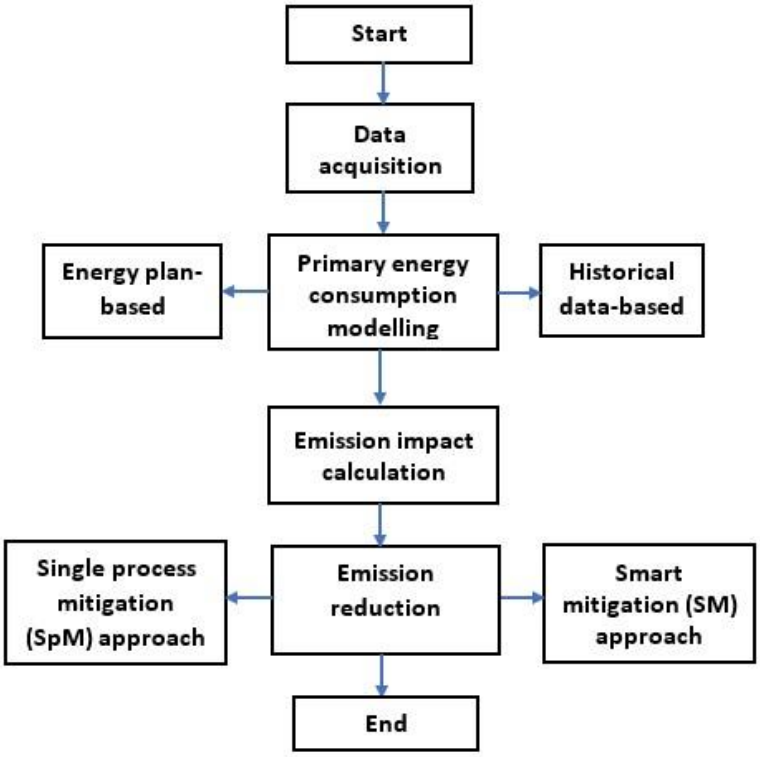


Figure 1. Flow chart of study pattern

2.1. Türkiye's primary energy consumption modelling

Table 2 shows Türkiye's primary energy consumption from 2020 till 2035 as obtained from Türkiye's energy plan [1]. The values are however limited to year 2020, 2025, 2030 and 2035. Using Equation 1, the data has been scaled up to determine the annual values from 2020 to 2035, which are then used in subsequent calculations.

$$E_{i+1} = E_{i+5} + \frac{E_{i+5} - E_i}{5} \tag{1}$$

In Equation 1, i represents year; E represents energy consumption in EJ; E_i is energy consumption for a given year i; E_{i+1} is energy consumption a year after E_i, and E_{i+5} is energy consumption five years after E_i. The accuracy of the results obtained was ascertained from its consistency with the original data as shown in Table SI.1.

Table 2. Türkiye’s primary energy consumption data based on the energy plan [1].

Year	Solid fuels (Mtoe)	Oil (Mtoe)	Gas (Mtoe)	Nuclear (Mtoe)	Renewables (Mtoe)
2020	40.6	42.2	39.8	0	24.6
2025	47	50.5	42.9	4	32.6
2030	47.9	54.8	47.7	8	40.6
2035	43.9	54.5	46.2	12	48.7

Table 3 also shows Türkiye’s historical primary energy consumption from 2009 to 2019 as obtained from the International Energy Agency (2023) report [33]. Based on the data values, a forecast has been carried out for year 2020 to 2035 using Equation 2 [34]. The first step was to determine the value of the model constant k for the equation. This was done by fitting the historical values with the equation. Thereafter, the obtained k value was substituted into the equation and used for the projection.

$$E_c = E_{c_o} exp\,[(k(t-t_o)] \qquad (2)$$

In Equation 2, E_C is energy consumption in EJ; E_{Co} is energy consumption in the base year; t is time in years; t_o is the base year, and k is the model constant. The accuracy of the results obtained was ascertained from its consistency with the historical data as shown in Table SI.2.

Table 3. Primary energy consumption historical data [33].

Year	Solid fuels (EJ)	Oil (EJ)	Gas (EJ)	Renewables (EJ)	TOTAL (EJ)
2009	1.29	1.41	1.21	0.36	4.27
2010	1.32	1.37	1.29	0.53	4.51
2011	1.42	1.34	1.51	0.54	4.81
2012	1.53	1.41	1.56	0.61	5.11
2013	1.32	1.51	1.58	0.66	5.07
2014	1.51	1.55	1.68	0.49	5.23
2015	1.45	1.85	1.65	0.76	5.71
2016	1.61	1.98	1.6	0.82	6.01
2017	1.65	2.07	1.86	0.79	6.37
2018	1.71	2	1.7	0.88	6.29
2019	1.7	2.03	1.56	1.2	6.49

2.2. Impact calculation

The impact calculations have been carried out for the year range 2020 to 2035 using four case studies: the business as usual-based forecast (Proj_BAU), the forecast (Proj), the business as usual-based energy plan (Eplan_BAU), and the energy plan (Eplan). By business as usual (BAU), we mean that the fractional share of the energy sources in the consumption mix is the same as that of the base year 2020. Thus, Proj_BAU implies the impact based on the forecasted data where the fractional share of the energy sources is the same as that of the base year. Proj refers to the impact based on the forecasted data where the fractional share of the energy sources takes their normal values. Eplan_BAU implies the impact based on the energy plan data where the fractional share of the energy sources is the same as that of the base year. Eplan refers to the impact based on the energy plan data where the fractional share of the energy sources takes their normal values. Using the energy plan analysis and historical data as guide, the fractional share of the individual energy sources has been computed from Table SI.3. For the impact calculations, Equations 3 and 4 are applicable. For Türkiye's energy system, Table 4 shows the different energy sources as well as their GWP impact factors. The impact factor of nuclear energy source is 6.67% of that of natural gas [35].

Mathematically, we have:

$$E_i = IFi \times x_i C_T \tag{3}$$

$$E_T = \sum_{i=1}^{n} E_i = \sum_{i=1}^{n} (IFi \times x_i C_T) \tag{4}$$

In Equations 3 and 4, x_i is the fraction of energy resource in the consumption mix, i represents the energy resource, IF_i is the impact factor of energy source ($GtCO_2/EJ$), E_i is CO_2 emission (Gt) from the energy source, E_T is total CO_2 emission (Gt), C is energy consumption (EJ), C_T is total energy consumption (EJ), and n is number of years.

Table 4. Impact factor (IF) of Türkiye's energy sources

Energy sources	Impact Factor, IF (as obtained)	Impact Factor, IF ($GtCO_2/EJ$)	References
Hard coal (HC)	93.64 (tCO_2/TJ)	0.09364	[36]
Lignite (L)	104.08 (tCO_2/TJ)	0.10408	[36]
Oil (O)	69.3 (tCO_2/TJ)	0.06930	[36]
Natural gas (NG)	55.43 (tCO_2/TJ)	0.05543	[36]
Nuclear (N)	3.70 (tCO_2/TJ)	0.00370	[36]
Wind (W)	7.3 (gCO_2eq./kWh)	0.00203	[27]
Solar (S)	29.5 (gCO_2eq./kWh)	0.00819	[28]
Hydro river (HR)	8.3 (gCO_2eq./kWh)	0.00231	[27]
Hydro stream (HS)	4.1 (gCO_2eq./kWh)	0.00114	[27]
Waste (Wst)	4.1 (gCO_2eq./kWh)	0.00114	[27]
Geothermal (GT)	63 (gCO_2eq./kWh)	0.01750	[27]

2.3. Emission mitigation approaches

In this study, we have explored the fundamental emission equations (Equations 3 and 4) to formulate different impact mitigation strategies for the emissions associated with energy consumption. Equations 3 and 4 show that emission (E) is a function of three parameters: the total energy consumption (C_T), fractional share (x_i), and impact factor (IF_i) of the energy sources as expressed in Equation 5. The direct proportionality indicates that the emission reduction potential of the energy sources depends on the parameters and reducing these parametric values can result into emission mitigation. However, the impact mitigation rate will depend on the specific approach used and necessitates the understanding of the parametric relationships. Energy consumption (C_T) reduction can be achieved through energy efficiency which is a major policy in Türkiye's energy system. Therefore, the approach has not been considered in this study. For fractional share (x), the parametric value itself is not reducible as a whole since the fractional shares (x_i) of the energy sources in the consumption mix must sum up to one. Therefore, a feasible approach is to increase the fraction of the lower emitting energy sources and reduce that of the high emitters by the same rate; i.e., the substitution of the high emitting energy sources (fossil fuels) with the lower emitting ones (renewables); hence, the energy substitution (ES) concept of emission mitigation. For the impact factor (IF_i) parameter, substantial emission mitigation through its reduction can be realized if the fractional share (x_i) of the energy source being considered is relatively high in the energy mix [6]. This implies that emission reduction based on impact factor (IF_i) is a function of the fractional share (x_i) of the energy sources just like the fractional share (x_i) is also a function of the impact factor (IF_i) as expressed in Equations 6 and 7.

$$E = f(x_i, C_T, IF_i) \quad (5)$$

$$x_i = f(IF_i) \quad (6)$$

$$IF_i = f(x_i) \quad (7)$$

Moreover, for Türkiye's energy mix, Table 1 shows that fossil fuels account for about 80% of the primary energy consumption. These energy sources also have high impact factors as shown in Table 4. Figure 2 expresses the fractional share (x) and impact factor (IF) relationship for Türkiye's energy mix. The figure shows that fossil fuels tend to have high emission mitigation potentials due to their high fractional shares and impact factors compared to renewables. For this reason, the impact factor reduction (IFR) approach has been used for fossil fuels. This implies that processes that can lead to the reduction in the fossil fuels' impact factor should be given utmost consideration and worth being investigated for abrupt emission mitigation.

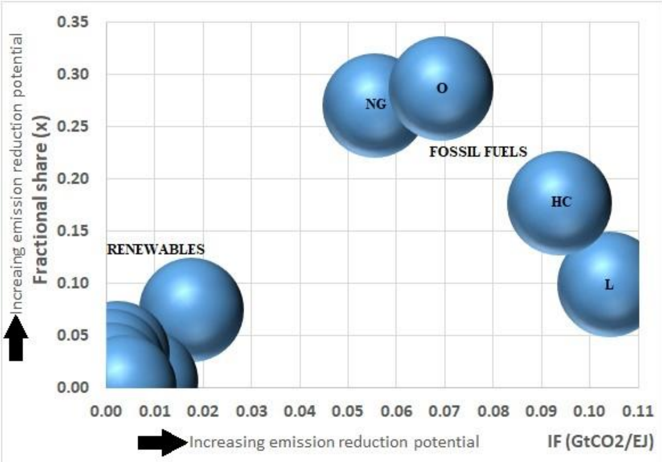


Figure 2. Emission reduction potential of energy sources based on impact factor (IF) and fractional share (x) relationship.

Based on the analysis, the emission reduction methods investigated have been divided into two as shown in Figure 3: the single process mitigation (SpM) and smart mitigation (SM) approach. The single process mitigation (SpM) approach uses only one mitigation method; in this case, either energy substitution (ES) or impact factor reduction (IFR). The smart mitigation (SM) approach combines two or more single process mitigation (SpM) methods; in this case, the energy substitution (ES) and impact factor reduction (IFR).

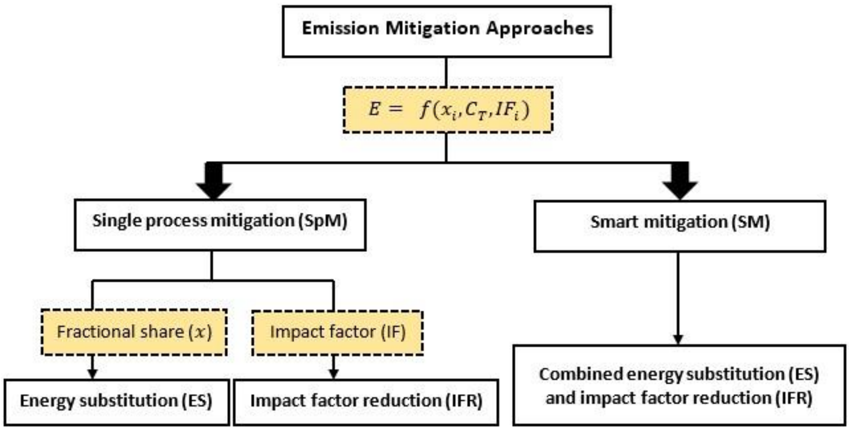


Figure 3. Emission mitigation approaches.

2.3.1. Single process mitigation (SpM) approaches

Energy substitution (ES): For emission mitigation through energy substitution, the sourced data were used to model different energy consumption scenarios and the impacts associated with each of them were calculated. According to the energy plan, Türkiye's energy supply is to be sourced majorly from local energy sources which are characterized by increased domestic energy utilization, majorly renewable energy sources. Based on this, the emission associated with substitution with these local energy sources has been calculated. The fossil fuel energy sources being substituted are hard coal (HC), natural gas (NG), and oil (O), excluding lignite (L) which is also a domestic energy source with high potential of being utilized for the goal of energy security [21]. It should however be noted that only substitution with renewables is regarded as mitigation measure. To study the impacts, six case studies were used: lignite (L), wind (W), solar (S), wind-solar (WS), lignite-wind-solar (LWS), and full renewable energy (RES) substitution. The energy plan (Eplan) from the previous section has been used as reference with which all the cases were compared. The assumptions are as follows [8]:

- All cases exhibit a business as usual (BAU) scenario up till year 2025, after which necessary substitution become applicable.
- Apart from the domestic energy (lignite, wind and solar) and substituted energy (natural gas, hard coal and oil), all other energy sources exhibit the business as usual (BAU) scenario. This implies that their fractions in the energy mix do not change.
- In the renewable energy system (RES) scenario, fossil fuels including lignite contribute nothing to the energy mix.
- Apart from the renewable energy system (RES) where the fossil fuel fractional shares are taken as zero, a general assumption is that 5% of the substituted energy sources remains in the energy mix.
- There is equal sharing of the share of the substituted energy resources within the indigenous energy sources.

Fossil impact factor reduction (IFR): Limiting the approaches of meeting the net zero emission transition goal to renewable energy substitution might not be fully effective due to the possible slow pace of such process, as well as its huge investment requirement; hence, the fossil impact factor reduction approach. First, this study uses the impact factor reduction approach reported by Adetayo and Kursun (2024). From the study, impact factor reduction of lignite through CO_2 utilization for urea production was investigated, and the same has been adopted in this study, but with the following modifications:

- Introduction of the CO_2 capture efficiency parameter (C_{eff}) as shown in Figure 4 and Equation 8 using a baseline efficiency of 90% set for carbon capture process [37].
- Extension of the carbon capture and utilization process to all fossil fuels in use.

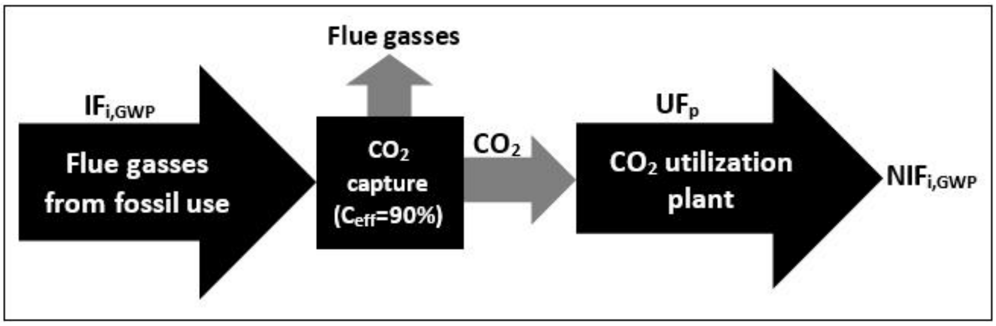


Figure 4. General description of CO_2 flow in a CO_2-based plant [8] with carbon capture efficiency.

$$NIF_{i,GWP} = \frac{(IF_{i,GWP} \times C_{eff}) \times IF_p}{UF_p} + (1 - C_{eff}) IF_{i,GWP} \quad \frac{gCO2}{kWh} \tag{8}$$

In Equation 8, $IF_{i,GWP}$, $NIF_{i,GWP}$, UF_p and IF_p are the initial impact factor, the net impact factor, the utilization factor (of plant/process) and impact factor (of plant/process), respectively [8]. C_{eff} is the CO_2 capture efficiency, and $(1 - C_{eff})IF_{i,GWP}$ represents the CO_2 losses. Substituting C_{eff}=100% into Equation 8 gives the main equation reported by Adetayo and Kursun (2024).

However, with the CO_2 utilization route of impact factor reduction, the choice of synthesized product and production route have great effect on the overall emission mitigation potential and determine the extent of sustainability of the approach in general. As a result of this, most of the CO_2 utilization routes have been reported as unsustainable due to their limited carbon benefits. In fact, approximately 75% of the CO_2 utilization-based products have been reported to be accounted for by compounds which would not correspond to long-term sequestration as the incorporated CO_2 is released once the products are used, which is the case with urea and methanol [38]. Therefore, a generalized impact factor-based sensitivity analysis has also been carried out irrespective of the impact factor reduction approach used as shown in Figure 5; therefore, the carbon capture process is not considered. By this, the impact associated with any process that gives specific impact factor reduction can be determined directly or using interpolation by comparing the net impact factor obtained from such process with the sensitivity analysis result. For the sensitivity analysis, the impact factor of the fossil fuels has been reduced by 20% (0.8_IF), 40% (0.6_IF), 60% (0.4_IF), 80% (0.2_IF) and 100% (0.0_IF) and the corresponding emission impacts and percentage impact reductions relative to that of the initial impact factor have been calculated. The description of the impact factor reduction approach is shown in Figure 5.

Additionally, considering future technological advancement in the CO_2 utilization routes that can result into better carbon credits, a generalized impact factor-based sensitivity analysis using CO_2

utilization has also been carried out to determine the emission associable with processes that might result into a different net impact factor aside the urea synthesis route investigated. Some of such technology which includes CO_2 utilization for cement and brick production that can trap the CO_2 permanently are currently being studied. In this case, the 90% carbon capture efficiency has also been used.

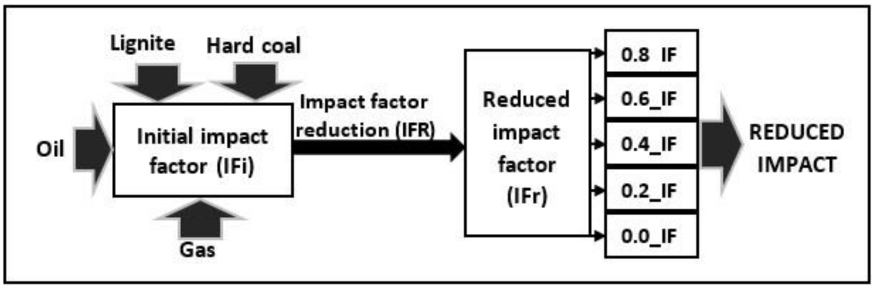


Figure 5. Description of the impact factor reduction (IFR) approach.

2.3.2. Smart mitigation (SM) approach

The smart mitigation (SM) approach refers to the combination of two or more emission mitigation methods as shown in Equations 9 and 10. Here, the two single process mitigation (SpM) approaches of energy substitution (ES) and fossil impact factor reduction (IFR) have been combined as shown in Equation 11 and the overall impact reduction has been calculated. For energy security purposes, Türkiye's energy policy targets the use of its domestic energy sources which include lignite prior to full renewable energy transition. Therefore, for energy substitution, the wind-solar (WS) and lignite-wind-solar (LWS) case scenarios have been used. For fossil impact factor reduction, a 50% IF reduction rate has been used. The syntax for the combined methods are WS_IFR/ LWS_IFR and WS_IFR(CO_2 uti)/ LWS_IFR(CO_2 uti) respectively for the general case without carbon capture and that of the CO_2 utilization where carbon capture is applicable.

$$IR_T = IR_{M1} + IR_{M2} + IR_{M3} + \ldots\ldots + IR_{Mn} \quad (9)$$

$$IR_T = \sum_{i=1}^{n} IR_{Mi} \quad (10)$$

In Equations 9 and 10, IR represents impact reduction, IR_T is the total impact reduction, M_n is the mitigation approach n, IR_{Mn} is the impact reduction from mitigation approach n.

Based on this study, Equations 9 and 10 can be expressed as Equation 11.

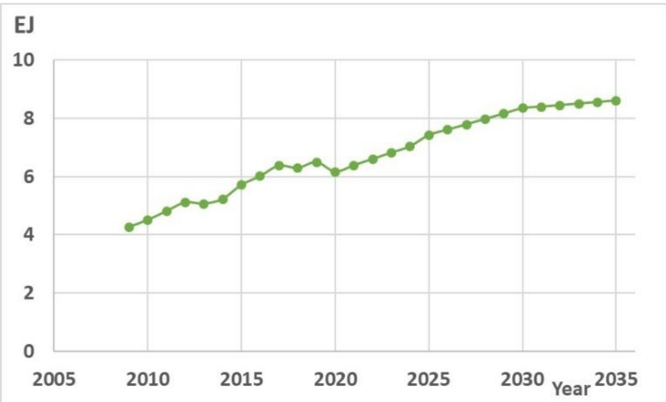
$$IR_T = IR_{ES} + IR_{IFR} \quad (11)$$

In Equation 11, ES and IFR represent energy substitution and impact factor reduction respectively.

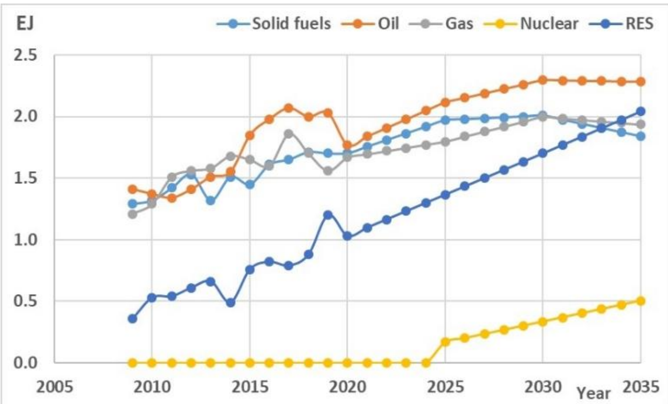
3. RESULTS AND DİSCUSSİON

3.1. Primary energy consumption

Based on Türkiye's energy plan, the results of the up-scaled primary energy consumption data (2020-2035) are shown in Figure 6. The historical data (2009-2019) is also included in the figure. The annual values are tabulated in Table SI.1. The scaling has been carried out for each category of the energy sources which includes solid fuels (hard coal and lignite), oil, gas, nuclear and renewable energy. According to the result, a cumulative energy consumption of 122.75 EJ corresponding to an average annual consumption of 7.67 EJ is obtained. Figure 6a shows that Türkiye's primary energy consumption plan is not only characterized by continuous increase, but also by continuous growth rate reduction, especially from 2030 onwards. The major cause of the growth rate reduction is evident from Figure 6b which shows the energy consumption for the individual energy sources. The figure shows that while the fossil fuel energy sources are characterized by reducing growth rate, that of renewable and nuclear energy sources continue to increase at a relatively high rate. However, due to the very low fractional share of renewables and nuclear energy in the energy mix compared to fossil fuels as shown in Table SI.3, there is an overall average reduction in consumption growth rate which results into the trend shown in Figure 6a.



a.



b.

Figure 6. Türkiye's primary energy consumption based on the energy plan and historical data for (a) total energy consumption, and (b) energy consumption based on sources.

For the historical data-based energy forecast, the constant k of the exponential method used is estimated as 0.042. The accuracy of the value is ascertained from the consistency in the reproduced and original historical data as shown in Table SI.2. According to the result shown in Figure 7, a cumulative primary energy consumption of 151.39 EJ corresponding to an average annual consumption of 9.46 EJ is obtained. Türkiye is a developing country with increasing population and energy demand. In line with this, the forecasted result shows that Türkiye's primary energy consumption should normally increase exponentially with increasing growth rate based on the historical trend. This is unlike the energy plan which is aimed towards a specific goal and therefore characterized by reducing growth rate. Based on the plan, Figure 6a shows that the growth rate reduces up to a point where energy consumption reaches an approximate balance point or peak. Compared to the forecasted data as shown in Figure 7, the reduced growth rate trend and balance point in the energy plan imply additional goals such as energy efficiency in Türkiye's energy system. Thus, the peak can imply a state at which energy efficiency is being fully integrated into the system. Energy efficiency is a major policy in Türkiye's energy system which is being utilized to reduce the pace of energy consumption increase, while ensuring quality energy supply. Increased energy efficiency is equivalent to energy quality where less energy can be utilized for increased work output. Similar result was obtained for Türkiye's electricity in a study carried out by Cekinir et al. (2022). According to the result of the study, with Türkiye's increasing power installation, a peak will be reached in 2050 where simply increasing energy efficiency of existing power plants can be sufficient to meet Türkiye's electricity energy need [29].

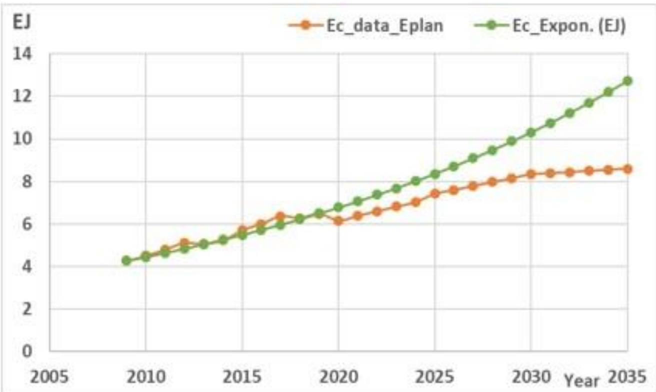
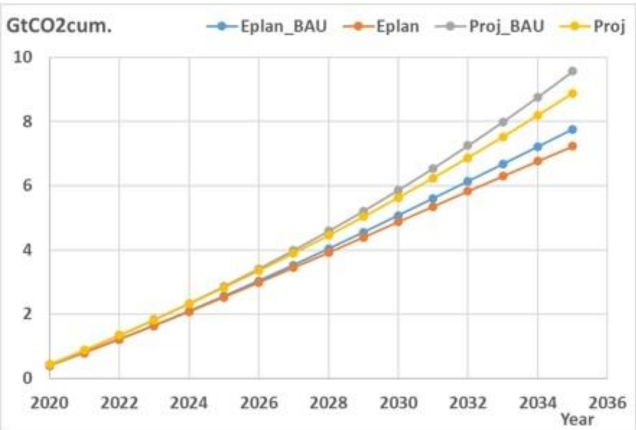


Figure 7. Türkiye's primary energy consumption projection based on the energy plan and historical data-based forecast.

3.2. Emission impacts

The emission impact associated with the energy consumption has been calculated and the results for the four case studies are shown in Figure 8a and 8b. According to Figure 8a which shows the cumulative emissions, the business as usual-based forecasted data (Proj_BAU) scenario has the highest cumulative impact of 9.57 $GtCO_2$, followed by forecasted data (Proj) with 8.88 $GtCO_2$, business as usual-based energy plan data (Eplan_BAU) with 7.76 $GtCO_2$, and the energy plan data (Eplan) having the least impact of 7.23 $GtCO_2$. These values are equivalent to average annual emissions of 0.60, 0.55, 0.49 and 0.45 $GtCO_2$ respectively. Compared with the Proj_BAU, Proj and Eplan_BAU cases, the results imply that the energy plan (Eplan) has emission reductions of 24.45%, 18.54% and 6.82% respectively. Even though these emission reductions are substantial, an average annual emission of 0.45 $GtCO_2$ obtained for the energy plan is enormous if the goal of net zero emission transition is to be achieved as envisaged. Moreover, Figure 8b which is based on the annual impacts shows that Türkiye's emission is expected to peak by 2032 after which a continuous reduction is expected; therefore, the impact reduction rate is critical in meeting up with the emission target. Furthermore, it should be noted that Türkiye's energy plan is majorly based on renewable energy transformation (i.e., fossil fuel to renewable energy transition), a very effective emission mitigation approach but which will be a gradual process as observed in the energy utilization trends of the plan (Table 1). This shows that there is necessity for the utilization of other sustainable approaches. However, with fossil fuels being the main source of greenhouse gas (GHG) emissions, utmost priority should be given to renewable energy investment and fossil fuel energy substitution with the resources. The efficacy and rate of impact reduction obtainable from the substitution processes as well as other emission mitigation approaches have also been determined and analyzed in the next section.



a.

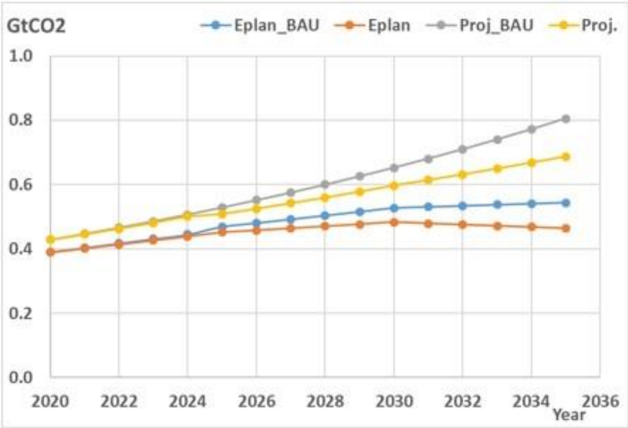
b. 

Figure 8. Emission impact based on (a) cumulative, and (b) annual primary energy consumption.

3.3. Emission mitigation approaches

Energy substitution: The substituted fossil energy sources are hard coal (HC), natural gas (NG), and oil (O), and the result is shown in Figure 9. According to the result, substitution with lignite (L) has the highest cumulative impact of 9.43 $GtCO_2$. This is followed by lignite-wind-solar (LWS) with 6.67 $GtCO_2$, solar (S) with 6.26 $GtCO_2$, wind-solar (WS) with 4.82 $GtCO_2$, wind (W) with 4.52 $GtCO_2$, and the full renewable energy system (RES) having the least impact of 3.17 $GtCO_2$. Systems like Case 1 (L), Case 2 (W), Case 3 (S) which are based on single energy source were carried out to determine the changes in impact relative to other cases. For effective comparison, we have calculated the emission reduction relative to the energy plan's (Eplan) impact of 7.23 $GtCO_2$ obtained in the previous section. Figure 9 shows that only lignite substitution (L) has higher impact than Eplan and gives an emission increase of 30.40 %. The LWS, S, WS, W and RES substitution cases give the corresponding emission reductions of 13.46, 33.34, 35.39, 37.44 and 56.10%. This result aligns with that of Kursun (2023) which was based on the impact reduction obtainable from wind energy utilization in Türkiye's electricity sector [39]. According to the result, lignite and hard coal substitution by wind energy would be the most environmental-friendly option for Turkish electricity mix [39]. From the overall results of this study, it can be ascertained as expected that the more the shift from fossil fuels to renewables, the lower the emission associated with the system. For Türkiye's energy system however, the major challenge is the pace of this shift; i.e. the transition rate.

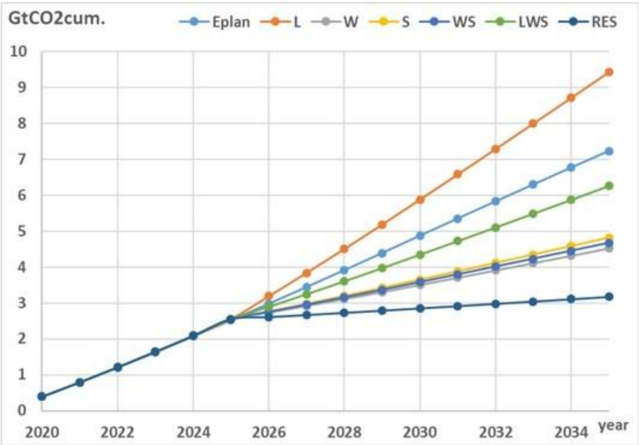
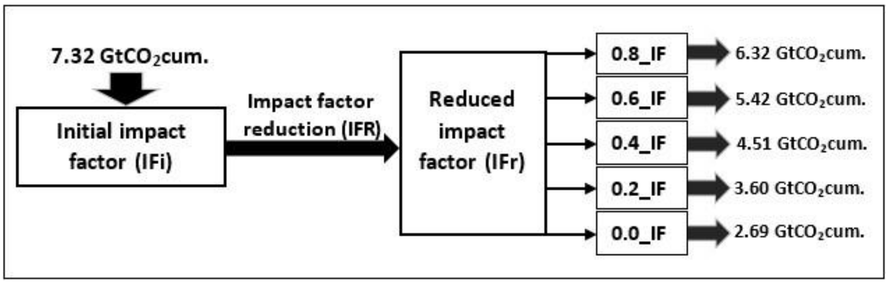


Figure 9. Emission impacts based on the energy plan (Eplan), lignite (L), wind (W), solar (S), wind-solar (WS), lignite-wind-solar (LWS), and renewable energy (RES) substitution.

Fossil impact factor reduction (IFR): Using the gasification process-based urea synthesis route reported by Adetayo and Kursun (2024), the result shows that with 100% carbon capture efficiency, the impact factors of lignite (L), hard coal (HC), natural gas (NG), and oil (O) reduce from the initial values of 0.10408, 0.09364, 0.05543, 0.0693 $GtCO_2/EJ$ to 0.0244, 0.0219, 0.0130, and 0.0162 $GtCO_2/EJ$ respectively, all with 76.58% impact factor reduction. The net impact factors were obtained by scaling the initial impact factors of the energy sources based on the respective input and output values of 1130 gCO_2eq./kWh and 241.26 gCO_2eq./kWh reported for lignite in the referenced study. Moreover, using the baseline target of 90% set for carbon capture process efficiency [37], the net impact factors of the energy sources give 0.302, 0.0271, 0.0201 and 0.0161 $GtCO_2/EJ$ respectively. Based on these results, the cumulative emissions for the initial impact factor (IFi), impact factor at 100% capture efficiency (NIF(Ceff=100%)) and impact factor at 90% capture efficiency (NIF(Ceff=90%)) give 7.23, 1.88 and 2.26 $GtCO_2$. Compared with the initial impact factor, these are equivalent to percentage emission reductions of 74.05% and 68.68% for NIF(Ceff=100%) and NIF(Ceff=90%) respectively.

Due to the limitations associated with the CO_2 utilization route as analyzed in the previous section, the result of the sensitivity analysis for the fossil fuel-based impact factor reduction carried out is shown in Figure 10a and does not consider carbon capture efficiency. The result shows that the initial fossil impact factor gives a total emission of 7.23 $GtCO_2$. Reducing this impact factor by 20% (0.8_IF), 40% (0.6_IF), 60% (0.4_IF), 80% (0.2_IF) and 100% (0.0_IF) results into the emission reductions to 6.32, 5.42, 4.51, 3.60 and 2.69 $GtCO_2$ respectively. This is equivalent to emission reductions of 12.55%, 25.09%, 37.64%, 50.19% and 62.74% respectively, relative to the energy plan (Eplan). The substantial reductions in emission show the high potential and efficacy of the fossil impact factor reduction approach. Using these results, if for example Türkiye meets up with a 50% fossil impact factor reduction rate, about 4.97 $GtCO_2$ which is equivalent to a 31.33% impact reduction will be achieved. This result implies that any process which can lead to the reduction in the fossil fuels' impact factor should be given utmost priority. Doing so is important because limiting the approaches of meeting the net zero emission transition goal to renewable energy transition might not be fully effective due to the possible slow pace of such process and its huge investment requirement.

Considering future technological advancement in the CO_2 utilization routes that can result into better carbon credits, a generalized impact factor-based sensitivity analysis using CO_2 utilization has also been carried out to determine the emission associable with processes that might result into a different net impact factor aside the urea synthesis route earlier investigated. Some of these technologies which include CO_2 utilization for cement and brick production and which trap the CO_2 permanently are currently being studied. With a 90% carbon capture efficiency, Figure 10b shows that the initial fossil impact factor gives a total emission of 5.49 $GtCO_2$. Reducing this impact factor by 20% (0.8_IF), 40% (0.6_IF), 60% (0.4_IF), 80% (0.2_IF) and 100% (0.0_IF) results into emission reductions to 4.67, 3.85, 3.04, 2.22 and 1.40 $GtCO_2$ respectively. This is equivalent to emission reductions of 14.88%, 29.76%, 44.65%, 59.53% and 74.41% respectively, relative to the energy plan (Eplan). By these, the emission associable with processes that might result into different net impact factors can be investigated. For example, urea synthesis gives the net impact factors of 0.302, 0.0271, 0.0201 and 0.0161 $GtCO_2$/EJ respectively with lignite (L), hard coal (HC), natural gas (NG), and oil (O), corresponding to a 78.65% impact factor reduction, and falls between 0.2_IF and 0.4_IF. Therefore, the corresponding emission of 2.26 $GtCO_2$ which is the same with the result earlier obtained can be determined by interpolation method. Also, given a hypothetical case where the impact factor reduces by 60%, such corresponds to 0.4_IF when compared with the result obtained. It therefore gives the impacts of 3.04 $GtCO_2$ and 4.51 $GtCO_2$ with the CO_2 utilization and general impact factor reduction cases respectively.



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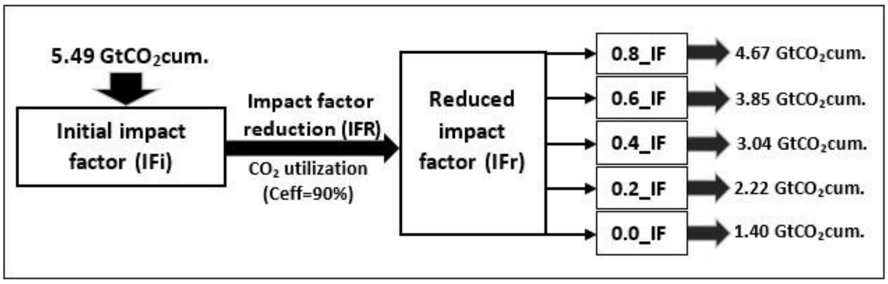

b.

Figure 10. Sensitivity analysis based on (a.) fossil impact factor reduction, and (b.) CO_2 utilization and 90% carbon capture efficiency.

Smart mitigation (SM) approach: The result of the combined energy substitution (ES) and fossil impact factor reduction (IFR) approaches is shown in Figure 11. For energy substitution, the wind-solar (WS) and lignite-wind-solar (LWS) substitution cases have been used. First, the general sensitivity analysis results represented as WS_IFR and LWS_IFR are shown alongside the wind-solar (WS) and lignite-wind-solar (LWS) substitution and all compared with the energy plan (Eplan). The specific case of CO_2 utilization for urea synthesis represented by WS_IFR(CO_2 uti) and LWS_IFR(CO_2 uti) using 90% carbon capture process efficiency is also shown in Figure 11**.** The result shows that WS_IFR and LWS_IFR give cumulative emissions of 3.89 and 4.72 $GtCO_2$ respectively. Compared with the energy plan (Eplan), this is equivalent to emission reductions of 46.26% and 34.71% respectively. When compared with the WS and LWS substitution cases, the emission reductions obtained are 16.82 and 24.55% respectively. Also, WS_IFR(CO_2 uti) and LWS_IFR(CO_2 uti) respectively give cumulative emissions of 3.81 and 4.57 $GtCO_2$, and corresponding emission reductions of 47.34% and 36.83%. When compared with the WS and LWS substitution cases, the emission reductions obtained are 18.50 and 27.00% respectively**.** According to Kursun's (2022) study which was based on a single process mitigation (SpM) approach of solar power utilization in Türkiye's electricity sector, if the solar power ratio in the mix increases to 15% by 2030, a GWP reduction of 0.03 Gt can be achieved. This reduction rate is also very low compared with what has been obtained from the smart mitigation (SM) approach investigated in this work**.**

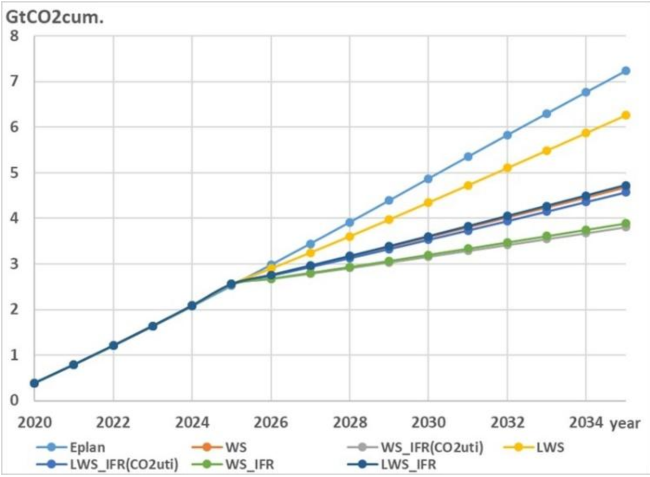

Figure 11. Smart mitigation approach based on wind-solar substitution/IFR (WS_IFR), lignite-wind-solar substitution/IFR (LWS_IFR), wind-solar substitution/IFR for urea (WS_IFR(CO_2 uti)) and lignite-wind-solar substitution/IFR for urea (LWS_IFR(CO_2 uti)), compared with the WS and LWS substitution cases.

4. CONCLUSION

In this study, we have calculated the emissions associated with Türkiye's envisaged energy utilization based on its energy plan and with respect to the primary energy consumption. We have also carried out a historical data-based primary energy and emission forecast relative to the plan for effective comparison and assessment. The novelty of this study lies in the fact that it explores the fundamental emission equations to formulate different impact mitigation strategies to the emission challenges. Through this, the potential of some mitigation methods like the single process mitigation (SpM) approach which includes energy substitution (ES) and impact factor reduction (IFR), and the smart mitigation (SM) approach which combines both SpM methods has been investigated. Unlike previous studies, the effect of carbon capture efficiency (C_{eff}) has been considered in this work. Moreover, the mathematical analysis approach adopted is unique and it gives scientific basis to why certain mitigation methods are being used as well as how their efficacy can be improved from the scientific point of view. All these reflect the originality of this study.

According to the results, the energy plan and forecast give cumulative energy consumptions of 122.75 EJ and 151.39 EJ respectively. These values correspond to average annual consumptions of 7.67 EJ and 9.46 EJ**.** In contrast to the forecasted result which is characterized by increasing growth rate, continuous consumption growth rate reduction is observed in the energy plan. Based on the Eplan, the emission peak year has been estimated as 2032. Furthermore, the emission reductions associated with the energy plan (Eplan) **r**elative to Proj_BAU, Proj and Eplan_BAU which are the other cases examined are estimated as 24.45%, 18.54% and 6.82% respectively.

Even though these emission reductions are substantial, an average annual emission of 0.45 $GtCO_2$ obtained for the energy plan is enormous if the goal of net zero emission transition is to be achieved as envisaged. Based on this, **t**he single process mitigation (SpM) approach of energy substitution and impact factor reduction (general case) give the emission reduction of ranges 13.46-56.10**%** and 12.55-62.74% respectively relative to the energy plan (Eplan). Also, the smart mitigation (SM) approach cases of WS_IFR and LWS_IFR give reductions of 46.26% and 34.71% respectively relative to the energy plan (Eplan), and 16.82 and 24.55% respectively relative to the WS and LWS substitution cases. These results show that the best emission reduction method based on percentage impact reduction is the smart approach**.** It also shows that the single process mitigation (SpM) approach of fossil impact factor reduction is very effective, especially for Türkiye's present energy mix which is dominated by fossil fuel. In general, the results have shown that intensifying the deployment of multiple sustainable emission reduction techniques is necessary for Türkiye's emission mitigation goals to be met. Some other mitigation methods include developing new fuels for transport such as advanced biofuels and hydrogen, improving energy efficiency, aiming rapid decline in renewable energy costs, continual technological breakthroughs, and well-informed policy making. These should take early effect if significant carbon emission mitigation is to be achieved. In the meantime, it is important for Türkiye to restructure its energy consumption pattern and make a speedy transition to lower emitting energy sources.

The results of this study if implemented will help to improve the overall performance of Türkiye's energy plan and policy towards the net zero emission transition goal, and serve as guide towards future planning processes. For future studies, the mitigation potential of other sustainable approaches like the afore-mentioned ones can be investigated.

NOMENCLATURE

SpM: Single process mitigation

ES: Energy substitution

IF: Impact factor

IFR: Impact factor reduction

SM: Smart mitigation

C_{eff}: *Carbon capture efficiency*

Eplan_BAU: Business as usual-based energy plan

Eplan: Energy plan

Proj_BAU: Business as usual-based projection

Proj: Projection

L: Lignite

W: Wind

S: Solar

HC: Hard coal

NG: Natural gas

RES: Renewable energy source

N: Nuclear

HR: Hydro river

HS: Hydro stream

Wst: Waste

GT: Geothermal energy

DECLARATION OF ETHICAL STANDARDS

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

CONTRIBUTION OF THE AUTHOR(S)

Mujeeb Babatunde Adetayo: Carried out all the tasks associated with the manuscript.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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