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RESEARCH ARTICLE

Mitigating the green deal impacts on Türkiye's cement and aluminium sector

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ABSTRACT

Cement and aluminium are two of the emission intensive sectors presently included in the carbon border adjustment mechanism (CBAM) instrument of the European Union's (EU) Green Deal (GD). Based on this, this study investigates the extent of emission and carbon price (CP) impact reduction obtainable from electricity consumption in Türkiye's cement and aluminium production. The study uses existing impact reduction approaches of recycling and CO_2 utilization for Türkiye's wind, solar and lignite energy sources. The calculations are based on historical data from year 2010 to 2020; thus, the research question answered is "what emission cut would have been obtained in Türkiye's cement and aluminium production using the aforementioned impact mitigation approaches if the CBAM had taken effect within year 2010 and 2020?". The results have been analyzed using the global warming potential (GWP). According to the results, the average annual emission intensity of Türkiye's cement and aluminium production reduces from a business as usual (BAU) value of 0.06 and 7.90 ton.CO_2/ton.prod. to 0.04 and 6.00 ton.CO_2/ton.prod. respectively using 50% wind and solar energy framework recycling rate. These values correspond to a 33.33% and 24.05% impact reduction respectively. For carbon price (CP), a corresponding reduction from 1.52 and 205.39 Euro/ton.prod. to 1.16 and 156.08 Euro/ton.prod. was obtained. These values correspond to a 23.68% and 24.01% impact reduction respectively. These results show that the circularity approaches investigated are effective means of achieving substantial emission mitigation in Türkiye's cement and aluminium production and reducing the negative impacts of the GD on its economy.

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INTRODUCTION

In the European Union (EU), there is the binding target set to reduce greenhouse gas (GHG) emissions by at least 40% by 2030 compared to 1990 levels [1, 2]. One of the ways of achieving this is by addressing the problem of carbon leakage. Therefore, starting with cement, aluminium, electricity, steel, and agricultural sectors which are regarded as being emission intensive, the EU recommends a border regulation known as the carbon border adjustment mechanism (CBAM) to reduce the risk of carbon leakage. The CBAM is one of the components of the European Union's Green Deal (GD). The GD is aimed at reducing the net GHG emissions in the EU region to zero by 2050. It is also aimed at providing safe, clean and affordable energy, mobilizing the industry for a linear to circular economy transition, as well as protecting and restoring the ecosystems and biodiversity in order to provide a non-toxic environment [3]. As a major exporting partner, Türkiye has a substantial share of EU's total trade volume and is one of the leading countries with respect to trade volume with Europe [4]. Therefore, decarbonization of Türkiye's carbon intensive sectors will be of great importance to reduce its GHG emissions [3] and consequently reduce the negative impacts of the GD on its economy. Earlier study carried out by Adetayo and Kursun (2024) on the GD focused on Türkiye's electricity, steel and agricultural sectors and its emission mitigation using recycling and CO_2 utilization approaches [5]. This work is an extension of the study. It further investigates Türkiye's cement and aluminium sectors by using the same mitigation approaches. The calculations are based on Türkiye's electricity mix from year 2010 to 2020; therefore, the research question answered is "what emission cut would have been obtained in Türkiye's cement and aluminium production using the aforementioned impact mitigation approaches if the CBAM had taken effect within year 2010 and 2020?".

Türkiye's aluminium and most especially the cement sector has high economic and investment prospects. Türkiye ranked seventh among cement-producing countries in the world [6]. Cement industry in Türkiye began with 20,000 tons of cement production capacity in 1911 [7] and reached up to 79 million tons in 2023 [8]. It is emphasized by experts that the Turkish

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cement industry can meet all the needs in both domestic and foreign markets with its capacity in case of an increase in demand depending on the need [9]. In terms of export, Turkish cement industry exports to 155 different countries of the world in 2021 and is regarded as the second largest cement exporter in the world, as well as the largest exporter in Europe [9]. Where the challenge lies is the energy and emission intensity of the sector. The main fuel sources in cement production are coal and pet coke, while fuel oil and liquefied petroleum gas (LPG) are also in use. It can therefore be said that the sector's energy needs are been majorly met by fossil fuels [6]. In addition, alternative fuels such as waste tyres, municipal and industrial sludge, oil and oily waste, refuse derived fuel (RDF), textile waste and biomass are also commonly used [7]. Before year 2015, the cement industry with energy consumption rate of 20% followed iron and steel as the second largest energy-consuming sector in Türkiye [6], [10]. As a result, the share of CO2 emissions in cement production has been significant and seems to keep growing in a higher rate [7]. According to the Technology Development Foundation of Türkiye (2023), Türkiye's cement energy consumption reached 7,692 thousand TOE in 2021 [9]. This value is equivalent to a 6.25% and 18.48% total energy and industrial sector consumption respectively. It is also equivalent to approximately 11-12% of Türkiye's total emissions [9]. Hence, given the high emissions and critical importance to the society, cement production is generally an area to explore in order to abruptly reduce GHG emissions [6], [11]. The sector's green transformation will play a critical role in further decarbonizing the country's energy sector, thereby reducing the negative consequences of the GD [7, 12].

According to the Technology Development Foundation of Türkiye (2023) [9], carbon capture, use, and storage technologies have the potential to play a major role in the construction sector (cement inclusive) and other emission-intensive sectors in order to achieve the net zero emission targets. Thus, considering the entire value chain of the sector, carbon capture, utilization and storage technologies are included in the decarbonization roadmap in cement production for the construction sector [9]. In a typical cement production plant today, the flue gas contains approximately 15-25% CO_2. Converting and using the carbon captured from cement production, where emissions are the most intense in the building-construction value chain, into another product (such as urea and methanol) can open the way for new investment opportunities and new market potential [5]. The impact of such carbon utilization approaches have been investigation in this study.

Furthermore, aluminium is the second most used metal after iron and steel worldwide. It is used in several sectors, including transportation, packaging, building and construction, furniture, equipment and machinery. However, like cement, the industry is also highly energy-consuming, especially in its production from virgin materials [13]. The production of primary aluminium produces large amounts of direct and indirect GHG emissions, especially from electricity consumption [1]. For example, it was reported that aluminium production consumes about 3.5% of electricity globally [41], and according to the International Aluminium Institute, its supply in 2018 is associated with a total carbon emission of 1.1 Gt, accounting for 2% of global carbon emissions [13]. In fact, high energy consumption and high emission have made the aluminium industry no other choice but to go through a low carbon transition. Contrary to Türkiye's cement sector, local primary aluminium production in Türkiye has limited capacity which is just a small proportion of its primary aluminium consumption [14]. Therefore, there is almost 95% reliance on primary aluminium imports. According to TALSAD (2021) [15], the envisaged emission mitigation approaches embarked on by the industry include low carbon aluminium as a primary input of manufacturing systems, increased recycled content, implementation of energy efficiency programs, and carbon footprint certification initiatives. It was stated that to achieve net zero carbon emissions by 2050, Türkiye's aluminium industry needs to reduce carbon emissions by 80% until 2050. Therefore, substitution of coal and natural gas-powered electricity production with non carbon power systems is regarded as a major decarbonisation approach [15] and has been investigated in this study.

There are numerous studies that have been carried out on Türkiye's cement sector; however, studies on aluminium are very limited. According to Oral and Saygin (2019) [6], studies on Türkiye's cement are mostly based on waste management, sustainable cement production [16], and solidification/stabilization techniques application of the cement production end products [17]. For example, the Technology Development Foundation of Türkiye (2023) [9] investigated carbon footprint reduction in Türkiye's cement industry using Deep Analysis Study. One of the recommended approaches is biological carbon capture by using microalgae (microalgae) from flue gas in cement production plants. Using Long-range Energy Alternatives Planning System (LEAP) software, Oral and Saygin (2019) [6] also investigated the ways by which Turkish cement sector emissions fit into the global context, and simulated the impacts of energy efficiency scenarios on GHG emitted from energy consumption of Turkish cement production and on total energy demands relevant with the cement production/tons from 2015 to 2030. The mitigation strategy recommendations to reduce CO_2 emissions relates to policy and strategy (increasing awareness, applying different strategies, and improving the governmental policies) and technological mitigation applications (improving the technology and materials, fuel and energy saving, and CO_2 capture and disposal). The simulation showed that for 2030, more than 15 Mtoe energy consumption will be the main reason for more than 53 million tons of CO_2-e emissions per year [6]. Rende et al. (2018) [7] also recommended several approaches which includes improving energy efficiency, waste heat recovery, use of waste, clinker substitution and innovative cements.

The present study is aimed at investigating the extent of impact mitigation obtainable in Türkiye's cement and aluminium sectors using the mitigation approaches of recycling and CO_2 utilization for the country's wind, solar and lignite energy sources. This will translate into mitigating the impact of the GD on Türkiye's energy sector and economy as a whole. The mitigation approaches of recycling and CO_2 utilization have previously been investigated by Adetayo and Kursun (2024) in a study based on Türkiye's steel and agricultural sectors [5].

METHODOLOGY

Earlier study carried out by Adetayo and Kursun (2024) investigated Türkiye's electricity, steel and agricultural sectors and their impact mitigation using energy framework material recycling and CO_2 utilization [5]. The study examined sustainable emission mitigation pathways for Türkiye's electricity through the impact factor reduction of its domestic energy sources: lignite, wind, and solar energy. This work is an extension of the study and further investigates the cement and aluminium sectors in the context of the GD and using the same mitigation approaches. Due to data limitation, the calculations are based on Türkiye's historical electricity mix from year 2010 to 2020, and consider all the energy sources. However, the mitigation approaches consider only wind, solar and lignite. Hence, impact of the decarbonization of Türkiye's electricity on the cement and aluminium sectors through these domestic energy sources is what has been investigated. The complete data of the fractional contribution of each energy source to the electricity mix is unavailable; therefore, estimates have been used where applicable. Generally, the study answers the question of what the impacts as well as extent of impact reduction would have been if the GD had been effected from 2010 to 2020.

The work begins with data validation. Thereafter, the reduced emission and CP impact calculations were carried out. It has to be noted that the electricity consumption of the sectors under study is a fraction of the total energy requirement. Hence, the impact from electricity consumption is expected to be lower compared with that of the sector as a whole. According to Oral and Saygin (2019) [6], producing a ton of cement requires 4.7 million British thermal unit (BTU) of energy, equivalent to about 1377.43 kWh, and generates nearly a ton of CO_2. According to Rende et al. (2018) [7], the specific heat consumption value of clinker in Europe where Türkiye belongs in 2012 is 3,720 MJ/ton, which is equivalent to 1033.33 kWh/ton. According to Çankaya et al. (2019) [18] whose data is specific to Türkiye, the thermal energy needed to produce one ton clinker is 3337 MJ in cement kiln, which is equivalent to about 926 kWh/ton and close to that of Oral and Saygin (2019) [6] and Rende et al. [7], while the electricity consumption for cement production is 109.85 kWh/ton. If the 926 kWh/ton.clinker is assumed to be the total thermal energy needed for one ton of cement production [18], it implies that electricity consumption of 109.85 kWh/ton is only 11.86 % of total energy needed to produce one ton of cement. For aluminium, the annual electricity consumption is shown in Table 1 [19]. According to Wordpress (2024) [20], the world's most efficient aluminium production uses about 13000kWh/ton of aluminium, while the global electricity consumption average is 15000kWh/ton. All these values are in the same range with the data values in Table 1.

Data Validation

Data based on Türkiye's electricity mix as well as the cement energy consumption were first validated through comparison of the BAU carbon emission impacts with that of literature. The BAU impacts were calculated using Equation 1 [5]. For cement, the emission impact of clinker has been used for the validation process. Clinker is the binding agent in cement production. Even though it has a very high energy consumption compared with cement [18], both have approximately the same emission impact [7]. Thereafter, the reduced emission and CP impact calculations were carried out. The foreground data include the historical electricity consumption based on Türkiye's energy mix and carbon price based on the EU's estimate, sourced from Turkish Electricity Transmission Corporation (TEIAS) [21] and Kirkegaad (2019) [22] respectively. The background data include the process energy/electricity consumption for Türkiye's cement [18] and aluminium production (Table 1) [19] and were sourced from literature.

$$E_T = \sum_{i=1}^{n} E_i = \sum_{i=1}^{n} (x_i IF_i C_T) \quad (1)$$

In the equation, i stands for different energy sources, IFi (in gCO2eq./kWh) is the impact factor specific to each energy source in question, Ei and ET are the individual and total emissions in Gt, CT is the total electricity consumption in TWh, and n is the number of years and x is the fraction of energy resource in the electricity consumption mix.

Table 1. Primary Aluminium average smelting energy intensity for 2010 to 2020 [19].

Year	kwh/ton.Al [19]
2010	14899
2011	14756
2012	14939
2013	14749
2014	14766
2015	14891
2016	14767
2017	14751
2018	14914
2019	14900
2020	14888

Green Deal Impact Calculation

After the validation, the impact mitigation approach which combines recycling and CO_2 utilization were used to calculate the reduced (net) emission and CP impacts. According to an earlier study [5], the GWP of Türkiye's wind, solar and lignite energy sources reduce from the base values of 7.3 $gCO_2eq./kWh$, 29.5 $gCO_2eq./kWh$ and 1130 $gCO_2eq./kWh$ to 2.72 $gCO_2eq./kWh$, 21.08 $gCO_2eq./kWh$ and 241.26 $gCO_2eq./kWh$ respectively. While the impact factor reduction of the wind and solar energy sources were based on the framework material recycling (using 50% framework recycling ratio), that of lignite was based on utilizing the CO_2 emission (from lignite) in the synthesis of urea. These values have been used accordingly in this study.

The calculations have been carried out using Equation 2 and 3 and the analyses are based on emissions (Equation 2) and carbon price, CP (Equation 3) [5]. The CP used are shown in Table 2 and obtained from Adetayo (2024) [23]. The CP in this case is the amount payable on exported products based on their carbon intensities as a result of the Carbon Border restrictions [5]. The first part of the equations addresses recycling, while the second part addresses CO_2 utilization. The percentage impact reduction relative to the BAU scenario is calculated using Equation 4 [5]. Another answer obtainable from these calculations is the specific percentage impact reduction obtainable from a specific percentage reduction in the impact factor of the energy sources.

$$E_{T,red}\ (\text{net emission}) = \sum_{i_{F,RE}}^{i_{F,RE}} \left[\left(IF_{i,IP} - \frac{\sum_{C_{V,R}}^{Cn_{V,R}} x_R m \Delta I_{C_{V,R}}}{P} \right) * x_i C_T \right] + \left(\frac{IF_{F,IP} * IF_p}{UF_p} \right) * x_i C_T \quad (2)$$

$$CP_{red} = m_e * \left[\left[\left(IF_{RE,IP} - \frac{\sum_{C_{V,R}}^{Cn_{V,R}} x_R m \Delta I_{C_{V,R}}}{P}\right) * x_i C_T\right] + \left[\left(\frac{IF_{F,IP} * IF_p}{UF_p}\right) * x_i C_T\right]\right] * P \quad (3)$$

$$IR_{GD}(\%) = \frac{I_{R(X),WSL}}{I_{BAU}} \times 100 \quad (4)$$

In Equation 2 and 3, i refers to different energy resources, IF (in $gCO_2eq./kWh$) is the impact factor of the energy sources, ET is the total CO_2 emissions in Gt, CT stands for the total energy consumption in TWh, n is the number of years, x is the fraction of energy resource in the consumption mix, CP is the carbon price in Euros, P refers to carbon price per tonne of product (Euros/ton), xe is the fraction of mass of material exported, while me and mT are masses (ton) of material exported and mass of total material exported respectively. For this study, xe and me are not applicable. In Equation 4, IRGD (%) is the percentage impact reduction, IR(X), WSL represents impacts based on recycled wind, solar framework and reduced impact factor of lignite, and IBAU is the total business as usual scenario impact from sector based on all energy sources [5].

Limitations of Study

This study is based on historical data and does not project future impacts. However, the use of such foreground (historical) data which are peculiar to Türkiye's energy systemensures the results' credibility.

Table 2. Carbon price [23]

Year	kwh/ton.Al [19]
2010	13.75
2011	15.00
2012	7.50
2013	6.25
2014	5.00
2015	7.40
2016	8.33
2017	6.00
2018	8.33
2019	24.00
2020	26.00

RESULT AND DISCUSSIONS

The GD focusses on the carbon intensity of products, and therefore makes the GWP impact potential most relevant [5]. With respect to total energy consumption, Table 3 shows the GWP impact values obtained from this study compared with the literature. According to Çankaya et al. (2019) [18], the thermal energy needed to produce one ton clinker is 3337.00 MJ in cement kiln, which is equivalent to about 926.00 kWh/ton.clinker. With this value, the average annual BAU emission impact obtained from this study is 0.55 ton. CO_2/ton.prod. According to Rende et al. (2018) [7], process based CO_2 emissions followed a slight decrease due to changes in the utilized fuel and raw material blend from 0.50 tonCO_2/ton cement in 2001 to 0.45 ton CO_2/ton cement in 2015. In Türkiye, CO_2 emissions from fuel combustion per ton of cement were 0.33 tCO_2 in 2005, however, due to increasing use of alternative fuels, the amount decreased to 0.32 tCO_2/ton cement in 2012 [7]. The similarity in the BAU impacts ascertain not just the credibility of the estimated fractional contribution of the energy sources used in Türkiye's electricity mix, but also the energy consumption data used for Türkiye's cement production. Moreover, the data and results obtained show that the enormous emission intensity associated with cement production majorly comes from the clinker, a very important binding agent in cements. It is identified as a major hotspot, and substantial emission reduction can be obtained from a more sustainable clinker production route.

The electricity consumption of 109.85 kWh/ton.cem. [18] has been used for the calculations. The annual emission obtained per ton of cement and aluminium are shown in Table 4, while the average annual emission and carbon price impacts are shown in Figures 1 and 2. The impacts are approximately the same for all recycling ratios from 50 to 100%. Therefore, optimum recycling ratio is taken as 50% [5]. Figure 1a shows that with the 50% recycling rate, the average annual emission impact of Türkiye's cement production reduces from the BAU value of 0.06 to 0.04 ton.CO_2/ton.prod. using the combined CO_2 utilization and recycling. For carbon price, a reduction from 1.52 Euro/ton.prod. to 1.16 Euro/ton.prod. is obtained according to Figure 1b. This is equivalent to an impact reduction of 33.33% and 23.68% respectively. For aluminium, Figure 2a shows that the impact reduces from the BAU value of 7.90 to 6.00 ton.CO_2/ton.prod. For carbon price, a reduction from 205.39 Euro/ton.prod. to 156.08 Euro/ton.prod. is obtained according to Figure 2b. This is equivalent to an impact reduction of 24.05% and 24.01% respectively. Compared with Adetayo and Kursun (2024), a 25.00 and 27.00% impact reduction was obtained from the steel and agricultural sector respectively. In line with these, the results from this study also give substantial impact reduction for all the sectors investigated.

Moreover, Figure 1 and 2 shows that aluminium production constitutes much more emission and CP impact compared with cement production. The result implies that given an equal production capacity of the two materials, Türkiye's aluminium sector should be of major focus and prioritized for substantial impact reduction. It should however be noted that the results are based on a "per tonne" functional unit, and therefore not a function of the quantity of the product produced. Thus, using the emission impact of 7.90 and 0.06 ton.CO_2/ton.prod. obtained from aluminium and cement respectively, it implies that it will take quite a huge production capacity of cement to reach the emission impact of aluminium. Therefore, despite the local primary aluminium production in Türkiye having limited capacity and representing a small proportion of the country's primary aluminium consumption [14], it is a sector to look out for for substantial emission reduction. All in all, given the substantial impact reduction obtained from the two sectors, it shows that the circularity approaches of framework material recycling and CO_2 utilization investigated are effective and should be given due consideration in Türkiye's energy policy. If this is done, the negative impact of the GD on Türkiye's economy will be substantially reduced. In addition to that, Türkiye’s 2022 energy plan which is aimed at the goal of energy transition and net zero emission will be positively impacted and will be achieved more effectively.

Table 3. Emission impact comparison.

	Year	Clinker/Cement (ton. CO2/ton.prod.)
This Study		Clinker: 0.550
[18]	2007	Clinker: 0.890 (Cradle to Gate) TS: Traditional scenario
	2013	Clinker: 0.878 (Cradle to Gate) AS: Alternative scenario
	2019	Cement: 0.529-0.864 Based on TS and AS
[24]	2001	Cement: 0.500
[25]	2012	Cement: 0.790
[26]	2015	Cement: 0.450
[26]	2005	Cement: 0.330 (fuel combustion)
	2012	Cement: 0.320 (fuel combustion)
[27]	Not specific	Cement: 0.650-0.950*
[28]	Not specific	Cement: 0.800–0.900*

* Country not specified (All others are based on Türkiye).

Table 4. Annual emission impact

Year	ton.CO_2/ton.cem.	ton.CO_2/ton.Al
2010	0.54	7.86
2011	0.57	8.09
2012	0.55	7.96
2013	0.53	7.58
2014	0.59	8.49
2015	0.53	7.64
2016	0.55	7.91
2017	0.57	8.09
2018	0.58	8.36
2019	0.52	7.52
2020	0.51	7.38

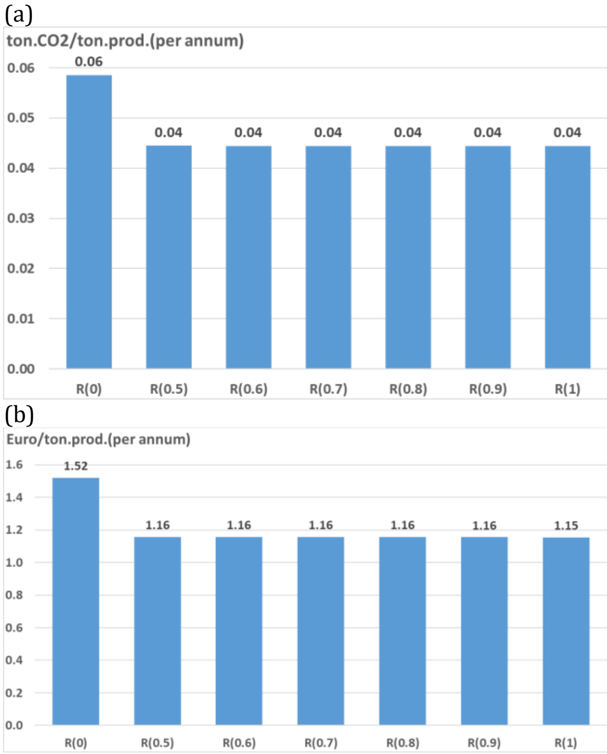

Figure 1. a. Eission and b. carbon price impact of Türkiye’s cement production

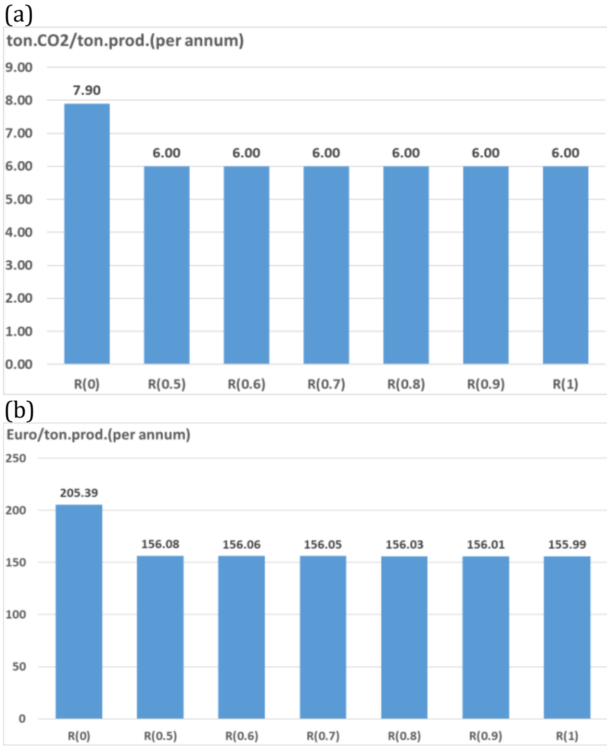

Figure 2. a. Emission, and b. carbon price impact of Türkiye’s aluminium production

CONCLUSIONS

Cement and aluminium are two of the emission intensive sectors presently included in the EU’s Green Deal (GD). Based on this, the present study has investigated the extent of impact mitigation obtainable in Türkiye’s cement and aluminium sectors using the mitigation approaches of recycling and CO_2 utilization for the country's wind, solar and lignite energy sources. This will translate into mitigating the impact of the GD on Türkiye's energy sector and economy as a whole. In this study, the calculations are based on historical data from year 2010 to 2020 and has been analyzed using the GWP. Based on the data used, the study shows that an impact reduction of 33.33% and 23.68%, and 24.05% and 24.01% is obtainable in Türkiye's cement and aluminium production for emission and carbon price respectively. What these imply is that if Türkiye recycles its wind and solar energy framework on reaching their end of life, and also utilizes the CO2 emissions associated with its lignite use for urea synthesis, an emission impact reduction of 33.33% can be achieved in its cement production compared with when no mitigation approach is applied. Similarly, an emission impact reduction of 23.68% can be achieved in its aluminium production. Consequently, the payable carbon price on cement and aluminium in case of export to the EU region with reduce by 24.05 % and 24.01% respectively. However, where the challenge lies is in the low carbon benefit of utilizing the CO_2 associated with lignite's consumption in chemical synthesis. For example, urea, despite being commercially viable, mostly ends up as emission in the atmosphere within a short period of usage, most especially in the case of its use as fertilizer. Therefore, studies on CO_2 utilization routes associated with much higher carbon benefits are highly recommended.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declares that there is no conflict of interest with any individual, institution, or organization in the preparation, evaluation, or publication of this study.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

ETHICS

There are no ethical issues with the publication of this manuscript.

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