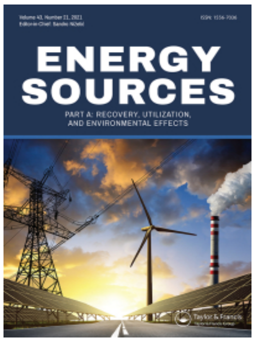


Taylor & Francis
Taylor & Francis Group

Energy Sources, Part A: Recovery, Utilization, and Environmental Effects

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/ueso20

Transforming Turkish electricity system in the context of circular economy and green deal: impacts on steel and agricultural production

Mujeeb Babatunde Adetayo & Berrin Kursun

To cite this article: Mujeeb Babatunde Adetayo & Berrin Kursun (2024) Transforming Turkish electricity system in the context of circular economy and green deal: impacts on steel and agricultural production, Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 46:1, 5344-5362, DOI: 10.1080/15567036.2024.2337314

To link to this article: https://doi.org/10.1080/15567036.2024.2337314

ENERGY SOURCES, PART A: RECOVERY, UTILIZATION, AND ENVIRONMENTAL EFFECTS
2024, VOL. 46, NO. 1, 5344–5362
https://doi.org/10.1080/15567036.2024.2337314

Transforming Turkish electricity system in the context of circular economy and green deal: impacts on steel and agricultural production

Mujeeb Babatunde Adetayo and Berrin Kursun

Department of Chemical Engineering, Engineering Faculty, Marmara University, Istanbul, Turkey

ABSTRACT

Two important but conflicting goals in Turkey's energy policy have been ensuring energy security through increased indigenous energy resource utilization and meeting the 2053 net zero emission commitment. Based on this, this work explores emission mitigation pathways for Turkey's electricity system through circularity approaches of CO_2 utilization and framework material recycling (FMR). Using mathematical models, eight life cycle impact potentials are evaluated including global warming potential (GWP). The extended impact on steel and agricultural production was also examined in the Green Deal context. The circularity approaches investigated showed that the GWP of Turkey'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. Fifty percent recycling ratio is also determined as the optimum for CO_2 utilization and FMR. With this ratio, 21.84% CO_2 emission reduction corresponding to 0.083 GT annual CO_2 savings is achieved in the Turkish electricity mix. The decarbonization of electricity results in 25.0% and 27.0% GWP impact reductions in the agricultural and steel sectors, respectively. Hence, the decarbonization of electricity mix can significantly ease the negative impacts of the Green Deal on Turkey's economy. Additionally, promoting and increasing the share of renewable energy sources in the electricity mix can further enhance these environmental benefits.

ARTICLE HISTORY
Received 1 November 2023
Revised 26 February 2024
Accepted 25 March 2024

KEYWORDS
Electricity mix decarbonization; Green Deal; framework material recycling; CO_2 utilization; lifecycle environmental impacts

Introduction

Turkey experienced a 54.36% growth in electricity generation from 2010 to 2022 due to its fast-growing population and economy (IEA 2023). In 2022, the share of fossil fuels (most of which are imported) in electricity generation was 57.72%. This high fossil fuel share resulted in Turkey's electricity sector as being one of the most carbon intensive, accounting for 35.86% of total greenhouse gas (GHG) emissions in 2021 (IEA 2023). Moreover, electricity is an unavoidable input to several sectors, which implies that the electricity-based emissions are spread across many other sectors depending on how much energy is being consumed. Thus, in a similar manner, decarbonization of the electricity sector indirectly translates into decarbonization of other sectors of the economy. This therefore necessitates the investigation and use of sustainable approaches to mitigate the emissions associated with Turkey's electricity system. It additionally implies that Turkey's ability to manage GHG emission growth primarily depends on policies to decarbonize its electricity sector (IEA 2021).

From policy and economy point of view, Turkey has responsibility to mitigate its GHG emissions. The country has a net zero emission transition commitment by 2053 under the United Nations Framework Convention on Climate Change (UNFCCC) (MENR 2022). Furthermore, the European

CONTACT Mujeeb Babatunde Adetayo berrin.kursun@marmara.edu.tr Department of Chemical Engineering, Engineering Faculty, Marmara University, Istanbul, Maltepe 34854, Turkey

Union (EU) functionalizes the Green Deal (GD) policy to facilitate a transition to a carbon neutral economy by 2050. Starting with the electricity, steel, aluminum, cement, and agricultural sectors, the EU recommends a border regulation mechanism (Carbon border Adjustment Mechanism (CBAM)) to reduce the risk of carbon leakage (Cekinir, Ozgener, and Ozgener 2022). As an exporting partner, Turkey has approximately 8% share of EU's total trade volume for consecutive five years and is one of the leading countries with respect to trade volume with Europe (Şahin, Taksim, and Yitgin 2021). However, Turkey's emission intensity of electricity grid is higher than most of the countries exporting to the EU, and more than the EU itself (Kılınc 2022). Therefore, decarbonization of the electricity sector in particular will be of great importance for Turkey to reduce its greenhouse gas emissions to prevent carbon tax regulations from posing an obstacle to the sustainability of the country's competitive power (Cekinir, Ozgener, and Ozgener 2022). All these necessitate the investigation and use of sustainable approaches to mitigate GHG emissions in Turkey's electricity sector.

Furthermore, another important goal for Turkey is energy security. To achieve this, two important components of Turkish energy policy have been an increased emphasis on the promotion of indigenous lignite reserves and the utilization of the country's renewable energy potential consisting mostly of solar and wind (Korkmaz and Önöz 2022). A major challenge here is that using more domestic energy resources to meet consumption needs might interfere with efforts to decarbonize the electricity sector, thereby jeopardizing Turkey's net zero transition target. In particular, the challenge has to do with the use of lignite having 1130 $gCO_2eq./kWh$ impact factor (Atilgan and Azapagic 2016), and whose emission intensity is higher than other energy sources. To mitigate these impacts, CO_2 emitted from lignite plants can be captured and sustainably used as intermediate for synthesis of various chemicals, materials, and fuels, given that renewable energy sources are used as energy input for the process (Huang and Tan 2014). In addition to lignite, Turkey also has a high potential for renewable energy, especially wind and solar. Most of the renewable energy sources are being used in power generation, and the rate has been increasing over the years (Kursun 2023). Table 1 shows the scenario developed by Turkey's Ministry of Energy in 2022 (MENR 2022). Based on the projections, the table shows that Turkey's renewable energy policy is more focused on wind and solar energy sources. The reason is due to their higher exploitability potentials than other renewable energy sources (Kursun 2023). However, the challenge is that the use of these resources could also pose imminent waste and emission challenges if proper plan is not put in place before their end of life (EoL). To solve these problems, the circularity approach of energy framework material recycling can be adopted. Framework material recycling implies the substitution of virgin framework materials of construction of the wind (Broadbent 2016) and solar energy (Chen et al. 2019) systems with recycled ones. Moreover, another important aspect of renewable energy is energy storage within the framework of circular economy. To ensure the necessary system flexibility for Turkey's net zero transformation, batteries, which are the most commonly used storage systems (Bist, Sircar, and Yadav 2020) are rapidly being integrated into the electricity system (Teimourzadeh et al. 2023). The total storage capacity is expected to reach 5.7 GW by 2030, increasing to 10.7 GW by 2035, and reaching approximately 40 GW by 2050 (Teimourzadeh et al. 2023). According to Pagliaro and Meneguzzo (2019), energy storage in lithium-ion battery is specifically essential for clean and renewable electricity due to its high potential of reuse (Ali, Khan, and Pecht 2021) and ease of recycling (Ali, Khan, and Pecht 2021). The European Commission in mid-2018 also reported that companies have already begun investing in recycling of used EV batteries in Europe (e.g., in Belgium and France) (Pagliaro and Meneguzzo 2019). Turkey can therefore key these approaches into its energy transformation processes.

Table 1. Target percentage distribution of electricity generation by source based on Turkey's 2022 energy plan (MENR 2022).

Year	Thermal (%)	Nuclear (%)	Hydro (%)	Wind (%)	Solar (%)	Others (%)
2020	57.5	0	25.5	8.1	3.6	5.2
2035	34.2	11.1	17.3	17.7	16.5	3.2

Utilization of CO_2 from lignite plants and framework materials recycling for wind and solar energy are concepts in accordance with circular economy. In this study, these emission mitigation approaches have been applied to Turkey's electricity system. Although there are dedicated literature studies on decarbonization pathways for Turkey's energy system, most of the studies are based on existing methods and different from the approaches employed in this study. For example, Acar, Aşıcı, and Yeldan (2022) study investigates the decarbonization approach of green financing based on Turkey's policy agenda. The policy includes energy efficiency, carbon prices, and renewable energy investment. Also, the major decarbonization pathways in Teimourzadeh et al. (2023) study are renewable energy investment and gradual closure of fossil fuel energy plants. Güllü et al. (2023) study is also based on the substitution of fossil fuels with renewable energy. However, our study uses a reduced impact factor-based decarbonization approach of mitigating the emission associated with the energy resources themselves. To achieve this, the combined circularity approaches of carbon utilization and energy framework material recycling were investigated. This method is novel, technical, and has not been studied before, especially for Turkey. The CBAM impact studies carried out are based on the resulting effect of these novel decarbonization approaches. For Turkey, most existing literature studies on CBAM are limited to impact studies and do not consider the mitigation; and where considered, are either non-technical or analyzed using existing decarbonization methods. For example, Kılınç's (2022) study is limited to the potential impacts of CBAM on Turkey's economy, and the analysis is based on Turkey's GDP reduction. Acar, Aşıcı, and Yeldan (2022) CBAM impact study also uses the decarbonization approach of green financing based on Turkey's policy agenda.

The circular economy is a system that aims to get the most out of materials, keep products and materials in use and design them to be recycled back into the economy, while eliminating emissions and waste (Figure 1). It is also a vital pillar of the energy transition (Broadbent 2016). Influence of circular approaches on impact factor which represents the emission intensity of energy sources can be evaluated by utilizing life cycle assessment (LCA) approach which is discussed in the next section. For Turkey's electricity system, Table SI.1a in the Supporting Information (SI) shows the different energy sources as well as their impact factors for different impact categories.

In the literature, there are several studies adopting circular economy approaches to impact factor reduction through LCA. However, these studies are only based on either material component like steel (Broadbent 2016), aluminum, copper (Chen et al. 2019) etc., or based on energy resource but not both. The impact of varying material recycling ratios is sometimes not also considered (Broadbent 2016). Additionally, the extended effect of recycling on the impact factor of any specific energy resource is not examined in these works. Table SI.1b contains the summary of these and similar studies as well as their reported virgin and recycled material GWP impacts. As for carbon utilization, several studies investigated the use of CO_2 as raw materials for methanol (Zang et al. 2021) and urea synthesis (Kumar et al. 2021) through LCA without considering the influence on the impact factor of any energy source. Moreover, the studies that are based on life cycle impacts of energy resources in Turkey do not

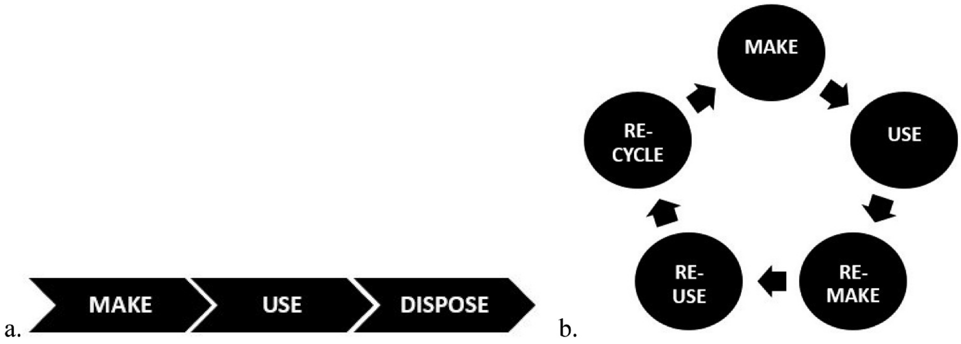


Figure 1. (a) Linear economic model, (b) Circular economic model.

fully investigate the impact of varying material recycling ratios. For example, the study carried out by Atilgan and Azapagic (2016) is limited to 50% and 20% recycling of metals and polymers. The GWP at these recycling ratios was reported as 7.3 gCO_2eq./kWh. Also, using a three-stage evaluation process, Kursun (2022) carried out the LCA of solar energy in Turkey. The work estimated the GWP of Turkey's solar energy as being 29.5 gCO_2eq./kWh and does not consider the impact of recycling. All these limitations are addressed in this study.

Based on the above analysis, the main objective of this study is to investigate sustainable and substantial decarbonization pathways for Turkey's electricity system through circularity approaches of CO_2 utilization and framework material recycling, and to additionally study the resulting effects on the CBAM through the steel and agricultural sector. The holistic approach which integrates and utilizes the results obtained from the different sub-areas (e.g., electricity forecasting, impact factor reduction, etc.) investigated strengthens the overall outcome of the study and reflects its novelty. For example, the electricity consumption forecast, and the impact factor results are used for the emission calculations, and additionally serves as input to the model which was used for the CBAM impact studies. They are additionally used to validate existing literature results before the modeling processes. Moreover, the originality of this study is also reflected in the detailed mathematical description of both material and energy level-based recycling processes, which to the best of our knowledge is not detailed in previous works. The study also introduces statistically built models which are applicable to Turkey's electricity system and can be used for varying case studies and projections. Additionally, the models, mathematical descriptions and calculation approaches are flexible and can be replicated for any region. Based on these, the study has a strong contribution potential to the present and future related research.

Methodology

This study aims to examine sustainable emission mitigation pathways for Turkey's electricity system. To achieve this, emission mitigation processes are examined through impact factor reduction of Turkey's lignite, wind, and solar energy. A wide range of foreground and background data which are peculiar to Turkey's electricity system have been used. Foreground data sources include reports from Turkey's (Ministry of Energy and Natural Resources [MENR] 2022, TEIAS Turkish Electricity Transmission Corporation [TEIAS] 2023Turkey Statistical Institute (TUIK (2022) and , Turkish Wind Energy Association (TWEA 2022). Other data sources include (International Energy Agency (IEA (2022)), British Petroleum (BP) Statistical Energy Review (BP 2022), literature and the SimaPro 8.1.1.16 software (PRé Sustainability 2022). Alongside these data, suitable mathematical formulas which are consistent with the study have been derived and used for the modeling processes. Figure 2 is a flow chart which summarizes the study pattern. For effective analysis of the results, eight impact potentials have been examined as detailed in Section 2.1 and are analyzed based on their impact factors. Unlike the term "impact" which is general and can represent the emission intensity of sectors, impact factors are numbers which represent life cycle emission intensity of products and are attributed to specific impact categories. In Figure 2, the term has been used specifically for lignite, wind, and solar energy sources.

Life cycle impact categories

Life cycle is a view of a product system as "consecutive and interlinked stages from raw material acquisition or generation from natural resources to final disposal" (Manfred 2020). This includes all material and energy inputs as well as emissions to air, land, and water. For Turkey's electricity system, Table SI.1 shows the different energy sources as well as their associated impact factors based on different impact potentials. These impacts are global warming potential (GWP), eutrophication potential (EP), acidification potential (AP), human toxicity potential (HTP), ozone layer depletion potential (OLDP), photochemical ozone creation potential (POCP), freshwater ecotoxicity potential (FWEP) and terrestrial ecotoxicity potential (TEP). These impact categories are of high relevance to

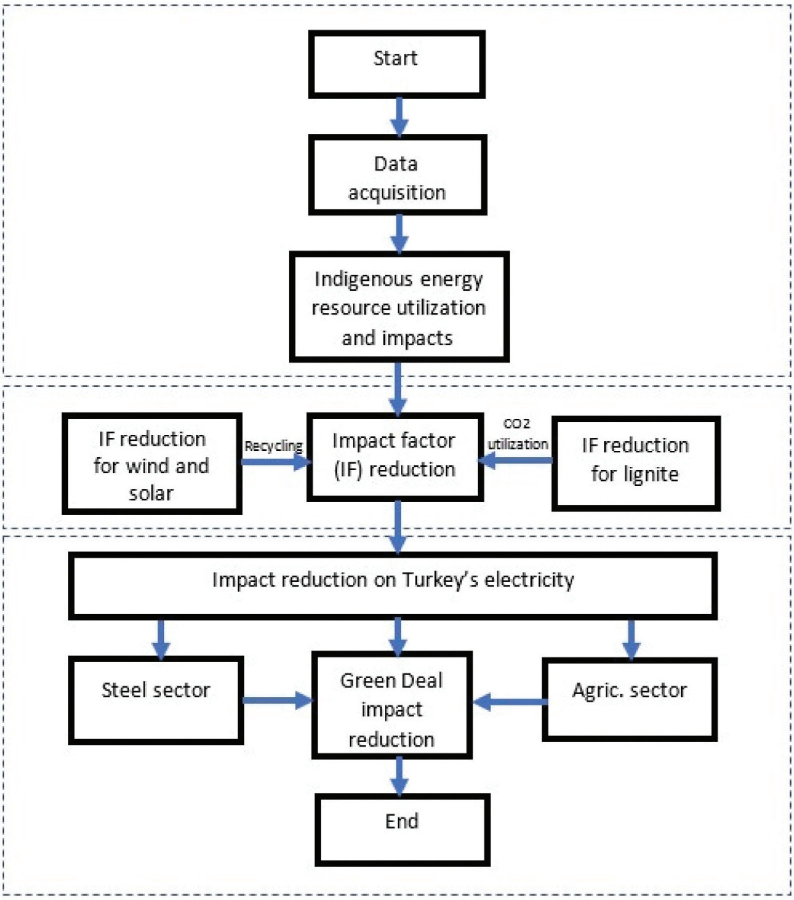


Figure 2. Flow chart of the study pattern.

the goals of this study. Global warming potential is of high public and institutional interest, and generally regarded as the most pressing environmental issue of our time. Eutrophication, acidification, and photochemical ozone creation potentials are closely connected to air, soil, and water quality, and capture the environmental burdens associated with commonly regulated emissions such as NO_x, SO_2, VOC, and others (Kursun 2022). Brief analysis of the impact categories is presented in Table SI.2.

Electricity consumption forecast

To ensure optimum accuracy, the forecast is carried out using two methods: the exponential (Eq. 1) and gradient (Equation 2) methods. The exponential method is time (t) dependent, and its equation contains the parameter t (in years). The gradient method is however not time dependent but based on annual changes (kEc_i) in the historical data. The forecasting is performed by first fitting the historical values with the equations using regression analysis. This is done to determine the model constants k that are used for the projection.

$$\mathrm{Ec} = \mathrm{Ec_o}\exp[\mathrm{k}(\mathrm{t} - \mathrm{t_o})] \tag{1}$$

$$\mathrm{Ec} = \mathrm{Ec}_{i-1} + \mathrm{kEc_i} \tag{2}$$

In the equations, Ec is electricity consumption in TWh; Ec_o is electricity consumption at the base year in TWh; Ec_{i-1} is electricity consumption at a given year before Ec_i in TWh; t is time in years; t_o is the base year; and k is the model constant. Taking Ec_o as 194.73 TWh and t_o as 2009 as shown in Table SI.3, the constant k has been estimated as 0.048 and 0.047 for the exponential and gradient methods, respectively. The electricity consumption forecast can therefore be modeled using any of the two methods since approximately the same constant value is obtained. The accuracy of the constants k generated has been ascertained by reproducing the historical data and comparing with the actual data. This is shown in Table SI.3.

Energy substitution scenarios

Seven cases have been created to study the impacts associated with Turkey's electricity utilization. Case 1 represents the business as usual (BAU) scenario which is the reference case with which all other cases are compared. The BAU scenario examines the impacts created if the fraction of each energy source in the mix remains the same as that of the base year 2021. Case 2 to 6 examine the impacts associated with the substitution of natural gas and hard coal with lignite (L), wind (W), solar (S), wind and solar (W/S), and wind, solar and lignite (W/S/L) respectively. Case 7 is a full Renewable Energy System (RES) where all fossil fuel fractions in the electricity mix including lignite are taken as zero after year 2025. Period up to 2025 is assumed as a window duration to functionalize the energy substitution processes. Other assumptions are detailed in Section 1 of the SI. Table SI.1 shows the impact factors (IF) of Turkey's energy sources in decreasing order. Using these impact factors (IF), the fraction of the energy resources in the 2021 electricity mix, and the projected electricity mix, the emission impacts of each energy substitution case are calculated through Eq. 3.

$$E_T = \sum_{i=1}^{n} E_i = \sum_{i=1}^{n} (x_i IF_i C_T) \tag{2}$$

In the equation, i stands for different energy sources. IFi (in $gCO_2eq./kWh$) is the impact factor specific to each energy source in question. Ei and E_T are the individual and total emissions in Gt. C_T is the total electricity consumption in TWh. n is the number of years and x is the fraction of energy resource in the electricity consumption mix.

Emission mitigation approaches

The net impact factor (NIF) calculations have been carried out based on two circularity approaches: framework material recycling and CO_2 utilization. For wind and solar energy sources, the impacts of virgin framework material substitution with the recycled ones have been investigated. For lignite, use of the CO_2 emitted from lignite combustion or gasification for urea and methanol synthesis have been investigated. Impact reductions other than GWP have not been performed for lignite due to lack of data.

Wind and solar energy framework recycling

Generally, the impacts associated with renewable energy frameworks can be attributed to the raw material acquisition and manufacturing stages of their life cycles (Zegardło et al. 2021). In most cases however, recycling conveys significant impact reduction and economic value for these frameworks (Vargas and Chesney 2021). The substitution of virgin framework materials with recycled ones is examined to investigate the extent of impact factor reduction achievable in Turkey's wind and solar energy sources. Here, the idea is to determine the impacts of a specific fraction of any given virgin material within the framework and substitute the same fraction with the recycled material. Through this, a new impact factor of the energy source can be obtained. This has been done using Equation 4 to 13, with full derivations shown in Section 1 of the SI. To calculate the net impact factor (NIF) associated with a full and partial/full substitution of multicomponent framework materials in recycling processes, Equations 4 to 6 are applicable.

$$\mathrm{NIF}_{\mathrm{RE,IP}} = \mathrm{IF}_{\mathrm{RE,IP}} - \frac{\sum_{\mathrm{C_{V,R}}}^{\mathrm{Cn_{V,R}}} \mathrm{m}(\mathrm{I}' - \mathrm{I}'')_{\mathrm{C}}}{\mathrm{P}} (4)$$

$$\mathrm{NIF}_{\mathrm{RE,IP}} = \mathrm{IF}_{\mathrm{RE,IP}} - \frac{\sum_{\mathrm{C}}^{\mathrm{C_n}} \mathrm{X}_{\mathrm{Cn,t}}}{\mathrm{P}} + \frac{\sum_{\mathrm{C_{V,R}}}^{\mathrm{Cn_{V,R}}} \mathrm{m}[(1 - \mathrm{x_R})\mathrm{I_V} + \mathrm{x_R}\mathrm{I_R}]}{\mathrm{P}} \tag{3}$$

Equation 4 is applicable to full substitution only but can also be expressed in form of both full and partial substitution by introducing the recycled fraction parameter $\mathrm{x_R}$ to obtain Equation 6.

$$\mathrm{NIF}_{\mathrm{RE,IP}} = \mathrm{IF}_{\mathrm{RE,IP}} - \frac{\sum_{\mathrm{C_{V,R}}}^{\mathrm{Cn_{V,R}}} \mathrm{x_R} \mathrm{m} \Delta \mathrm{I}_{\mathrm{C_{V,R}}}}{\mathrm{P}} \tag{4}$$

Where $\Delta \mathrm{I}_{\mathrm{C_{V,R}}} = (\mathrm{I}' - \mathrm{I}'')_{\mathrm{C}}$. Substituting $\mathrm{x_R} = 1$ into Equation 6 results in Equation 4.

Here, $\mathrm{NIF}_{\mathrm{RE,IP}}$ refers to net impact factor (g eq./kWh) for the impact potential (IP) in question. $\mathrm{IF}_{\mathrm{RE,IP}}$ is the initial impact factor (g eq./kWh). $\mathrm{C_n}\ _{\mathrm{V,R}}$ is the component (virgin or recycled) in framework; e.g., steel, glass. RE is renewable energy technology; e.g., wind, solar. m, m' and m" represent mass of component (virgin or recycled) in framework (tonnes, t), mass of virgin component (tonnes, t) and mass of recycled component (tonnes, t), respectively. I, I' and I" are the impacts of component (virgin or recycled) in framework (g/t of component), impact of virgin component (g/t of component) and impact of recycled component (g/t of component), respectively.

As shown in Table SI.4a, the modeling has been carried out using two different data sets: literature (l) and SimaPro (m) data. Based on the work of Rodriguez-Garcia et al. (2021) which focuses on solar glass and that of Yong et al. (2018) which is based on copper, the impacts of recycled solar glass and copper can be taken as half of that of their virgin materials. The calculations for wind energy were conducted for 2-MW Vestas (2015) onshore wind turbines whose inventories are shown in Table SI.4b and SI.5. Table SI.6 also contains other data for the wind and solar frameworks alongside the full SimaPro categories chosen for the modeling process (Alsaleh and Sattler 2019). The base case impact factors used for our study follow that of Atilgan and Azapagic (2016) for wind energy, and Kursun (2022) for solar energy. For the GWP impact category, the values are given as 7.3 and 29.5 $\mathrm{gCO_2eq.}$/kWh respectively for both energy sources. The modeling for solar framework material substitution ranges from 0% to 100% recycling ratio since the impact factor does not involve recycling. However, the impact factor reported for wind energy was based on 50% and 20% recycling of the metals and polymer components, respectively. As an extension to this recycling base case, and in order to depict the concept of circularity, this work investigates the cases of increased recycling process up to 100% for wind power. To do this, the impact factor of the wind energy source at 0% metal and polymer recycling is first determined using optimization process available in the Solver Module of Excel, after which the

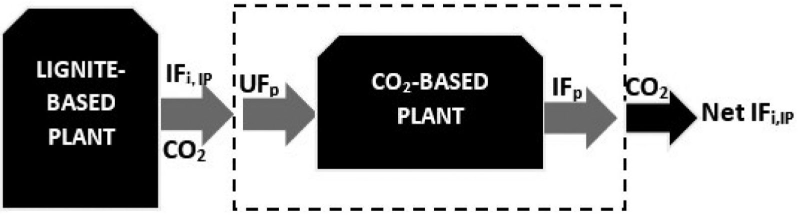


Figure 3. General description of $\mathrm{CO_2}$ flow in a $\mathrm{CO_2}$-based plant.

impact factors based on other recycling ratios are calculated. The net impact factors are shown in Table SI.17.

Carbon dioxide utilization

Figure 3 shows the input and output flows for a typical CO_2 utilization plant used for this study and to which Equation 7 and 8 are applicable. Tables SI.7 and SI.8 show the data used for the calculations. To obtain the desired result, the per kWh equivalents of the inflow and outflow values have been determined and scaled using Equation 8 to calculate the net impact factor which correspond to 1130 gCO_2eq./kWh, the impact factor of Turkey's lignite (Atilgan and Azapagic 2016). The main assumption is that there exists a proportional relationship between the mass of CO_2 utilized per unit energy consumed and the impact factor of the product. The data for methanol synthesis were obtained from Zang et al. (2021), a study based on the techno-economic analysis and environmental life cycle analysis of 3 systems with integrated and stand-alone CO_2 supplies. M1 in Table SI.7 represents the stand-alone process with market CO_2 feedstock while M2-M9 represent the integrated processes with CO_2 from integrated coproduction system. For this study, the CO_2 is considered as being sourced from a non-integrated coproduction system, making the stand-alone process (M1) most consistent. However, the calculations have been carried out for all three synthesis processes. The same is applicable to urea. U1-U8 (Shi et al. 2020) and U9 (Kumar et al. 2021) in Table SI.8 represent different urea synthesis processes. U1-U8 use combustion, while U9 uses gasification for urea synthesis.

$$\mathrm{NIF}_{\mathrm{L,GWP}} = \frac{\mathrm{IF}_{\mathrm{L,GWP}} \times \mathrm{IF}_{\mathrm{p}}}{\mathrm{UF}_{\mathrm{p}}} \tag{5}$$

$$\mathrm{NIF}_{\mathrm{L,GWP}} = \frac{1130 \times \mathrm{IF}_{\mathrm{p}}}{\mathrm{UF}_{\mathrm{p}}} \frac{\mathrm{gCO2}}{\mathrm{kWh}} \tag{6}$$

In Eqs. 7 and 8, $\mathrm{IF}_{\mathrm{L,GWP}}$, $\mathrm{NIF}_{\mathrm{L,GWP}}$, 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. The utilization factor (UF) is the amount of CO_2 utilized by the processes per kWh of power consumed, and its unit is in gCO_2 utilized/kWh.

Impacts on Turkey's electricity system and the green deal (GD)

Turkey's electricity system

Using the reduced impact factors calculated for Turkey's wind, solar, and lignite energy sources, the impact reductions obtainable from Turkey's electricity sector have been calculated using the forecasted electricity consumption data generated. The calculations have been carried out using Equation 3. The percentage impact reductions have also been determined using Equation 9.

$$\mathrm{IR}(\%) = \frac{\mathrm{I}_{\mathrm{WSL}}}{\mathrm{I}_{\mathrm{electr.sector}}} \times 100 \tag{7}$$

Here, IR (%) is the percentage impact reduction based on Turkey's electricity sector. $\mathrm{I}_{\mathrm{WSL}}$ represents the impacts from the electricity sector based on the reduced impact factors of the wind, solar, and lignite energy sources, and $\mathrm{I}_{\mathrm{electr.\ sector}}$ represents the impacts from the electricity sector using the initial impact factors before impact reduction.

Green Deal (GD)

According to the EU Commission, steel and agricultural sector are two of the most energy-intensive sectors which are exposed to high risk of carbon leakage (Yurtkuran 2021). Hence, impacts of the decarbonization of electricity is extended to the steel and agricultural sectors of the Green Deal. The calculations have been carried out using Equation 10 to 13 and the derivations are available in

Section 1 of the SI. The electricity data used for the steel sector is sourced from Özdemir et al. (2018), while that of the agricultural sector is sourced from the International Energy Agency (IEA) report as shown in Figure SI.1, Table SI.9 and Table SI.10. Both sectors were analyzed based on emissions (Equation 10). In addition to that, the steel sector has also been analyzed based on carbon price, CP (Equation 11). The carbon price in this case is the amount payable on exported products based on their carbon intensities as a result of the Carbon Border restrictions. It is assumed that carbon price and exported steel quantity in 2020 increase by 5% up till 2035 (Napp et al. 2019). The increment is much envisaged because of the urgent need by the European Union to ensure climate change compliance on imported products into the region. For lignite, the upper limit of the net impact factor obtained through the CO_2 utilization process is used in the calculations. This is done for conservative purposes. For the impact per unit mass, the agricultural sector calculation uses the total mass of the first six primary crops produced in 2017 according to quantity. The products are wheat (21.2 million tons/year), sugar beet (180 million tons/year), tomatoes (123 million tons/year), barley (6 million tons/year), maize (6 tons/year), and apricots (767 million tons) (Kropff et al. 2021).

$$\mathrm{E_T(tonCO2e.)} = \mathrm{m_T(ton)} \times \mathrm{C_T}\left(\frac{\mathrm{kWh}}{\mathrm{ton.mat.}}\right) \times \mathrm{IFi}\left(\frac{\mathrm{gCO2eq.} \times 10^6}{\mathrm{kWh}}\right) \tag{8}$$

$$\mathrm{CP(Euro)} = \mathrm{m_e(ton)} \times \mathrm{C_T}\left(\frac{\mathrm{kWh}}{\mathrm{ton.mat.}}\right) \times \mathrm{IFi}\left(\frac{\mathrm{gCO2eq.} \times 10^6}{\mathrm{kWh}}\right) \times \mathrm{P}\left(\frac{\mathrm{Euro}}{\mathrm{tonCO2}}\right) \tag{9}$$

$$\mathrm{m_e(ton)} = x_e \times \mathrm{m_T(ton)} \tag{10}$$

$$\mathrm{IR_{GD}}(\%) = \frac{\mathrm{I_{R(X),WSL}}}{\mathrm{I_{BAU}}} \times 100 \tag{11}$$

In Equations 10 and 11, i refers to different energy resources, IF (in $gCO_2eq./kWh$) is the impact factor of the energy sources, E_T is the total CO_2 emissions in Gt, C_T 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), x_e is the fraction of mass of material exported, while m_e and m_T are masses (ton) of material exported and mass of total material exported respectively. In equation 13, IR_{GD} (%) is the percentage impact reduction, $I_{R(X),WSL}$ represents impacts based on recycled wind, solar framework and reduced impact factor of lignite, and I_{BAU} is the total business as usual scenario impact from sector based on all energy sources.

Results and discussion

Electricity use projection

The current state of Turkey's electricity mix is evaluated and the electricity consumption up till 2053 is projected. As seen in Figure 4, the estimation results for electricity consumption modeled by the gradient and exponential methods coincide with each other.

It has been estimated that Turkey's electricity consumption in 2030, 2035, and 2053 will be 505.710 TWh, 649 TWh, and 1490 TWh, respectively. The projection results for each year are given in Table SI.1. These results relatively align with that of Bilgili and Pinar (2023) who reported a value of 501.92 TWh for 2030, Ayvaz and Kusakci (2017) who reported 534.19 TWh for 2030, and Emek and Akkaya (2022) who also reported 465.844 TWh for the same year, and used machine learning, gray modeling (GM) and regression analysis method respectively. Based on Turkey's 2022 energy plan, 455.30 TWh and 510.50 TWh was reported for 2030 and 2035, respectively (MENR 2022). The lower estimation is due to factors like energy efficiency considered in the study. In this study, the gradient and modeling methods have been used for the projection, and both methods give approximately the same values

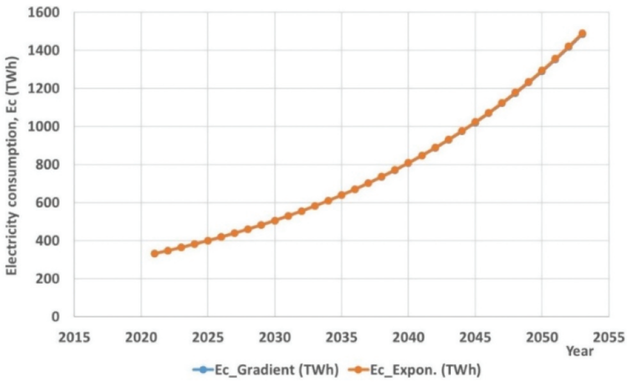


Figure 4. Electricity consumption projection for Turkey using the exponential and gradient methods.

(Table SI.1). The results are also validated and ascertained using historical data. The prediction results show that Turkey's electricity consumption will increase exponentially. This exponential increase points out how important the goal of energy security is for Turkey. It implies that if energy resource dependency in electricity generation continues, attaining a balance point or peak of energy production becomes difficult.

Turkey's electricity utilization impacts

The business as usual (BAU) scenario estimates the environmental impacts resulting from electricity consumption from 2021 to 2053 if the percentages of the energy sources in the electricity mix remain the same as the base year 2021. Figure 5 shows Turkey's BAU values for each impact category from 2021 to 2053. According to the figure, the impact values for GWP, FWEP, and HTP are high and characterized by visible trends, while other impact potentials have relatively low values with their trends superimposed on one another. The annual results are shown in Table SI.13. The result shows that Turkey's GWP and OLDP will have the highest and lowest impact values of 489 g/kWh and 2.34×10^{-5} g/kWh, respectively. Other impact categories in decreasing order are FWEP, HTP, AP, EP, TEP, and POCP with 333 g/kWh, 239 g/kWh, 3.10 g/kWh, 1.97 g/kWh, 1.05 g/kWh, and 0.17 g/kWh, respectively. The high GWP impact is as a result of the dominating coal and natural gas in Turkey's electricity mix, leading to continuous release of greenhouse gases such as carbon dioxide (CO_2) and methane (CH_4). On average, the GWP impact of 489 gCO_2/kWh is equivalent to 0.38 GT of CO_2 per

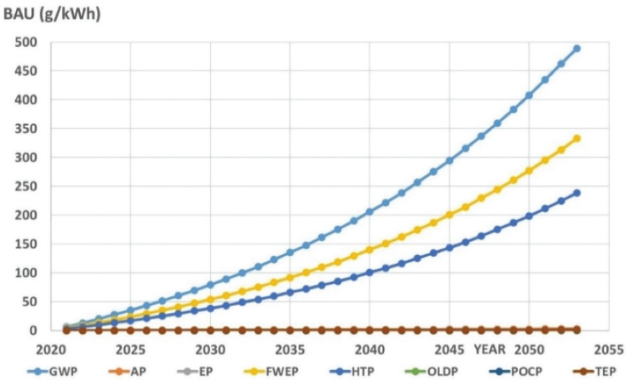


Figure 5. Business as usual scenario for all the impact categories.

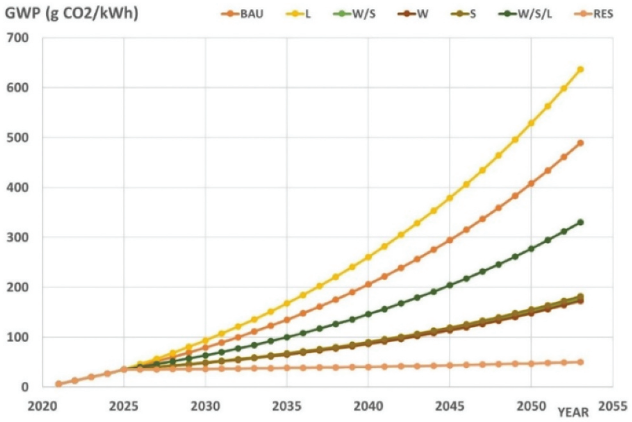


Figure 6. Impacts from energy resource substitution.

annum which is more than two times higher than the 2022 value of 0.17 Gt. Therefore, the nature of Turkey's present electricity mix has the potential to jeopardize efforts toward meeting the emission mitigation goals.

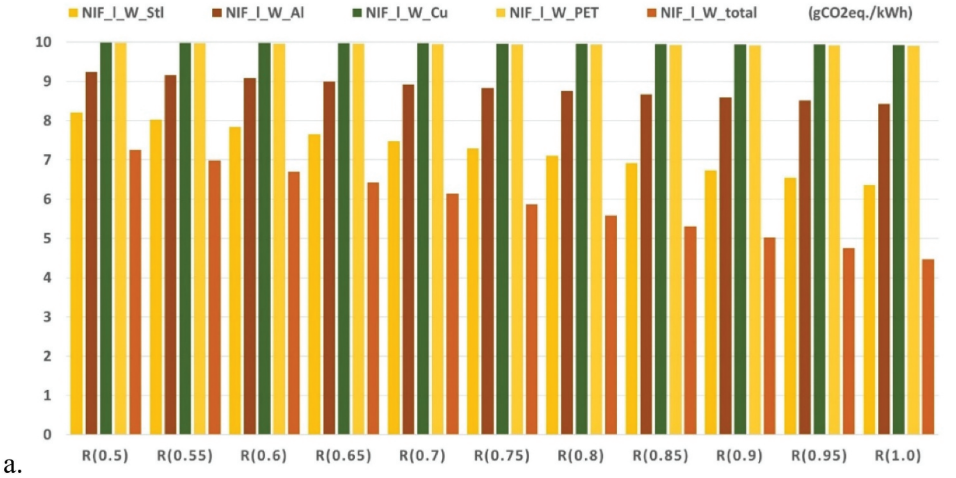
Moreover, the BAU scenario has been used as the reference case. Through this, comparison becomes possible with the energy resource substitution scenarios and the performance of one scenario relative to another can be known. The energy substitution result shown in Figure 6 implies that if Turkey substitutes its natural gas and hard coal energy sources with lignite, the GWP will rise to 637 gCO_2/kWh by 2053. This is equivalent to a percentage increase of 30.1%. Furthermore, all the energy mixes containing lignite rank highest in almost all impact categories. Generally, what the result implies is that dominating the electricity consumption mix with lignite without considering clean coal technologies is negatively impactful and not sustainable for Turkey's electricity and energy system as a whole. This finding aligns with that of Kursun (2023) who investigated the impact reduction obtainable from utilization of wind power. According to the result of the study, lignite and hard coal substitution would be the most feasible option in improving environmental performance of Turkish electricity mix. In addition to GWP, the results for other impact categories, their cumulative values, as well as a generalized and detailed analysis for each energy substitution case is available in Section 1 of the SI. Moreover, the result also shows that the full renewable energy system (RES) has the lowest impact compared to other substitution cases except for OLDP as shown in Table SI.15. However, renewable energy sources like wind and solar energy also have huge potential for waste challenges when decommissioned. Hence, implementing the circular economy approach of impact factor reduction for these technologies is crucial. All in all, for effective means of solving the highlighted challenges associated with Turkey's domestic lignite, wind, and solar energy sources, the proposed impact factor reduction techniques should be applied.

Circular economy approaches for impact reduction

Framework material recycling for wind and solar energy sources

Figure 7 shows the GWP impact results for the combined framework materials of wind and solar energy while the results for the individual framework materials are shown in Figure SI.3 and SI.4. Full substitution cases are not practically feasible due to factors such as process efficiency and limited scrap availability. Therefore, the impact of varying recycling ratios is investigated.

For the wind energy source, impact factor for 100% virgin material use is 10.05 gCO_2eq./kWh, and the upper limit of the base case recycling ratio as mentioned is 50%. Hence, recycling ratios from 50% to 100% are examined. As seen in Figure 7(a), if recycled steel is used for the wind turbine framework



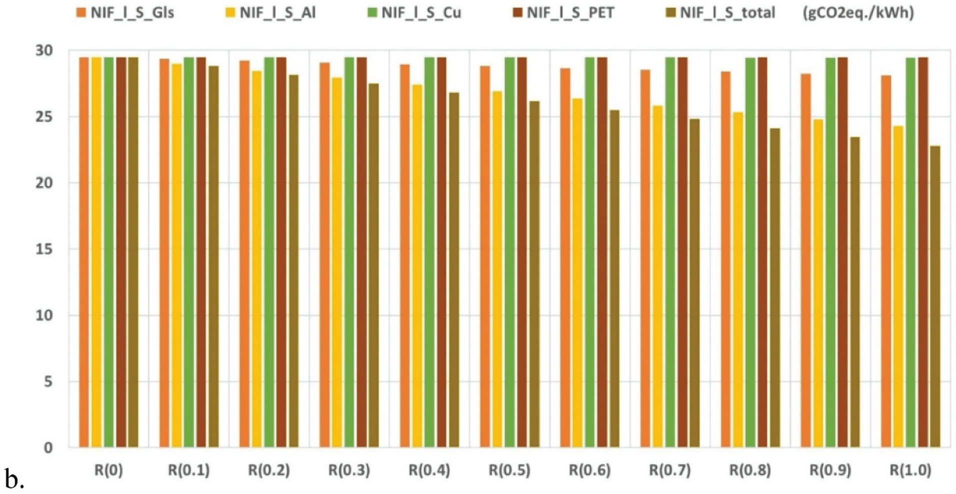
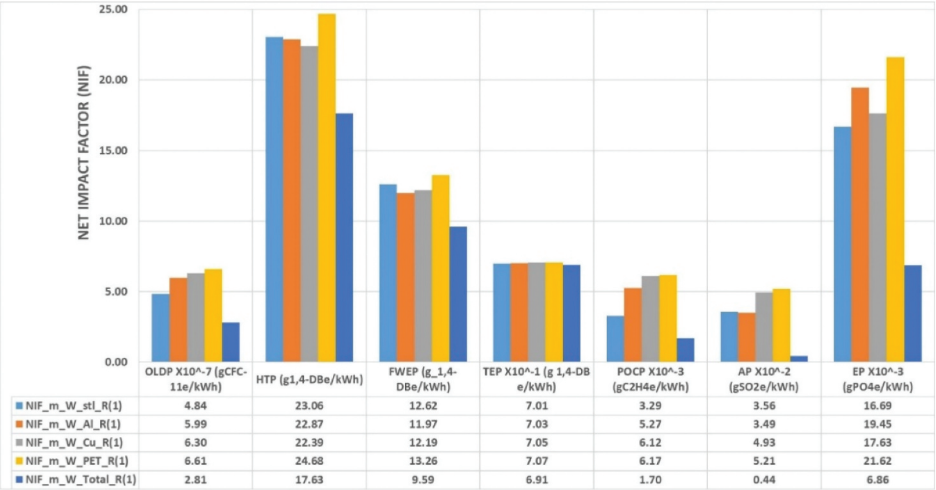


Figure 7. Net impact factor (NIF) comparison based on the (a) wind, and (b) solar power framework material substitution.

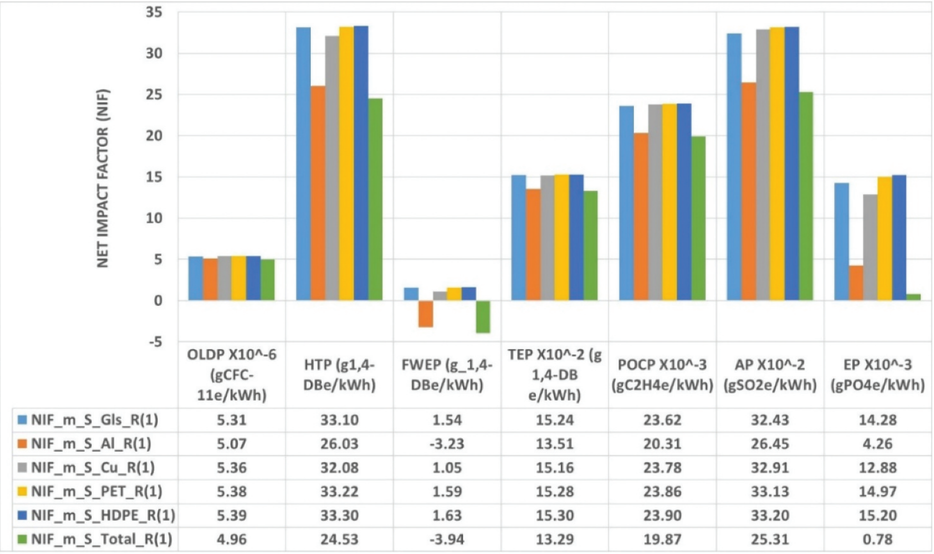
in place of virgin materials, the impact factor will reduce to 6.36 $gCO_2eq./kWh$ at full recycling. Similarly, recycled aluminum reduces the impact factor to 8.43 $gCO_2eq./kWh$. In contrast to the results obtained for steel and aluminum, other framework materials result in negligible impact reduction. For example, the use of recycled copper (Cu) and PET reduces the impact factors to 9.93 $gCO_2eq./kWh$ and 9.90 $gCO_2eq./kWh$, respectively. Moreover, the percentage masses of the turbine framework materials which include steel, PET, aluminum, and copper are 85.14%, 9.9%, 3.69%, and 1.27% respectively as shown in Table SI.5. This shows that steel constitutes a major fraction of the framework and its recycling leads to a substantial reduction in the overall impact factor, accordingly. The impact reduction of 36.7%, 16.1%, 1.19%, and 1.49% is obtained for steel, aluminum, copper, and PET at full recycling, and is equivalent to a total impact reduction of 76.2%. For solar energy, Figure 7(b) shows that aluminum recycling exhibits the highest GWP impact reduction to 24.3 $gCO_2eq./kWh$ from the base case impact factor of 29.5 $gCO_2eq./kWh$. This is followed by solar glass, copper, PET, and HDPE recycling with impact reductions to 28.11 gCO_2e/kWh, 29.45 gCO_2e/kWh, 29.47 $gCO_2eq./kWh$ and 29.5 $gCO_2eq./kWh$, respectively. According to Table SI.5, solar glass, aluminum, PET, copper, and HDPE of the solar framework have the respective mass composition of 76.9%, 19.0%, 3.01%, 0.9%, and 0.21%. Thus, the increased impact reduction in aluminum that has lower mass fraction than solar glass shows that the ultimate impact of any energy source is not only a function of the mass fraction of substituted materials but also the impacts of the individual virgin and recycled materials. The higher impact factor reduction exhibited by aluminum than solar glass can be attributed to two reasons: the change in impacts of the virgin and recycled material, and the virgin to recycled material impact ratio, both of which are relatively high for aluminum. In terms of percentages, the impact reduction of 2.81%, 25%, 0.17%, 0.54%, and 0.034% occurs for solar glass, aluminum, copper, PET, and HDPE recycling. This is equivalent to a total impact reduction of 28.5%. Hence, for emission reduction in the wind and solar energy framework, Turkey should prioritize the use of recycled steel and aluminum respectively, while recycled steel and solar glass with the highest mass fraction should be prioritized for waste reduction.

The calculations for other impact potentials are based on the SimaPro data (m) since the literature data (l) is limited to GWP impact only. Using the same approach adopted in computing the net impact factors of GWP, Figure 8 shows the results for all other impact potentials based on full recycling of the



	OLDP X10^-7 (gCFC-11e/kWh)	HTP (g1,4-DBe/kWh)	FWEP (g_1,4-DBe/kWh)	TEP X10^-1 (g 1,4-DB e/kWh)	POCP X10^-3 (gC2H4e/kWh)	AP X10^-2 (gSO2e/kWh)	EP X10^-3 (gPO4e/kWh)
NIF_m_W_stl_R(1)	4.84	23.06	12.62	7.01	3.29	3.56	16.69
NIF_m_W_Al_R(1)	5.99	22.87	11.97	7.03	5.27	3.49	19.45
NIF_m_W_Cu_R(1)	6.30	22.39	12.19	7.05	6.12	4.93	17.63
NIF_m_W_PET_R(1)	6.61	24.68	13.26	7.07	6.17	5.21	21.62
NIF_m_W_Total_R(1)	2.81	17.63	9.59	6.91	1.70	0.44	6.86

a.



	OLDP X10^-6 (gCFC-11e/kWh)	HTP (g1,4-DBe/kWh)	FWEP (g_1,4-DBe/kWh)	TEP X10^-2 (g 1,4-DB e/kWh)	POCP X10^-3 (gC2H4e/kWh)	AP X10^-2 (gSO2e/kWh)	EP X10^-3 (gPO4e/kWh)
NIF_m_S_Gls_R(1)	5.31	33.10	1.54	15.24	23.62	32.43	14.28
NIF_m_S_Al_R(1)	5.07	26.03	-3.23	13.51	20.31	26.45	4.26
NIF_m_S_Cu_R(1)	5.36	32.08	1.05	15.16	23.78	32.91	12.88
NIF_m_S_PET_R(1)	5.38	33.22	1.59	15.28	23.86	33.13	14.97
NIF_m_S_HDPE_R(1)	5.39	33.30	1.63	15.30	23.90	33.20	15.20
NIF_m_S_Total_R(1)	4.96	24.53	-3.94	13.29	19.87	25.31	0.78

b.

Figure 8. Net impact factor for all impact potentials of the (a) wind, and (b) solar energy framework based on full substitution (Note the different multiplication factors used in the scale).

Table 2. Net impact factor of Turkey's lignite for different urea and methanol synthesis processes using CO_2 (U1: Average plant value for coal combustion processes; U2-U8: Individual plant values for coal combustion processes; U1-U8 (Shi et al. 2020), U9 (Kumar et al. 2021). U9: Plant value for coal gasification process (Kumar et al. 2021). M1: stand-alone CO_2 source; M2-M9: CO_2 sourced from connected plants with renewable energy electricity (Zang et al. 2021.).

Urea (U)	Net impact factor (NIF) ($gCO_2eq./kWh$)	Methanol (M)	Net impact factor (NIF) ($gCO_2eq./kWh$)
U1	3300	M1	2.76
U2	3040	M2	18.8
U3	3250	M3	23.7
U4	3510	M4	48.3
U5	3590	M5	52.3
U6	7880	M6	53.6
U7	3390	M7	110
U8	3710	M8	117
U9	241	M9	119

materials. The figure shows the individual impact of each material in the framework as well as the total impact at full recycling. The impact at any recycling ratio can also be obtained using the model designed for the purpose. In contrast to the GWP result for the wind energy framework, and despite the huge percentage mass of steel, the result shows that the material does not give the lowest impact reduction for a number of the impact categories examined. According to Figure 8(a), steel gives the highest impact reduction in OLDP, POCP, and EP; aluminum of lower percentage mass gives the highest impact reduction in FWEP and AP; and copper with the lowest percentage mass gives the highest impact reduction in HTP. A different scenario is observed for the solar energy framework. According to Figure 8(b), recycled aluminum gives the highest impact reduction in all the impact categories.

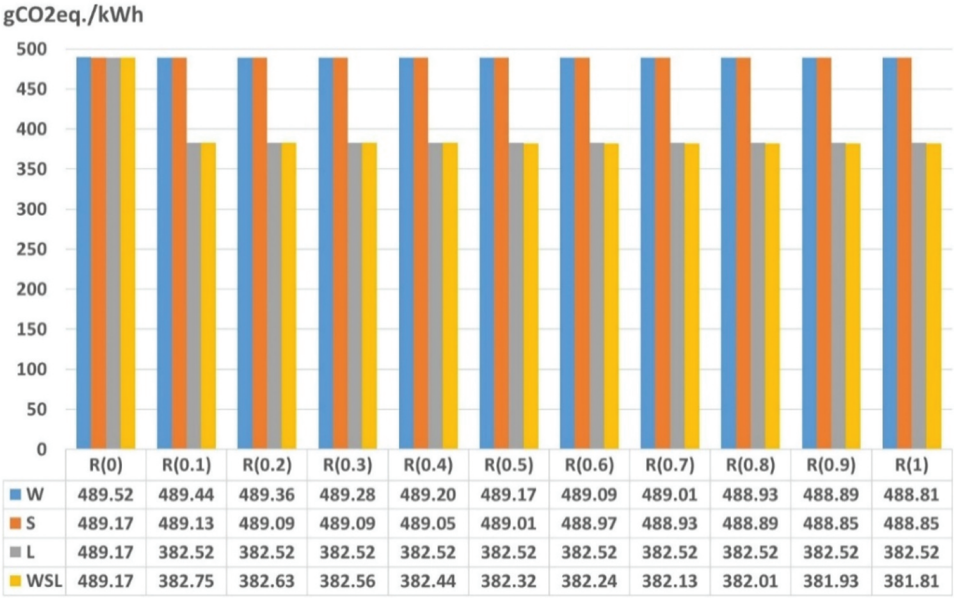
Carbon dioxide utilization in lignite impact mitigation

The process of utilizing the emitted CO_2 from lignite is adopted to minimize the impact factor of the energy source. This is beneficial to the system in two ways: emission reduction and offsetting the cost of carbon capture. Two CO_2-based products which are considered commercially viable with huge global market are urea (Kumar et al. 2021) and methanol (Zang et al. 2021). Being products that are locally producible in Turkey, the net impact factor (for lignite) associated with their productions when CO_2 from lignite utilization is used as raw material is calculated. Table 2 shows the results for the net impact factors associated with CO_2 utilization for urea and methanol synthesis. Two processes utilized for urea synthesis are gasification and combustion. According to the result, if Turkey utilizes the gasification process route for urea synthesis, the GWP of lignite will reduce from the base value of 1130 $gCO_2eq./kWh$ to 241 $gCO_2eq./kWh$. Such a process implies that Turkey's GWP emission associated with lignite consumption can be reduced by 78.7%. In contrast, the use of combustion process results into an increased impact factor ranging from 3040 to 7880 $gCO_2eq./kWh$ depending on the operating processes. These further ascertain combustion processes as being unsustainable for the system. Table 2 also gives the results for methanol synthesis. According to the table, the GWP of lignite can be reduced to a value ranging from 2.76 to 119 $gCO_2eq./kWh$ with such approach. This low net impact factor is as a result of carbon capture and utilization as well as renewables being used as energy sources in the process. The net impact factor calculations for urea and methanol synthesis are shown in Section 2 of the SI.

Turkey's mitigated electricity impacts and the green deal

Overall impact on turkey's electricity sector

With the net impact factors calculated for wind and solar energy sources from 10% to 100% recycle ratios, Figure 9 shows the electricity-based impact reduction in the ranges of 489.4–488.8 $gCO_2eq./kWh$ and 489.1–488.8 $gCO_2eq./kWh$, respectively. This is equivalent to a percentage impact reduction of 0.01–0.14% and 0.01–0.07% respectively for the two energy sources. For lignite, an impact reduction to 382.5



	R(0)	R(0.1)	R(0.2)	R(0.3)	R(0.4)	R(0.5)	R(0.6)	R(0.7)	R(0.8)	R(0.9)	R(1)
■ W	489.52	489.44	489.36	489.28	489.20	489.17	489.09	489.01	488.93	488.89	488.81
■ S	489.17	489.13	489.09	489.09	489.05	489.01	488.97	488.93	488.89	488.85	488.85
■ L	489.17	382.52	382.52	382.52	382.52	382.52	382.52	382.52	382.52	382.52	382.52
■ WSL	489.17	382.75	382.63	382.56	382.44	382.32	382.24	382.13	382.01	381.93	381.81

Figure 9. GWP impact reduction of Turkish electricity mix based on different recycling ratios.

$gCO_2eq./kWh$ that is equivalent to 21.8% is observed. For the combined impact of wind, solar and lignite, the figure shows that by 2053, the electricity sector-based GWP emission reduces to a range of 382.8–381.8 $gCO_2eq./kWh$ depending on the recycle ratio of the wind and solar frameworks. This is equivalent to a percentage impact reduction ranging from 21.8% to 22.0%. Similar to what has been obtained in the energy substitution results (Figure 6 and Table SI.15) with respect to the high sensitivity of GWP to lignite, these results also show that the rate of impact reduction is highly sensitive to lignite compared to the wind and solar energy sources. The reason behind this can be attributed to two factors: reduced impact factor of the energy sources and their fractional contributions in the energy mix. For energy technologies in general, the emission reduction potential is majorly a function of these two parameters whose values have to be relatively high if substantial impact reduction is to be achieved. Turkey's electricity mix is made up of about 12%, 8%, and 4% of lignite, wind, and solar energy, respectively (IEA 2022). In addition to that, the GWP impact factors of the energy sources are 1130 $gCO_2eq./kWh$, 7.30 $gCO_2eq./kWh$ (Atilgan and Azapagic 2016) and 29.5 $gCO_2eq./kWh$ (Kursun 2022), respectively. The relatively high impact factor reduction of lignite from 1130 to 241 $gCO_2eq./kWh$, as well as the high fractional contribution in the energy mix is responsible for its higher impact reduction than the wind and solar energy resources. Therefore, to allow increased impact reduction sensitivity to the wind and solar energy sources, an increase in the fractional share of both energy resources in the energy mix is necessary. Furthermore, the result shows that if Turkey can meet up with the CO_2 utilization goal, as well as 50% in the wind and solar framework material recycling corresponding to R(0.5), there will be an emission reduction of about 21.84%. This is equivalent to a cumulative emission saving of 106.9 $gCO_2eq./kWh$ by 2053 and an average of 0.083 GT of CO_2 per annum. This average annual GWP saving is about half the 0.17 Gt impact obtained from Turkey's electricity consumption in 2022 which is substantial considering the fact that the calculations are limited to only three domestic energy sources. This shows how beneficial the circularity approaches can be to Turkey's electricity system, especially the CO_2 utilization route. Lastly, another important observation from Figure 9 is that no significant impact change occurs after 50% recycling ratio (R(0.5)) for wind and solar resources. Therefore, the R (0.5) recycling ratio can be taken as optimum.

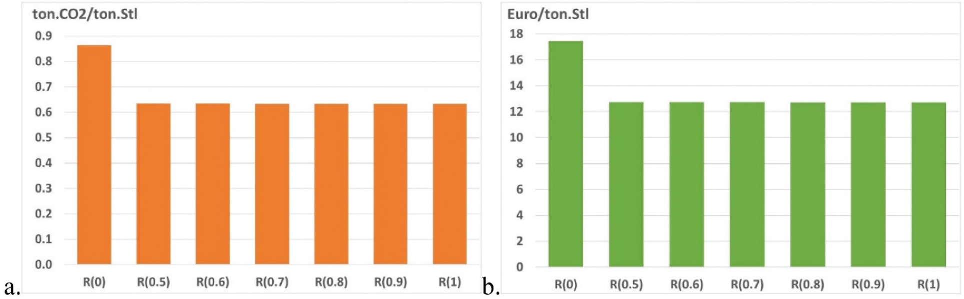


Figure 10. Impacts on the steel sector based on (a) emission, and (b) carbon price.

Influence in the Green Deal (GD) context

The Green Deal focuses on the carbon intensity of products, and therefore makes the GWP impact potential most relevant. The impacts obtained per ton of steel and agricultural product are shown in Figures 10 and 11, respectively. Figures SI.6, SI.7, Table SI.18 and SI.19 present the full impact values for Turkey's steel and agricultural sectors based on Green Deal estimations. Also, the optimum recycling ratio of 50% obtained from the result of the last section is used for the analysis. According to Figure SI.6a, it has been estimated that the projected emission impact of Turkey's steel products reduces from the initial BAU value of 0.376 $GtCO_2$ to 0.276 $GtCO_2$ at 50% recycling rate. This is equivalent to a percentage emission reduction of 26.7%. For carbon price, a reduction from 7590 MEuro to 5545 MEuro is obtained according to Figure SI.6b. This is equivalent to an emission reduction of 26.9%. With these results, Figure 10 shows that the emission and carbon price impacts per ton of steel reduces from 0.86 tCO_2 and 17.4 Euro to 0.63 tCO_2 and 12.7 Euro, respectively. This is equivalent to an impact reduction of 27.1% and 27.2%, respectively. In agricultural production, Figure SI.18 shows that the emission impact of Turkey's agricultural products reduces from the initial BAU value of 0.0420 $GtCO_2$ to 0.0317 $GtCO_2$, thst is equivalent to an emission reduction of 24.5%. Figure 11 shows that the emission impact per ton of agricultural product reduces from 0.0032 tCO_2 to 0.0024 tCO_2, that is equivalent to an emission reduction of 25.0%. Compared to Acar, Aşıcı, and Yeldan (2022), who investigated the carbon-trading approach of decarbonization, the green scenario emission reduction reported was 34.27%, and higher than the result obtained in this study. However, periodical changes in carbon price are not considered in the study; instead, a fixed carbon price is used. The reported value is also not sector-specific. In this study, yearly increase in carbon price is considered in line with the historical carbon pricing trend. This is because in CBAM impact calculations, the carbon price is a very important parameter whose increment is much envisaged because of the urgent need by

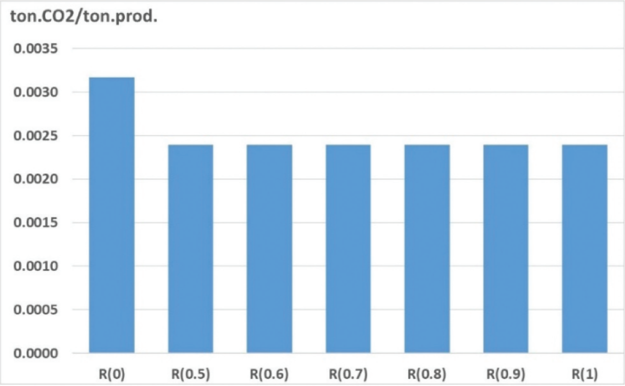


Figure 11. Emission impacts on the agricultural sector.

the European Union to ensure climate change compliance on imported products into the region. Moreover, the carbon-trading approach of decarbonization utilized by Acar, Aşıcı, and Yeldan (2022) follows Turkey's policy agenda which is based on existing technology. In this study however, the impact factor-based decarbonization approach of reducing the emission associated with the energy resources is used.

Based on our results, if Turkey meets up with a recycling rate of 50%, negative impacts of the Green Deal on Turkey's economy can lessen by 25.0% and 27.0% in the agricultural and steel sectors, respectively. As earlier emphasized, these emission reductions are based on Turkey's lignite, wind, and solar energy sources only, all of which account for about 24.0% of the electricity mix (IEA 2022). This leaves enough potential for further mitigation processes.

Conclusion

This work examines sustainable and substantial emission mitigation pathways for Turkey's electricity system through circularity approaches of CO_2 utilization and framework material recycling. An extended step of the work is also to determine how the decarbonization of Turkish electricity mix through the circularity approaches affects the GWP of steel and agricultural production in the country. The emission mitigation methods employed are the aspects creating the uniqueness and novelty of the presented work. The holistic approach which integrates and utilizes the results obtained from the different sub-areas (e.g. electricity forecasting, impact factor reduction, etc.) investigated also reflects the novelty of the study.

According to the results, the substitution of imported fossil energy sources with indigenous lignite is found to increase GHG emissions from 489 to 637 gCO_2 eq./kWh by 2053 without CO_2 utilization. All other impact categories also worsen. Hence, dominating the electricity mix with lignite without considering clean coal technologies is negatively impactful and not sustainable for Turkey's electricity and energy system as a whole. Although the full renewable energy system (RES) is found to have the lowest impact of 50 gCO_2 eq./kWh, the potential end of life (EoL) waste and emission challenges necessitate circularity measures. The circularity approaches investigated show that the GWP impact factor of Turkey's wind and solar energy sources reduces from the base values of 7.3 gCO_2eq./kWh and 29.5 gCO_2eq./kWh to 2.72 gCO_2eq./kWh and 21.08 gCO_2eq./kWh respectively at full framework material recycling. Also, GWP of lignite reduces from 1130 gCO_2eq./kWh to 241 gCO_2eq./kWh and a range of 2.76–118.69 gCO_2eq./kWh through urea and methanol synthesis, respectively. Compared with other framework materials, the impact factor of wind and solar energy is found to be most sensitive to steel and aluminum respectively, and their recycling should therefore be prioritized for substantial emission reduction. The result also shows that the emission reduction potential of energy technologies is majorly a function of the reduced impact factor of the energy sources and their fractional contributions in the energy mix. Hence, lignite shows a much higher impact reduction potential than the combined wind and solar energy resources, and the CO_2 utilization route for its emission reduction should be prioritized. Furthermore, analysis of CO_2 utilization from lignite and framework material recycling levels reveals 50% recycling ratio as the optimum. When 50% recycling ratio is adopted, a total of 21.84% CO_2 emission reduction is achieved in the Turkish electricity mix, corresponding to 0.083 GT of annual CO_2 savings. The decarbonization of electricity through the proposed circularity approaches translates into 25.0% and 27.0% GWP impact reductions in agricultural and steel sectors, respectively. Hence, the decarbonization of electricity mix can significantly ease negative impacts of the Green Deal on Turkey's economy.

In addition to the application of CO_2 utilization and framework material recycling approaches, promoting and increasing the share of renewable energy sources in the electricity mix can further enhance these environmental benefits. For future studies, the circularity approaches investigated can be extended to other energy sources, especially renewable energy.

Acknowledgements

This research was partially supported by Marmara University Institute of Science under projects FEN-C-DRP-150513-0186 and FEN-C-DRP-150513-0175. We are also in dept of Prof. Dr Gökçen Çiftçioğlu for her support in this research.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The work was supported by the Marmara University Institute of Science [FEN-C-DRP-150513-0186 and FEN-C-DRP-150513-0175].

Notes on contributors

Mujeeb Babatunde Adetayo Ph. D student at Marmara University Chemical Engineering Department.

Dr. Berrin Kursun Assistant Prof of Chemical Engineering at Marmara University.

ORCID

Berrin Kursun http://orcid.org/0000-0002-2111-4416

References

Acar, S., A. A. Aşıcı, and A. E. Yeldan. 2022. Potential effects of the EU's carbon border adjustment mechanism on the Turkish economy. *Environment, Development and Sustainability* 24 (6):8162–94. doi:10.1007/s10668-021-01779-1.

Ali, H., H. A. Khan, and M. G. Pecht. 2021. Circular economy of Li batteries: Technologies and trends. *Journal of Energy Storage* 40:102690. doi:10.1016/j.est.2021.102690.

Alsaleh, A., and M. Sattler. 2019. Comprehensive life cycle assessment of large wind turbines in the US. *Clean Technologies and Environmental Policy* 21 (4):887–903. doi:10.1007/s10098-019-01678-0.

Atilgan, B., and A. Azapagic. 2016. Renewable electricity in Turkey: Life cycle environmental impacts. *Renewable Energy* 89:649–57. doi:10.1016/j.renene.2015.11.082.

Ayvaz, B., and A. O. Kusakci. 2017. Electricity consumption forecasting for Turkey with nonhomogeneous discrete grey model. *Energy Sources, Part B: Economics, Planning, & Policy* 12 (3):260–67. doi:10.1080/15567249.2015.1089337.

Bilgili, M., and E. Pinar. 2023. Gross electricity consumption forecasting using LSTM and SARIMA approaches: A case study of Türkiye. *Energy* 284:128575. doi:10.1016/j.energy.2023.128575.

Bist, N., A. Sircar, and K. Yadav. 2020. Holistic review of hybrid renewable energy in circular economy for valorization and management. *Environmental Technology & Innovation* 20:101054. doi:10.1016/j.eti.2020.101054.

BP (British Petroleum). 2022. *Statistical review of world energy 2022*. US: British Petroleum.

Broadbent, C. 2016. Steel's recyclability: Demonstrating the benefits of recycling steel to achieve a circular economy. *The International Journal of Life Cycle Assessment* 21 (11):1658–65. doi:10.1007/s11367-016-1081-1.

Cekinir, S., O. Ozgener, and L. Ozgener. 2022. Türkiye's energy projection for 2050. *Renewable Energy Focus* 43:93–116. doi:10.1016/j.ref.2022.09.003.

Chen, J., Z. Wang, Y. Wu, L. Li, B. Li, D. Pan, and T. Zuo. 2019. Environmental benefits of secondary copper from primary copper based on life cycle assessment in China. *Resources, Conservation & Recycling* 146:35–44. doi:10.1016/j.resconrec.2019.03.020.

Emek, S., and G. Akkaya. 2022. Turkey's long-term electricity consumption forecast using regression analysis. *Journal of Scientific & Industrial Research* 81:12. 10.56042/jsir.v81i12.40731

Güllü, A. B., H. Aksoy, S. Serhadlıoğlu, Y. Taranto, R. Y. Çalışkan, A. D. Vita, V. Karakousis, M. Rogner, P. Godron, and G. Dinçel. 2023. *Net zero 2053: A roadmap for the Turkish electricity sector*. Istanbul, Turkey: SHURA Energy Transition Center, Sabanci University.

Hong, J., Y., Chen, J. Liu, X. Ma, C. Qi, and L. Ye 2018. Life cycle assessment of copper production: A case study in China. *The International Journal of Life Cycle Assessment* 23 (9):1814–24.

Huang, C.-H., and C.-S. Tan. 2014. A Review: CO2 utilization. *Aerosol and Air Quality Research* 14 (2):480–99. doi:10.4209/aaqr.2013.10.0326.

IEA (International Energy Agency). 2021. *Turkey 2021 - Energy policy review*. Paris, France: International Energy Agency.

IEA (International Energy Agency). 2022. Key energy statistics. Accessed June 8, 2023. https://www.iea.org/countries/turkiye.

IEA (International Energy Agency). 2023. Key energy statistics. Accessed December 12, 2023. https://www.iea.org/countries/turkiye.

Kılınc, A. 2022. *Impact of carbon border adjustment mechanism on iron-steel and cement sectors in Turkey: A social accounting matrix multiplier analysis*. Ankara, Turkey: Middle East Technical University.

Korkmaz, O., and B. Önöz. 2022. Modelling the potential impacts of nuclear energy and renewables in the Turkish energy system. *Energies* 15 (4):1392. doi:10.3390/en15041392.

Kropff, W., A. Eitzinger, E. Hasiner, K. Schroeder, A. Juergenliemk, A. Horst, and A. Jarvis. 2021. *CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS)*, 17. Rome, Italy: FAO.

Kumar, P., S. Verma, A. Gupta, A. R. Paul, A. Jain, and N. Haque. 2021. Life cycle analysis for the production of urea through syngas. *IOP Conference Series: Earth and Environmental Science* 795 (1):012031. doi:10.1088/1755-1315/795/1/012031.

Kursun, B. 2022. Role of solar power in shifting the Turkish electricity sector towards sustainability. *Clean Energy* 6 (2):313–24. doi:10.1093/ce/zkac002.

Kursun, B. 2023. Exploitable wind power potential in Turkey with technological advancement and resulting environmental-economic aspects. *Energy Exploration & Exploitation* 41 (1):187–209. doi:10.1177/01445987221115814.

Manfred, R. 2020. *Life cycle assessment of a Nordex windfarm with Delta4000 turbines*. Stuttgart, Germany: Sphera Solutions.

Ministry of Energy and Natural Resources (MENR). 2022. *Türkiye national energy plan*. Ankara, Turkey.

Napp, T. A., S. Few, A. Sood, D. Bernie, A. Hawkes, and A. Gambhir. 2019. The role of advanced demand-sector technologies and energy demand reduction in achieving ambitious carbon budgets. *Applied Energy* 238:351–67. doi:10.1016/j.apenergy.2019.01.033.

Özdemir, A., Z. Günkaya, A. Özkan, O. Ersen, M. Bilgiç, and M. Banar. 2018. Life cycle assessment of steel rebar production with Induction melting furnace: Case study in Turkey. *Journal of Hazardous, Toxic, and Radioactive Waste* 22 (2):04017027. doi:10.1061/(ASCE)HZ.2153-5515.0000385.

Pagliaro, M., and F. Meneguzzo. 2019. Lithium battery reusing and recycling: A circular economy insight. *Heliyon* 5 (6): e01866. doi:10.1016/j.heliyon.2019.e01866.

PRé Sustainability. 2022. SimaPro. Accessed December 2, 2022. https://www.pre-sustainability.com/simapro.

Rodriguez-Garcia, G., E. Aydin, S. De Wolf, B. Carlson, J. Kellar, and I. Celik. 2021. Life cycle assessment of coated-glass recovery from perovskite solar cells. *ACS Sustainable Chemistry & Engineering* 9 (45):15239–48. doi:10.1021/acssuschemeng.1c05029.

Şahin, G., M. A. Taksim, and B. Yitgin. 2021. Effects of the European green deal on Turkey's electricity market. *İşletme Ekonomi ve Yönetim Araştırmaları Dergisi* 4 (1):40–58. doi:10.33416/baybem.835052.

Shi, L., L. Liu, B. Yang, G. Sheng, and T. Xu. 2020. Evaluation of industrial Urea Energy Consumption (EC) based on Life Cycle Assessment (LCA). *Sustainability* 12 (9):3793. doi:10.3390/su12093793.

TEIAS (Turkish Electricity Transmission Corporation). 2023. Turkish electricity production and transmission statistics. Accessed May 15, 2023. https://www.teias.gov.tr/tr-TR/turkiye-elektrik-uretim-iletim-istatistikleri.

Teimourzadeh, S., O. Tör, B. Kat, Ü. Şahin, K. Demirkol, A. Künar, E. Voyvoda, and E. Veldan. 2023. *Turkey's decarbonization pathway: Timeline and geography of the transition (2020-2050)*. Istanbul, Turkey: Istanbul Policy Centre (IPC), Sabanci University.

TUIK (Turkish Statistical Institute). 2022. Turkish population projections. Accessed August 3, 2023. https://data.tuik.gov.tr/Kategori/GetKategori?p=Nufus-ve-Demografi-109.

Turkish Wind Energy Association (TWEA) (2022). Turkish wind energy statistics report July 2022.

Vargas, C., and M. Chesney. 2021. End of life decommissioning and recycling of solar panels in the United States. A real options analysis. *Journal of Sustainable Finance & Investment* 11 (1):82–102. doi:10.1080/20430795.2019.1700723.

Vestas. 2015. Life cycle assessment of electricity production from an onshore V110-2.0 MW wind plant – 18th December 2015. Vestas Wind Systems A/S, Hedeager 42, Aarhus N, 8200, Denmark.

Yurtkuran, S. 2021. The effect of agriculture, renewable energy production, and globalization on CO2 emissions in Turkey: A bootstrap ARDL approach. *Renewable Energy* 171:1236–45. doi:10.1016/j.renene.2021.03.009.

Zang, G., P. Sun, A. Elgowainy, and M. Wang. 2021. Technoeconomic and life cycle analysis of synthetic methanol production from hydrogen and industrial byproduct CO2. *Environmental Science & Technology* 55 (8):5248–57. doi:10.1021/acs.est.0c08237.

Zegardlo, N., and K. Abd Druzba. 2021. Evaluation of Traditional Container Glass Recycling Systems against Selected Environmental Impact Criteria Using the LCA Method. *Journal of Ecological Engineering* 22 (6):2025.