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ELECTRICITY INTENSITY AND CO_2e EMISSION PERFORMANCE IN PAPER PRODUCTION: BENCHMARKING AND DECOMPOSITION ANALYSIS OF AN INDUSTRIAL PLANT IN TÜRKİYE

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ABSTRACT

The pulp and paper industry is characterized by substantial energy and resource requirements, making improvements in process efficiency important for reducing environmental impacts. This study evaluates the electricity- and process-related performance of an anonymized paper-production facility in Türkiye through an integrated benchmarking and decomposition framework. Plant-level data were used to quantify electricity intensity, electricity-related CO_2e emission intensity, recycled-pulp utilization, steam utilization, and wastewater generation. The facility was evaluated against a product-matched European reference for recycled-fibre (RCF) mills without deinking producing packaging paper, an industrial reference from Türkiye, and broader sector-level estimates for Türkiye, Europe, and the United States. The analyzed plant exhibited an electricity intensity of 320 kWh/ton, approximately 8.6% below the lower boundary and 28.9% below the upper boundary of the product-matched European reference range of 350–450 kWh/ton. Its electricity-related CO_2e emission intensity was approximately 141 kg CO_2e/ton. When the product-matched European electricity-intensity range was combined with the European grid emission factor of 0.251 kg CO_2e/kWh, the corresponding illustrative emission-intensity range was approximately 88–113 kg CO_2e/ton. Decomposition analysis showed that the lower electricity intensity of the analyzed plant reduced emissions by approximately 13–57 kg CO_2e/ton relative to the product-matched European reference, whereas the higher Turkish grid emission factor increased them by approximately 67–86 kg CO_2e/ton, resulting in a net increase of approximately 29–54 kg CO_2e/ton. Relative to the estimated Türkiye sector-level reference, the approximately 242 kg CO_2e/ton reduction was entirely attributable to lower electricity intensity because both systems shared the same grid emission factor. Process assessment further indicated an 85% recycled-pulp ratio and a 64.3% steam-utilization ratio. Overall, the results demonstrate that comparatively low plant-level electricity consumption does not necessarily result in lower electricity-related CO_2e emissions when the electricity supply has a higher carbon intensity. The proposed framework provides a practical approach for distinguishing plant-level electricity-efficiency effects from electricity-grid carbon-intensity effects in paper-production benchmarking.

Keywords: paper production; electricity intensity; CO_2e emission intensity; benchmarking; decomposition analysis; recycled pulp.

INTRODUCTION

The pulp and paper industry is an important manufacturing sector, but it is also highly resource- and energy-intensive, requiring substantial amounts of electricity, thermal energy, water, and fibrous raw materials

(Farla et al. 1997; Szabó et al. 2009; Laurijssen et al. 2012; Kong et al. 2016; Sun et al. 2018). Improving energy efficiency and reducing associated greenhouse-gas emissions have therefore become major priorities for the sector (Worrell et al. 2009; Fleiter et al. 2012; Shabbir et al. 2022). Energy demand arises from operations such as stock preparation, refining, pumping, vacuum generation, drying, ventilation, and auxiliary systems, and can vary considerably according to product grade, process configuration, plant integration, and equipment efficiency (Kramer et al. 2009; Laurijssen et al. 2012; Kong et al. 2016).

Production-normalized indicators are widely used to compare the performance of paper-production systems. Specific electricity or energy consumption per ton of paper enables facilities with different production scales to be evaluated on a common basis and can reveal substantial performance differences among mills (Laurijssen et al. 2012; Rogers et al. 2018; Shabbir et al. 2022). However, comparisons require consistent system boundaries because total energy intensity may include electricity, fuels, and thermal energy, whereas electricity intensity refers specifically to electricity consumption per unit of production (Rogers et al. 2018). This distinction is particularly important when evaluating electricity-related CO_2e emissions.

Electricity-related CO_2e emission intensity depends on both the electricity consumed per ton of paper and the emission factor of the electricity supply. Because electricity-generation mixes differ among countries and regions, identical electricity intensities can result in different CO_2e intensities (Intergovernmental Panel on Climate Change (IPCC) 2006; European Environment Agency 2024; U.S. Environmental Protection Agency 2024). Conversely, a plant operating under a relatively carbon-intensive grid may still achieve comparatively low electricity-related emissions if its electricity consumption per ton is sufficiently low. Previous studies have shown that process energy-efficiency improvements can substantially reduce industrial CO_2e emissions, while the final environmental benefit also depends on the surrounding energy system (Siitonen et al. 2010; Sun et al. 2018).

Resource utilization is another important aspect of paper-production sustainability. Recycled fiber or pulp can reduce dependence on virgin resources and support circular material use, while steam utilization and wastewater generation provide additional information on process-level efficiency (Pokhrel and Viraraghavan 2004; Villanueva and Wenzel 2007; Suhr et al. 2015; Hubbe et al. 2016). Cogeneration systems are particularly relevant because they can simultaneously supply electricity and steam, linking electrical and thermal performance within the production process (Kramer et al. 2009).

Benchmarking can identify performance differences, but it does not by itself explain why one system performs better than another. Decomposition approaches can separate the contribution of individual drivers to differences in energy use or emissions (Hoekstra and van den Bergh 2003; Ang 2005; Su and Ang 2012). In the context of electricity-related paper-production emissions, this allows the influence of plant-level electricity intensity to be distinguished from the influence of the electricity-grid emission factor.

Accordingly, this study evaluates an anonymized paper-production facility in Türkiye using an integrated framework combining plant-level operational assessment, electricity-intensity benchmarking, electricity-related CO_2e emission comparison, normalized contextual assessment, and decomposition analysis. The industrial dataset includes paper production, electricity consumption, recycled-pulp ratio, steam generation and utilization, wastewater generation, and major process characteristics. The plant is evaluated against a product-matched European RCF packaging-paper reference, a representative Turkish producer, and broader sector-level estimates for Türkiye, Europe, and the United States. Decomposition analysis is used to distinguish the contribution of electricity intensity from that of grid carbon intensity. This approach provides a concise framework for evaluating the relative influence of internal process electricity efficiency and external electricity-system characteristics on the electricity-related environmental performance of paper production.

METHODS

Data Sources and Study Design

This study employs a comparative benchmarking and decomposition framework to evaluate the electricity-related and environmental performance of a paper production system. The analysis integrates two categories of data sources: (i) an anonymized industrial dataset obtained from a paper manufacturing facility in Türkiye, and (ii) publicly available technical, institutional, and industry sources used to establish product-matched and broader sector-level reference values.

The anonymized dataset includes annual paper production, electricity consumption, recycled pulp ratio, steam production and utilization, wastewater generation, and key process characteristics. To ensure confidentiality, all data are presented in aggregated form without identifying the facility.

For benchmarking, two complementary types of reference values were considered. First, a product-matched European reference was obtained from the European Commission Best Available Techniques (BAT) Reference Document for the Production of Pulp, Paper and Board (Suhr et al. 2015), which reports indicative electricity consumption of 350–450 kWh/ton for recycled-fibre (RCF) mills without deinking producing packaging paper, including Testliner and corrugated medium. This reference was considered the most directly comparable benchmark for evaluating the electricity intensity of the analyzed plant because of the similarity in production route and product category. The reported values represent entire-mill net production and include RCF processing, papermaking, major auxiliary electrical loads, and peripheral subsystems.

Second, broader sector-level reference values for Türkiye, Europe, and the United States were derived from publicly available institutional and industry statistics. These sources included the Turkish Ministry of Energy and Natural Resources (T.C. Enerji ve Tabii Kaynaklar Bakanlığı 2024),the Confederation of European Paper Industries (Confederation of European Paper Industries (CEPI) 2024), the European Environment Agency (European Environment Agency 2024), the U.S. Environmental Protection Agency (U.S. Environmental Protection Agency 2024), the U.S. Energy Information Administration (U.S. Energy Information Administration 2025), and sector-specific reports for Türkiye and the United States. Because these aggregate datasets encompass broader product mixes, mill configurations, and statistical boundaries, the resulting values were used as contextual sector-level references rather than directly product-matched benchmarks. Detailed derivations of the benchmark values are provided in the subsequent benchmark calculations.

Performance Indicators

To ensure consistent comparison across all regions and the anonymized plant, three key performance indicators were defined: electricity intensity, electricity-related CO_2e emission factor, and CO_2e emission intensity. These indicators are commonly used to characterize energy and emission performance in industrial and pulp-and-paper systems, particularly when comparing facilities or regions with different production levels and energy structures (Laurijssen et al. 2012; Rogers et al. 2018).

1. Electricity Intensity: It represents the amount of electricity consumed per unit of paper produced and provides a production-normalized measure of electricity use. Similar indicators have been reported in the literature as electricity intensity, specific electricity consumption, or specific electricity use in pulp-and-paper benchmarking studies (Laurijssen et al. 2012). Electricity intensity was calculated as:

$$Electricity\ Intensity\ = \frac{Electricity\ Consumption\ (kWh)}{Paper\ Production\ (ton)} \quad (1)$$

where electricity consumption is expressed in kWh and paper production in tons, resulting in an electricity intensity of kWh/ton. For the anonymized plant, electricity consumption and production values were directly measured. The product-matched European reference was obtained from the indicative electricity-consumption range reported by Suhr et al. (2015) for RCF mills without deinking producing packaging paper. Broader national and regional sector-level estimates were obtained by combining reported electricity consumption and production statistics and were used as contextual references rather than directly product-matched benchmarks.

2. CO_2e Emission Factor: The electricity-grid CO_2e emission factor represents the amount of CO_2e emitted per unit of electricity generated and is expressed as kg CO_2e/kWh. Emission factors are commonly used to relate activity data to the associated emissions (Intergovernmental Panel on Climate Change (IPCC) 2006). Because electricity-generation mixes differ among countries and regions, electricity-related emission factors also vary geographically.

$$CO_2e\ Emission\ Factor\ = \frac{CO_2e\ Emission}{Electricity\ Consumption} \quad (2)$$

Country- and region-specific electricity-generation emission factors were used. The value for Türkiye was obtained from ETKB statistics (T.C. Enerji ve Tabii Kaynaklar Bakanlığı 2024), the European value was obtained from EEA data (European Environment Agency 2024),and the U.S. value was derived from EPA eGRID data (U.S. Environmental Protection Agency 2024).

3. CO_2e Emission Intensity: CO_2e emission intensity represents the electricity-related CO_2e emissions associated with producing one ton of paper. In this study, it was calculated by combining the electricity intensity of paper production with the corresponding electricity emission factor:

$$CO_2e\ Intensity\ =\ Electricity\ Intensity\ x\ Emission\ Factor \quad (3)$$

The resulting indicator is expressed as kg CO_2e/ton of paper. This formulation provides a production-normalized estimate of indirect electricity-related CO_2e emissions and enables comparison among paper production systems operating under different electricity-grid conditions.

Material and Process Efficiency Metrics

Additional indicators were defined to evaluate process-level performance:

- **Recycled pulp ratio** represents the proportion of recycled pulp used in paper production.
- **Steam utilization ratio** represents the proportion of generated steam utilized in the production process. It was calculated as the ratio of steam utilization to total steam generation:

  Steam utilization ratio = Steam utilized / Steam generated

- **Wastewater generation intensity** represents the amount of wastewater generated per unit of paper production. It was calculated by normalizing annual wastewater generation to annual paper production and expressed as tons of wastewater/ton of paper.

These indicators were derived from the anonymized industrial dataset and used to characterize resource utilization and process performance.

Benchmarking Approach

A comparative benchmarking approach was applied to evaluate the performance of the anonymized plant using reference values with different levels of comparability. The analysis included:

· A product-matched European reference for recycled-fibre (RCF) mills without deinking producing packaging paper, including Testliner and corrugated medium (Suhr et al. 2015),

· A representative industrial producer in Türkiye (Kartonsan Karton Sanayi ve Ticaret A.Ş. 2024),

· An estimated sector-level reference for Türkiye, and

· Aggregate sector-level references for Europe and the United States.

The product-matched European reference of 350–450 kWh/ton was considered the most directly comparable benchmark for evaluating the electricity intensity of the analyzed plant because it represents a similar production route and product category. The Türkiye, European, and U.S. sector-level values were retained to provide broader context but were not considered directly product-matched benchmarks because of differences in product mix, mill integration, and statistical boundaries. Benchmark values were obtained from industry reports, statistical databases, and institutional sources, as detailed in Table 2. All values were converted to consistent units (kWh/ton for electricity intensity and kg CO_2e/ton for CO_2e emission intensity) prior to comparison.

Decomposition Analysis

To identify the relative contributions of electricity intensity and electricity emission factors to electricity-related CO_2e emission intensity, a two-step decomposition analysis was performed, following the general principles of decomposition analysis used in energy and emission studies (Ang 2005; Su and Ang 2012). The difference in CO_2e emission intensity between the two systems was expressed as the sum of two components:

$$\Delta CO_{2e} = \Delta CO_{2e,grid} + \Delta CO_{2e,energy} \quad (4)$$

where:

- **Grid effect** represents the impact of differences in emission factors:

$$\Delta CO_{2e,grid} = E_{ref}\, x\, (F_{target} - F_{ref}) \quad (5)$$

- **Electricity-intensity effect** represents the impact of differences in electricity intensity:

$$\Delta CO_{2e,electricity} = (E_{target} - E_{ref})\, x\, F_{target} \quad (6)$$

Here, E denotes electricity intensity, and F denotes the emission factor. This approach allows the separation of internal process-efficiency effects from external energy-system characteristics. The decomposition was applied to compare the anonymized plant with the product-matched European electricity-intensity reference and the estimated Türkiye sector-level reference.

Visualization and Data Analysis

All calculations and visualizations were performed using MATLAB. The analysis included bar charts for benchmarking, bar charts for process-level performance indicators, radar plots for normalized contextual comparison, waterfall diagrams for decomposition analysis, and scatter plots to examine the relationship between electricity intensity and electricity-related CO_2e emission intensity. Normalization for the radar plot was performed using inverted min–max scaling, mapping lower indicator values to higher normalized scores.

Assumptions and Limitations

The analysis focuses on electricity-based energy consumption and excludes thermal energy inputs, such as steam generated from fossil fuels or biomass. Therefore, the reported electricity and emission intensities represent electricity-related performance rather than total energy use. The product-matched European reference was selected to provide a more directly comparable electricity-intensity benchmark; however, differences in individual mill configuration and operating conditions may still affect comparability. Broader national and regional values are based on aggregated sector-level statistics and may differ from the analyzed plant in terms of product mix, mill integration, production boundaries, and reporting methodologies. These values were therefore used primarily to provide sector-level context rather than direct plant-level benchmarks. Additionally, emission factors are treated as constant values and do not account for temporal variations in electricity generation mixes. Despite these limitations, the selected indicators and methodology provide a consistent framework for evaluating electricity-related performance.

RESULTS

Operational Characteristics of The Analyzed Plant

The key operational characteristics of the anonymized paper production system are summarized in Table 1. The facility has an annual paper production of 262,800 tons, with a total electricity consumption of 84,096 MWh/year. Based on these values, the electricity intensity was calculated as 0.320 MWh/ton (320 kWh/ton). The plant has a recycled pulp ratio of 85%, indicating a high utilization of recycled pulp in paper production.

The facility operates a cogeneration system producing both electricity and steam. Steam generation is approximately 1,400 tons/day (511,000 tons/year), of which approximately 900 tons/day (328,500 tons/year) is utilized in the production process, corresponding to a steam utilization ratio of approximately 64.3%. Wastewater generation is approximately 75 tons/day (27,375 tons/year). The main energy source is pulverized coal, and the primary product is corrugated cardboard. Overall, the operational data provide the basis for the subsequent assessment of electricity performance, resource utilization, and electricity-related CO_2e emissions.

Table 1. Operational Characteristics of The Anonymized Paper Plant

PARAMETER	VALUE	UNIT	NOTE
ANNUAL PAPER PRODUCTION	262,800	ton/year	Provided
ELECTRICITY CONSUMPTION	84,096	MWh/year	Provided
ELECTRICITY INTENSITY	0.320	MWh/ton	Calculated
ELECTRICITY INTENSITY	320	kWh/ton	Converted

RECYCLED PULP RATIO	85	%	Provided
STEAM GENERATION	1,400	ton/day	Provided
STEAM GENERATION	511,000	ton/year	Annualized
STEAM UTILIZATION	900	ton/day	Provided
STEAM UTILIZATION	328,500	ton/year	Annualized
STEAM UTILIZATION RATIO	64.3	%	Calculated (900/1,400)
WASTEWATER GENERATION	75	ton/day	Provided
WASTEWATER GENERATION	27,375	ton/year	Annualized
MAIN ENERGY SOURCE	Pulverized coal	–	Provided
ENERGY SYSTEM	Cogeneration (electricity + steam)	–	Provided
PRODUCT TYPE	Corrugated cardboard	–	Provided

Electricity Intensity of the Analyzed Plant

The electricity intensity of the anonymized paper production system was calculated to be 320 kWh/ton, based on an annual electricity consumption of 84,096 MWh and an annual paper production of 262,800 tons. This value provides a production-normalized measure of the plant's electricity consumption and forms the basis for comparison with the product-matched and broader sector-level reference values in the subsequent analysis.

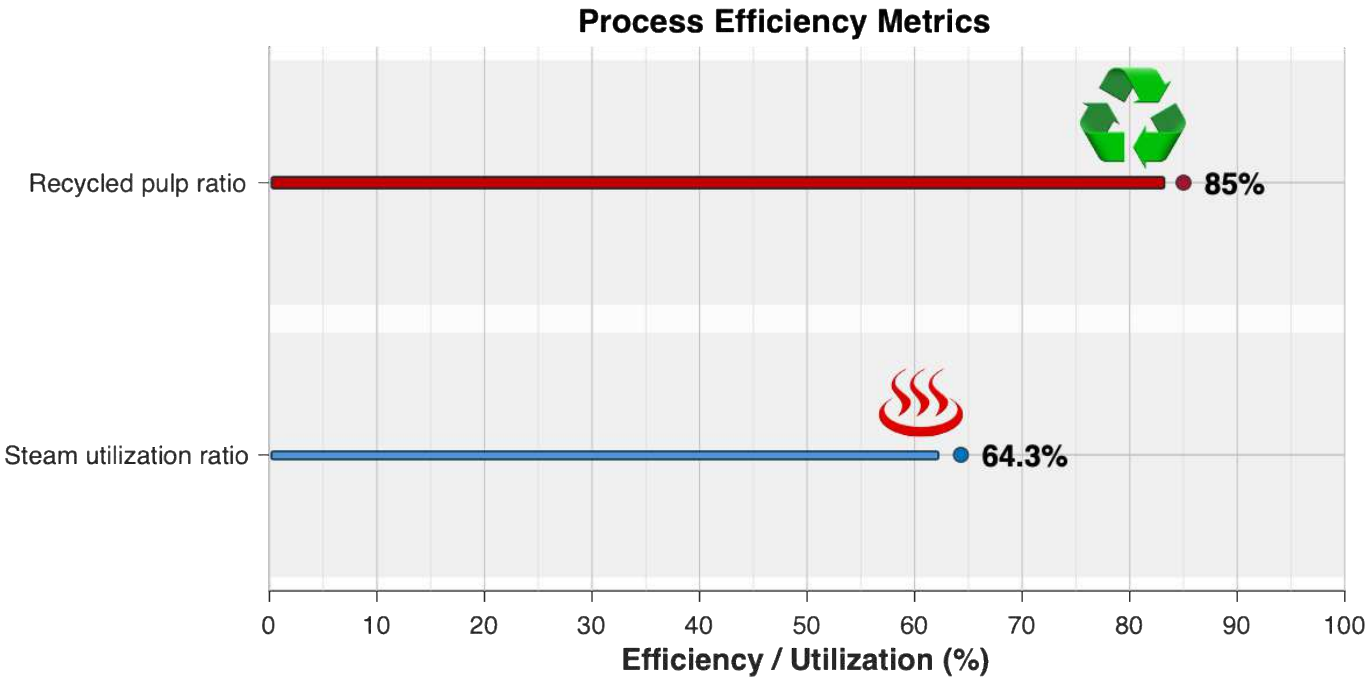


Figure 1. Process-level resource utilization indicators of the anonymized paper production system, showing the recycled pulp ratio and steam utilization ratio.

Process Efficiency Indicators

Key process-level indicators of the anonymized plant are summarized in Figure 1. The recycled pulp ratio was reported as 85%, indicating that recycled pulp constitutes a substantial proportion of the pulp used in paper production. The steam utilization ratio was calculated as 64.3%, based on a steam generation rate of 1,400 tons/day and a steam utilization rate of 900 tons/day (900 / 1,400 × 100 = 64.3%). Annual wastewater generation was calculated from the reported daily wastewater generation of 75 tons/day as 75 × 365 = 27,375 tons/year. Based on the annual paper production of 262,800 tons, the wastewater generation intensity was calculated as 27,375 / 262,800 = 0.104 ton wastewater/ton paper. These indicators provide complementary information on recycled material utilization, steam utilization, and wastewater generation within the analyzed production system.

Steam Flow Analysis

The steam flow within the cogeneration system is presented in Figure 2. The facility generates approximately 1,400 tons of steam per day, corresponding to 511,000 tons/year. Of this amount, approximately 900 tons/day (328,500 tons/year) is utilized in the production process, resulting in a steam utilization ratio of approximately 64.3%. The remaining 500 tons/day (182,500 tons/year) represents the portion of generated steam not directly utilized in the production process. These data characterize steam generation and utilization within the plant's cogeneration system.

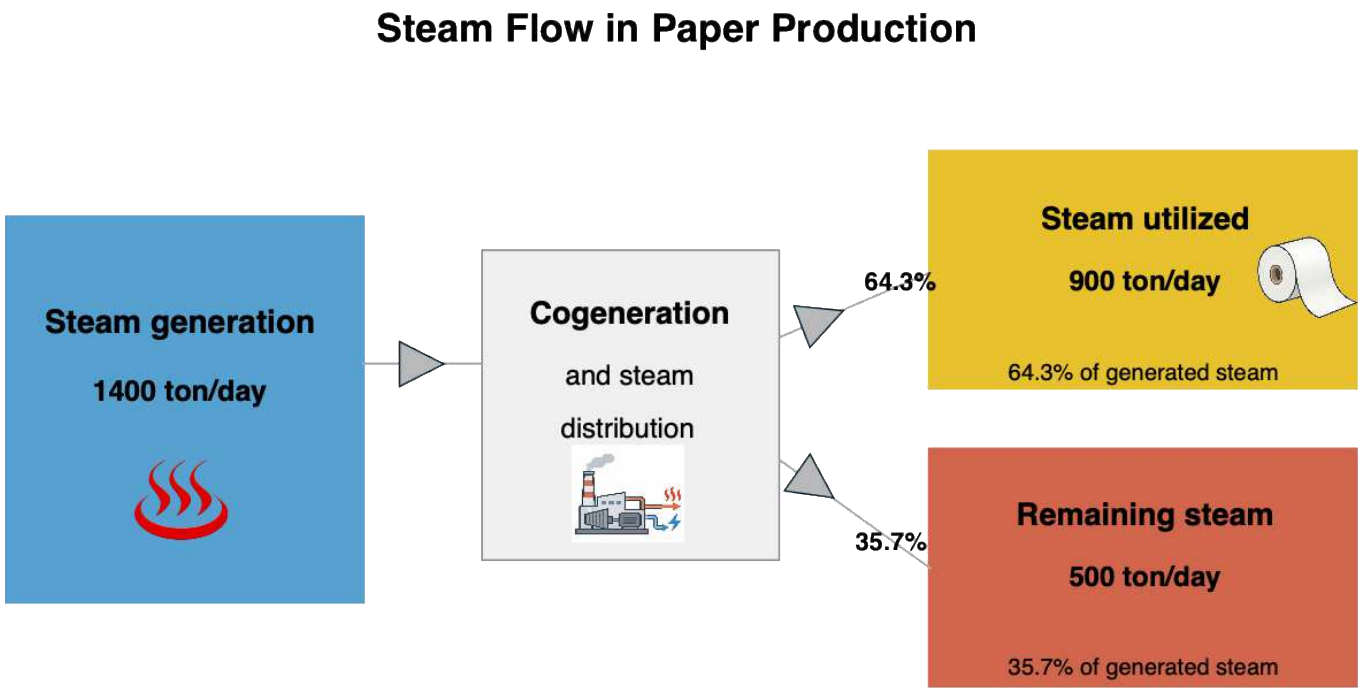


Figure 2. Steam generation and distribution within the cogeneration system of the anonymized paper plant, showing the utilized and remaining steam fractions.

Calculation of Benchmark Values

Table 2. Comparison of electricity and electricity-related emission indicators using product-matched and sector-level reference values

Region / Plant	Electricity Intensity (kWh/ton)	CO_2e Emission Factor (kg CO_2e/kWh)	CO_2e Emission Intensity (kg CO_2e/ton)	Reference Type
Anonymized Plant (Türkiye)	320 (Calculated Value 1)	0.442 (ETKB, 2024; 2022 data)	141 (Calculated Value 2)	Analyzed plant
European RCF Packaging-Paper Reference	350–450 (Suhr et al. 2015)	-	-	Product-matched reference
Kartonsan (Türkiye)	475 (Calculated Value 3)	0.442 (T.C. Enerji ve Tabii Kaynaklar Bakanlığı 2024)	210 (Calculated Value 4)	Industrial reference
Türkiye (Estimated Sector Level)	~867 (Calculated Value 5)	0.442 (T.C. Enerji ve Tabii Kaynaklar Bakanlığı 2024)	~383 (Calculated Value 6)	Aggregate sector-level estimate
Europe (Estimated Sector Level)	~1,019 (Calculated Value 7)	~0.251 (European Environment Agency 2024)	~256 (Calculated Value 8)	Aggregate sector-level estimate
USA (Estimated Sector Level)	~1,181 (Calculated Value 9)	~0.375 (Calculated Value 10)	~443 (Calculated Value 11)	Aggregate sector-level estimate

The European RCF packaging-paper reference represents the most directly product-matched electricity-intensity benchmark used in this study. Suhr et al. (2015) report indicative electricity consumption of 350–450 kWh/ton for RCF mills without deinking producing packaging paper, including Testliner and corrugated medium. In contrast, the Türkiye, European, and U.S. values in Table 2 were derived from aggregate sector-level statistics and are therefore presented primarily to provide broader context rather than as directly product-matched plant-level benchmarks.

The calculated benchmark values presented in Table 2 were obtained as follows.

Calculated Value 1 – Electricity intensity of the anonymized plant: The electricity intensity of the anonymized plant was calculated by dividing its annual electricity consumption by its annual paper production:

$$84{,}096 \text{ MWh/year} \div 262{,}800 \text{ ton/year} = 0.320 \text{ MWh/ton}$$

The result was converted from MWh/ton to kWh/ton:

$$0.320 \text{ MWh/ton} \times 1000 = 320 \text{ kWh/ton}$$

Calculated Value 2 – CO_2e emission intensity of the anonymized plant: The electricity-related CO_2e emission intensity was calculated by multiplying the plant electricity intensity by the Turkish grid emission factor:

$$320 \text{ kWh/ton} \times 0.442 \text{ kg } CO_2e\text{/kWh} = 141.44 \text{ kg } CO_2e\text{/ton}$$

Accordingly, the emission intensity was reported as approximately 141 kg CO_2e/ton.

Calculated Value 3 – Electricity intensity of Kartonsan: Kartonsan Sustainability Report (2024) (Kartonsan Karton Sanayi ve Ticaret A.Ş. 2024) reports specific electricity consumption values of 501.09 kWh/ton and 448.76 kWh/ton for the two production units. For the present benchmarking analysis, the arithmetic mean of these reported values was calculated:

$$(501.09 \text{ kWh/ton} + 448.76 \text{ kWh/ton}) \div 2 = 474.93 \text{ kWh/ton}$$

Therefore, the electricity intensity used for the Kartonsan benchmark was approximately 475 kWh/ton.

Calculated Value 4 – CO_2e emission intensity of Kartonsan: Kartonsan's electricity-related CO_2e emission intensity was estimated using its reported electricity intensity and the Turkish grid CO_2e emission factor:

$$475 \text{ kWh/ton} \times 0.442 \text{ kg } CO_2e/\text{kWh} = 209.95 \text{ kg } CO_2e/\text{ton}$$

Therefore, the estimated emission intensity was approximately 210 kg CO_2e/ton.

Calculated Value 5 – Estimated sector-level electricity intensity for the Turkish paper industry: According to the Orman, Kağıt Ürünleri, Mobilya ve Basım Sanayi İklim Değişikliğine Uyum Kapasitesinin Arttırılması Yol Haritası Raporu, the manufacture of paper and paper products consumed 48,090 TJ of final energy in 2023, of which 34% was supplied as electricity (İstanbul Sanayi Odası and TÜBİTAK Marmara Araştırma Merkezi 2026). Electricity consumption was therefore estimated as:

$$48{,}090 \text{ TJ} \times 0.34 = 16{,}350.6 \text{ TJ}$$

Using the conversion 1 TWh = 3600 TJ:

$$16{,}350.6 \text{ TJ} \div 3600 = 4.542 \text{ TWh}$$

National paper and paperboard production in 2023 was approximately 5.24 million tons (İstanbul Sanayi Odası 2025). Therefore:

$$4.542 \times 10^9 \text{ kWh} \div 5.24 \times 10^6 \text{ ton} = 866.8 \text{ kWh/ton}$$

Therefore, the estimated sector-level electricity intensity for Türkiye was approximately 867 kWh/ton. Because the electricity-consumption and production statistics represent different sectoral boundaries, this value was treated as an approximate contextual reference rather than an official national or product-matched benchmark.

Calculated Value 6 – Estimated sector-level CO_2e emission intensity of the Turkish paper industry: The estimated national CO_2e emission intensity was calculated using the estimated electricity intensity and Turkish grid emission factor:

$$867 \text{ kWh/ton} \times 0.442 \text{ kg } CO_2e/\text{kWh} = 383.214 \text{ kg } CO_2e/\text{ton}$$

Therefore, the estimated national CO_2e emission intensity was approximately 383 kg CO_2e/ton.

Calculated Value 7 – Aggregate sector-level electricity-intensity estimate for Europe: According to CEPI Key Statistics 2023, total electricity consumption by the European pulp and paper industry was 86,571

GWh in 2022, while paper and board production was 84,933 thousand tons (Confederation of European Paper Industries (CEPI) 2024). The average electricity intensity was therefore estimated as:

$$86{,}571 \text{ GWh/year} \div 84{,}933 \times 10^3 \text{ ton/year} = 1.019 \text{ MWh/ton}$$

The result was converted from MWh/ton to kWh/ton:

$$1.019 \text{ MWh/ton} \times 1000 = 1{,}019 \text{ kWh/ton}$$

Therefore, the aggregate sector-level electricity intensity estimated from the European statistics was approximately 1,019 kWh/ton. Because the electricity-consumption data represent the broader European pulp-and-paper industry and encompass a range of products and mill configurations, this value was used as a contextual sector-level estimate rather than as a directly product-matched benchmark for the analyzed plant.

Calculated Value 8 – Aggregate electricity-related CO_2e emission-intensity estimate for Europe: The average European CO_2e emission intensity was estimated by multiplying the reported electricity intensity by the average European electricity emission factor:

$$1{,}019 \text{ kWh/ton} \times 0.251 \text{ kg } CO_2e\text{/kWh} = 255.769 \text{ kg } CO_2e\text{/ton}$$

Therefore, the aggregate electricity-related CO_2e emission-intensity estimate for Europe was approximately 256 kg CO_2e/ton. This value was used as a sector-level contextual estimate and not as a product-matched plant-level emission benchmark.

Calculated Value 9 – Aggregate sector-level electricity-intensity estimate for the U.S. paper industry: According to the U.S. Energy Information Administration (EIA) 2022 Manufacturing Energy Consumption Survey (MECS), total electricity consumption for pulp mills, paper mills, and paperboard mills was 19,673, 25,430, and 34,640 million kWh, respectively (U.S. Energy Information Administration 2025). Total electricity consumption was therefore calculated as:

$$19{,}673 + 25{,}430 + 34{,}640 = 79{,}743 \text{ million kWh} = 79.743 \times 10^9 \text{ kWh}$$

U.S. paper and paperboard production in 2022 was approximately 67.5 million metric tons (U.S. Department of Energy 2025). Therefore:

$$79.743 \times 10^9 \text{ kWh} \div 67.5 \times 10^6 \text{ ton} = 1{,}181.4 \text{ kWh/ton}$$

Therefore, the aggregate sector-level electricity-intensity estimate for the U.S. paper industry was approximately 1,181 kWh/ton. This value was used as a contextual sector-level reference rather than a directly product-matched benchmark.

Calculated Value 10 – Average electricity-grid CO_2e emission factor for the United States: According to the U.S. Environmental Protection Agency (EPA) eGRID2022 Summary Tables, the U.S. average total output greenhouse-gas emission rate was 827.5 lb CO_2e/MWh in 2022 (U.S. Environmental Protection Agency 2024). The value was converted to kg CO_2e/kWh as follows:

$$827.5 \text{ lb } CO_2e\text{/MWh} \times 0.453592 \text{ kg/lb} \div 1000 = 0.375 \text{ kg } CO_2e\text{/kWh}$$

Therefore, the average U.S. electricity-grid emission factor used in this study was approximately 0.375 kg CO_2e/kWh.

Calculated Value 11 – Aggregate electricity-related CO_2e emission-intensity estimate for the United States: Using the values reported in Table 2:

$$1{,}181 \text{ kWh/ton} \times 0.375 \text{ kg } CO_2e/\text{kWh} = 442.875 \text{ kg } CO_2e/\text{ton}$$

Therefore, the aggregate electricity-related CO_2e emission-intensity estimate for the United States was approximately 443 kg CO_2e/ton.

Benchmarking of Electricity Intensity

A comparative analysis of electricity intensity using product-matched and broader sector-level reference values is presented in Figure 3. The anonymized plant exhibited an electricity intensity of 320 kWh/ton. The most directly comparable European reference identified in this study is the indicative electricity-consumption range of 350–450 kWh/ton reported for recycled-fibre (RCF) mills without deinking producing packaging paper, including Testliner and corrugated medium (Suhr et al. 2015). The electricity intensity of the analyzed plant was approximately 8.6% below the lower boundary and 28.9% below the upper boundary of this product-matched reference range.

The plant also exhibited lower electricity intensity than Kartonsan (475 kWh/ton). Broader sector-level estimates were approximately 867 kWh/ton for Türkiye, 1,019 kWh/ton for Europe, and 1,181 kWh/ton for the United States. These aggregate values provide broader sectoral context but should not be interpreted as directly product-matched benchmarks because they encompass differences in product mix, mill integration, production boundaries, and reporting methodologies.

Since no official national electricity intensity for the Turkish paper industry is publicly reported, the national average value used in this study was estimated by combining sectoral electricity-consumption and paper-production statistics. According to the Orman, Kağıt Ürünleri, Mobilya ve Basım Sanayi İklim Değişikliğine Uyum Kapasitesinin Arttırılması Yol Haritası Raporu, the manufacture of paper and paper products consumed 48,090 TJ of final energy in 2023, of which 34% was electricity (İstanbul Sanayi Odası and TÜBİTAK Marmara Araştırma Merkezi 2026). This corresponds to an estimated electricity consumption of 4.542 TWh. National paper and paperboard production in 2023 was approximately 5.24 million tons (İstanbul Sanayi Odası 2025). Accordingly, the sector-level electricity intensity was estimated as 867 kWh/ton. The corresponding CO_2e emission intensity was subsequently calculated using the national electricity-generation emission factor (0.442 kg CO_2e/kWh). Because the sectoral energy statistics include the entire manufacture of paper and paper products (Eurostat 2008), whereas the production statistics refer specifically to paper and paperboard production, this value should be interpreted as an approximate sector-level reference rather than an official national or product-matched average.

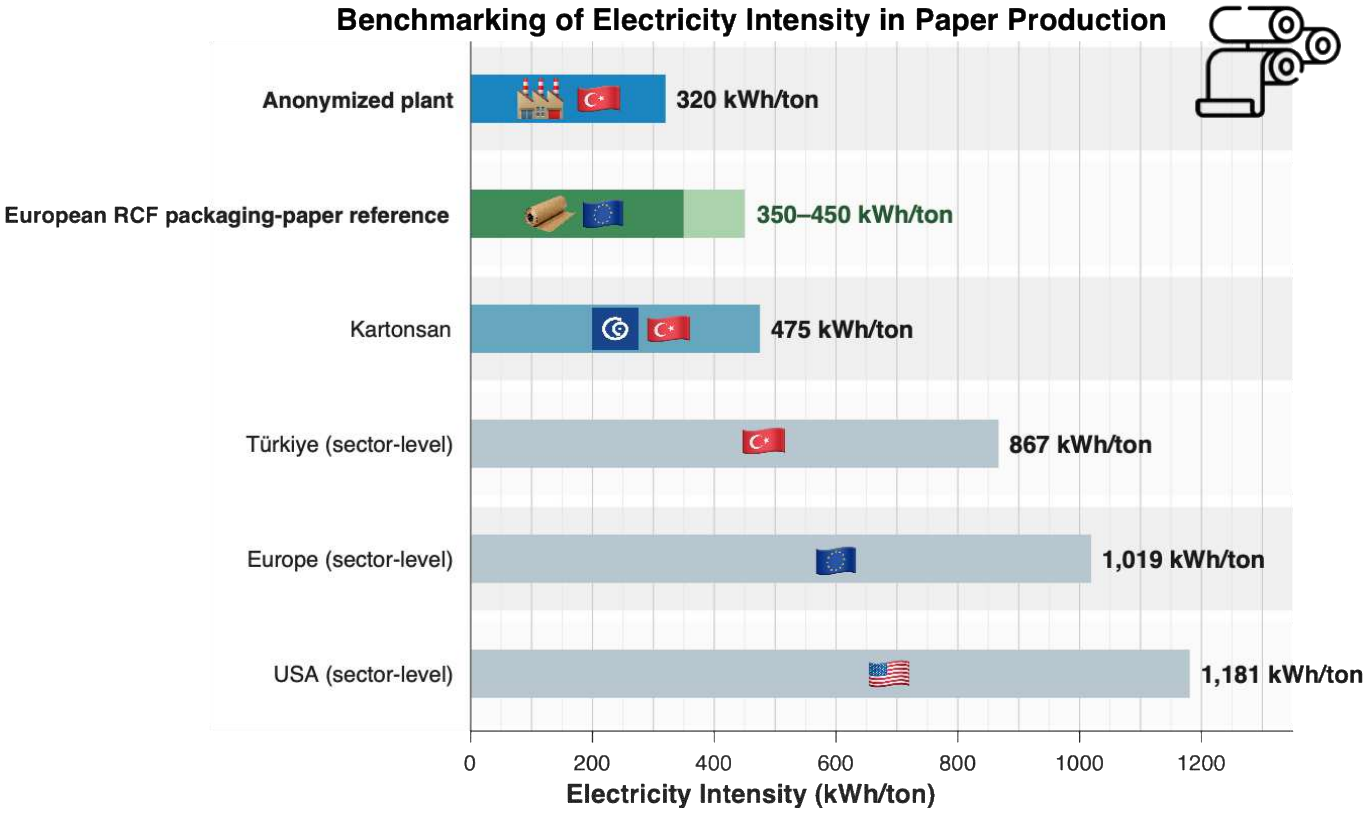


Figure 3. Comparison of the electricity intensity of the anonymized paper plant with a product-matched European RCF packaging-paper reference and broader industrial and sector-level reference values. The Türkiye, European, and U.S. sector-level values are presented for contextual comparison.

CO_2e Emission Intensity Comparison

The comparison of electricity-related CO_2e emission intensity is presented in Figure 4. The anonymized plant exhibited an electricity-related CO_2e emission intensity of approximately 141 kg CO_2e/ton, compared with 210 kg CO_2e/ton for Kartonsan and approximately 383 kg CO_2e/ton for the estimated Türkiye sector-level reference. For a product-matched European comparison, the indicative electricity-intensity range of 350–450 kWh/ton reported for RCF mills without deinking producing packaging paper was combined with the European electricity-grid emission factor of 0.251 kg CO_2e/kWh. This illustrative calculation yields an electricity-related CO_2e emission-intensity range of approximately 88–113 kg CO_2e/ton.

Although the analyzed plant has a lower electricity intensity (320 kWh/ton) than the product-matched European reference range (350–450 kWh/ton), its calculated electricity-related CO_2e emission intensity (141 kg CO_2e/ton) is higher than the corresponding European-grid scenario (88–113 kg CO_2e/ton). This difference reflects the higher electricity-grid emission factor used for Türkiye (0.442 kg CO_2e/kWh) compared with Europe (0.251 kg CO_2e/kWh), demonstrating that lower electricity consumption per ton does not necessarily result in lower electricity-related CO_2e emissions when the carbon intensity of electricity generation differs substantially.

The aggregate sector-level estimates for Europe (256 kg CO_2e/ton) and the United States (443 kg CO_2e/ton) are retained as broader contextual values but are not interpreted as directly product-matched emission benchmarks.

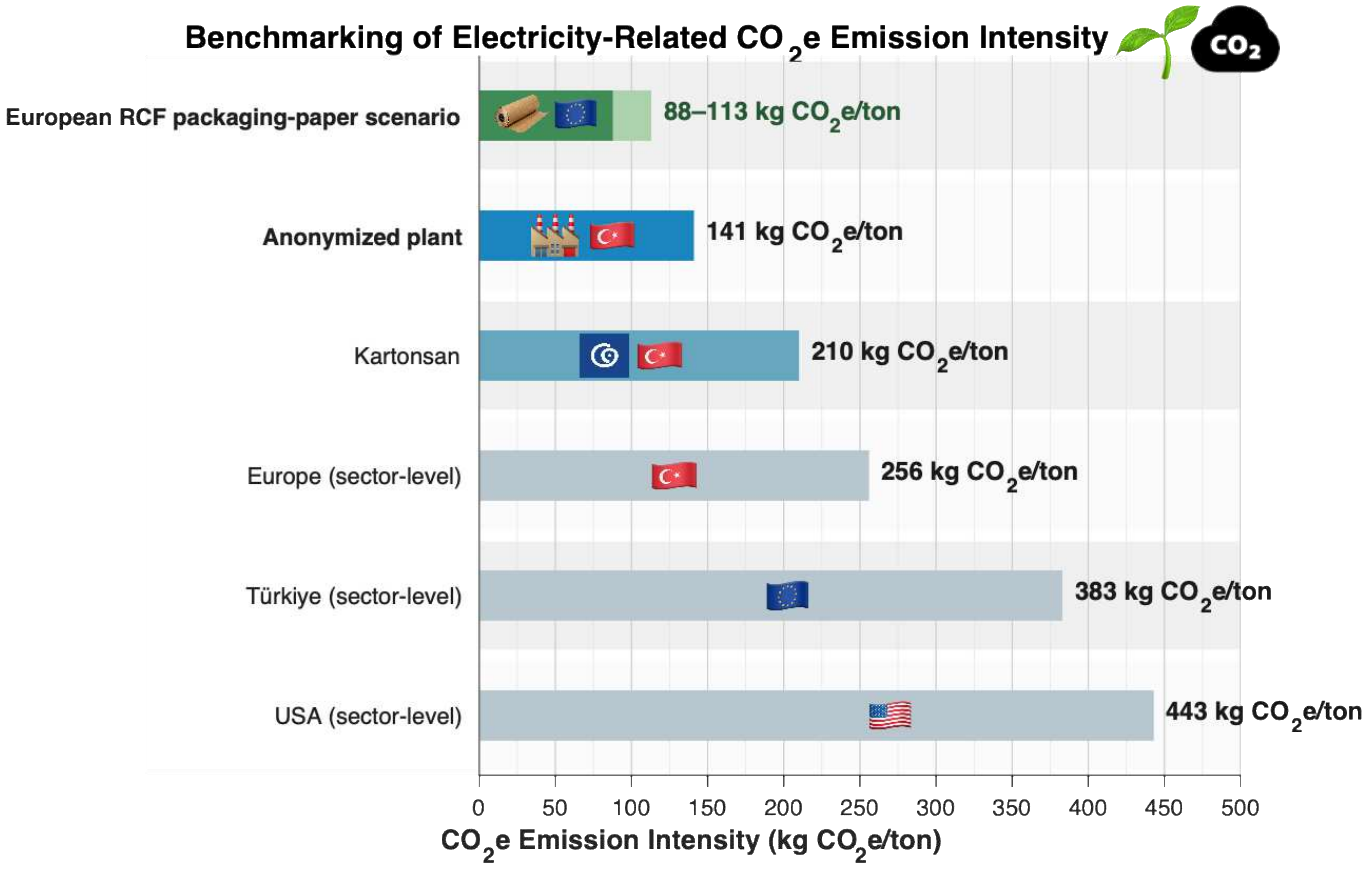


Figure 4. Comparison of electricity-related CO_2e emission intensity for the anonymized paper plant, an illustrative product-matched European RCF packaging-paper scenario, and broader industrial and sector-level reference values. The European RCF scenario was calculated by combining the electricity-intensity range reported by Suhr et al. (2015) with the European electricity-grid emission factor; aggregate Türkiye, European, and U.S. values are presented for contextual comparison.

Integrated Performance Assessment

A multidimensional comparison of the selected electricity-related indicators is presented in Figure 5 using inverted min–max normalization. Since lower values indicate more favorable values for all three indicators, the normalization was defined such that 1 represents the lowest value and 0 represents the highest value within the selected comparison set. The normalized scores therefore provide a relative visualization of the included values rather than an absolute measure of efficiency or overall environmental performance.

The comparison includes the anonymized plant, Kartonsan, broader sector-level estimates for Türkiye, Europe, and the United States, and the product-matched European RCF packaging-paper scenario. For the latter, the midpoint of the reported electricity-intensity range (400 kWh/ton) was used solely for visualization, while the full range of 350–450 kWh/ton is reported in the benchmarking analysis. Using the European grid emission factor of 0.251 kg CO_2e/kWh, this midpoint corresponds to an illustrative electricity-related CO_2e emission intensity of approximately 100 kg CO_2e/ton. Because the Türkiye, European, and U.S. sector-level estimates represent broader and non-equivalent production boundaries,

their normalized values are interpreted as contextual indicators rather than direct rankings of plant performance.

The integrated comparison illustrates the interaction between electricity consumption and grid carbon intensity. The anonymized plant combines relatively low electricity intensity with a comparatively high electricity-grid emission factor. In contrast, the product-matched European scenario has somewhat higher electricity consumption per ton but benefits from a substantially lower grid emission factor. Consequently, the plant's low electricity intensity does not translate into the lowest electricity-related CO_2e emission intensity when the carbon intensity of electricity generation is considered. This illustrates the complementary roles of production-side electricity efficiency and electricity-grid decarbonization in determining electricity-related CO_2e emissions.

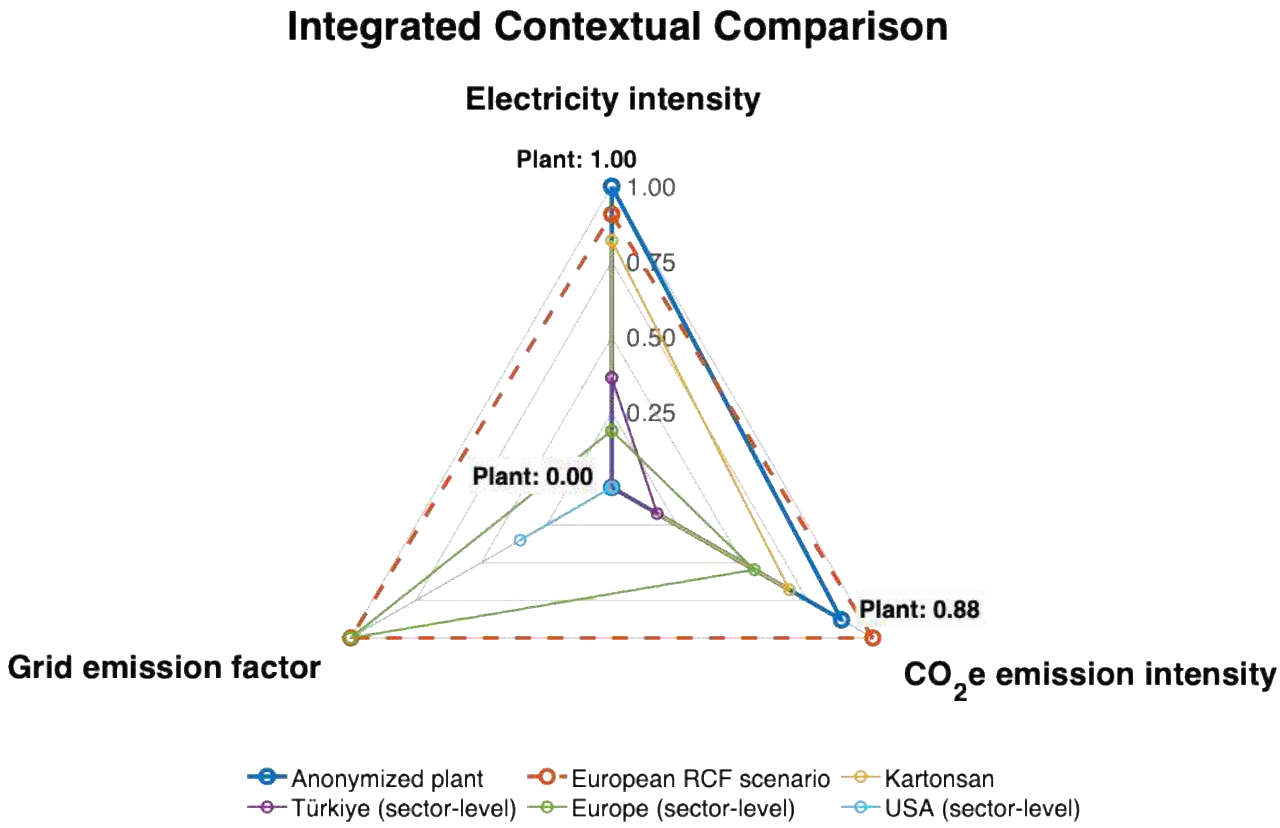


Figure 5. Normalized contextual comparison of electricity intensity, electricity-related CO_2e emission intensity, and grid emission factor for the anonymized paper plant and selected reference values. Inverted min–max normalization was used, with higher scores representing lower values for each indicator. The midpoint of the European RCF packaging-paper electricity-intensity range (400 kWh/ton) was used for visualization only. Sector-level estimates are presented for contextual comparison and should not be interpreted as direct plant-performance rankings.

Decomposition of CO_2e Intensity Differences

To further examine the factors underlying differences in electricity-related CO_2e emission intensity, a decomposition analysis was performed, as shown in Figure 6. For the product-matched European comparison (Figure 6a), the indicative electricity-intensity range of 350–450 kWh/ton for RCF mills without deinking producing packaging paper was combined with the European grid emission factor of 0.251 kg CO_2e/kWh. Relative to this reference range, the higher Turkish grid emission factor of 0.442 kg CO_2e/kWh produced a positive grid effect of approximately +67 to +86 kg CO_2e/ton. In contrast, the lower electricity intensity of the anonymized plant (320 kWh/ton) produced an electricity-intensity effect corresponding to an emission reduction of approximately 13 to 57 kg CO_2e/ton. The resulting net difference was approximately +29 to +54 kg CO_2e/ton, consistent with the higher electricity-related CO_2e emission intensity of the anonymized plant (141 kg CO_2e/ton) relative to the illustrative product-matched European-grid scenario (approximately 88–113 kg CO_2e/ton). Thus, although the anonymized plant has lower electricity consumption per ton than the product-matched European reference range, this advantage is more than offset by the higher carbon intensity of the Turkish electricity grid.

In the comparison with the estimated Türkiye sector-level reference (Figure 6b), the grid effect is zero because the same national grid emission factor (0.442 kg CO_2e/kWh) is applied to both systems. The difference therefore arises entirely from electricity intensity. Reducing electricity intensity from approximately 867 kWh/ton for the estimated Türkiye sector-level reference to 320 kWh/ton for the anonymized plant corresponds to an electricity-intensity effect of approximately −242 kg CO_2e/ton. This is consistent with the difference between their estimated electricity-related CO_2e emission intensities (383 and 141 kg CO_2e/ton, respectively). Within this national sector-level comparison, the lower electricity intensity of the anonymized plant is therefore the sole contributor to the estimated difference in electricity-related CO_2e emissions.

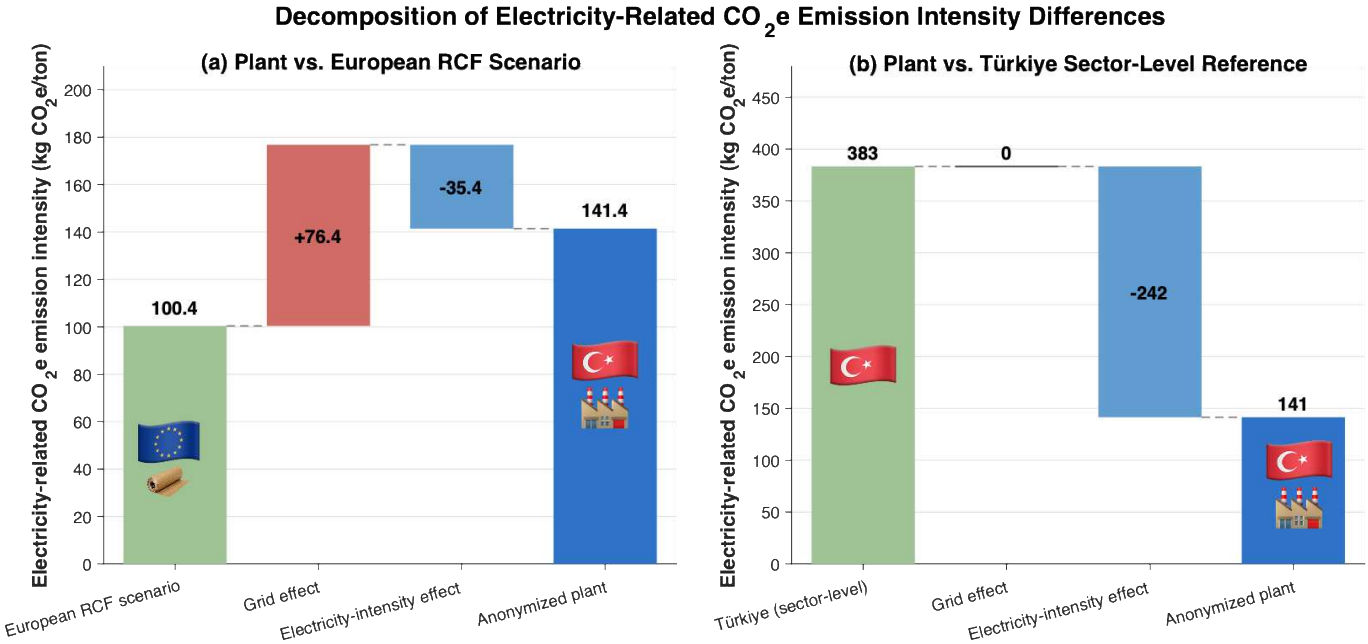


Figure 6. Decomposition of electricity-related CO_2e emission-intensity differences between the anonymized paper plant and (a) an illustrative product-matched European RCF packaging-paper scenario and (b) the estimated Türkiye sector-level reference. For Figure 6a, the midpoint of the reported European RCF electricity-intensity range (400 kWh/ton) was used for visualization only. The grid effect represents

the contribution of differences in electricity-grid emission factors, while the electricity-intensity effect represents the contribution of differences in electricity consumption per ton of paper produced. Positive values indicate an increase in CO_2e emission intensity, whereas negative values indicate a reduction.

Relationship Between Electricity Intensity and CO_2e Emissions

The relationship between electricity intensity and electricity-related CO_2e emission intensity across the selected reference values is illustrated in Figure 7. The anonymized plant is positioned at a relatively low electricity-intensity value (320 kWh/ton), below the product-matched European RCF packaging-paper reference range of 350–450 kWh/ton. However, when the European grid emission factor is applied to this product-matched range, the corresponding illustrative CO_2e emission intensity is approximately 88–113 kg CO_2e/ton, which is lower than the plant value of approximately 141 kg CO_2e/ton. This demonstrates that lower electricity consumption per ton does not necessarily lead to the lowest electricity-related CO_2e emission intensity when electricity-grid carbon intensity differs substantially.

The broader sector-level values for Türkiye, Europe, and the United States show the same general interaction between electricity consumption and grid emission factors but are interpreted primarily as contextual references because they represent different product mixes and statistical boundaries. Overall, Figure 7 illustrates that electricity-related CO_2e emissions are jointly determined by production electricity intensity and the carbon intensity of the electricity supply.

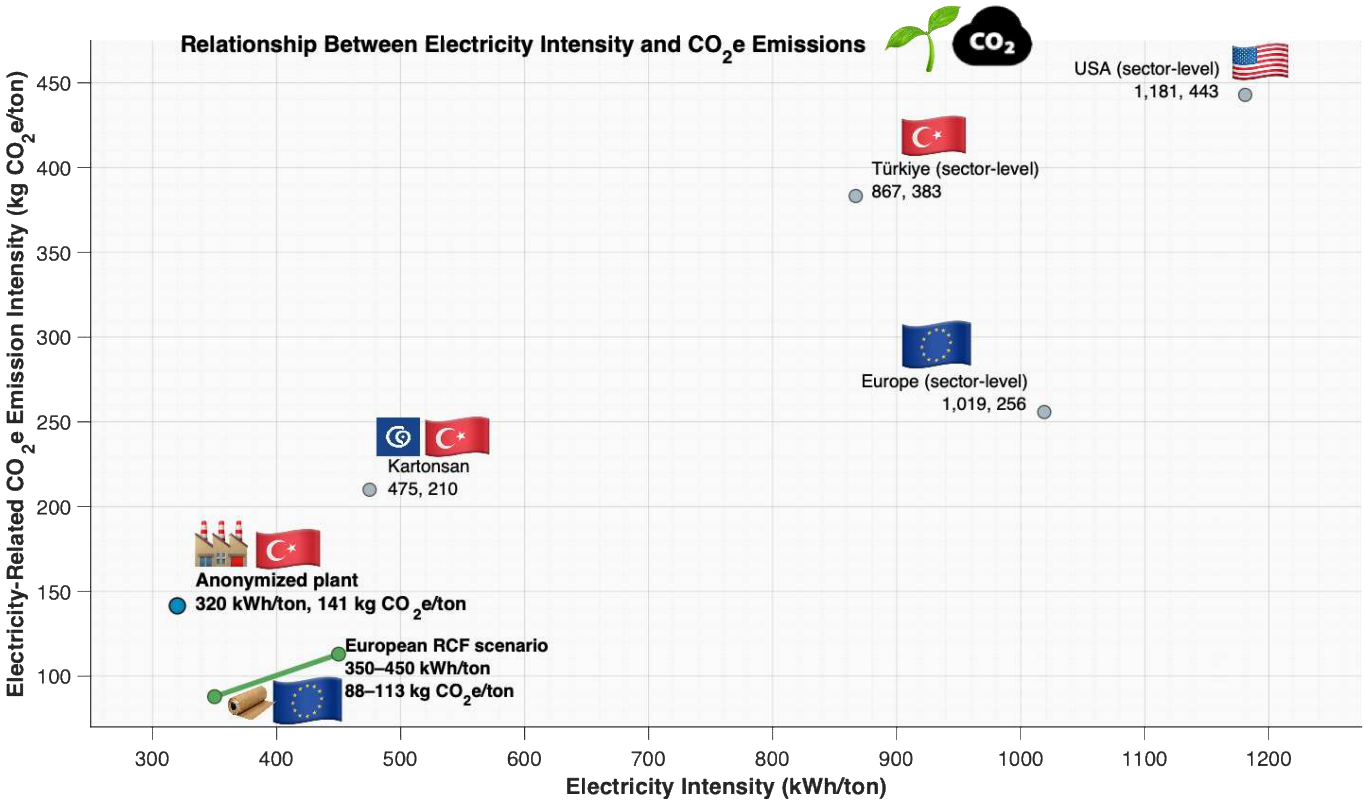


Figure 7. Relationship between electricity intensity and electricity-related CO_2e emission intensity for the anonymized paper plant, the product-matched European RCF packaging-paper scenario, and selected industrial and sector-level reference values. The European RCF scenario illustrates the effect of combining the product-matched electricity-intensity range with the European grid emission factor, while the Türkiye, European, and U.S. sector-level values are presented for contextual comparison.

DISCUSSION

The present study provides an integrated assessment of the electricity-related and process performance of an anonymized paper-production facility in Türkiye. The analyzed plant exhibited an electricity intensity of 320 kWh/ton. The most directly comparable reference identified in this study was the indicative electricity-consumption range of 350–450 kWh/ton reported for recycled-fibre (RCF) mills without deinking producing packaging paper, including Testliner and corrugated medium (Suhr et al. 2015). The electricity intensity of the analyzed plant was approximately 8.6% below the lower boundary and 28.9% below the upper boundary of this product-matched reference range, indicating comparatively low electricity consumption for this production route and product category. The plant also exhibited lower electricity intensity than Kartonsan (475 kWh/ton). Broader sector-level estimates for Türkiye (approximately 867 kWh/ton), Europe (approximately 1,019 kWh/ton), and the United States (approximately 1,181 kWh/ton) were substantially higher; however, these values represent broader product mixes, mill configurations, and statistical boundaries and should therefore be interpreted as contextual sector-level references rather than directly product-matched benchmarks. Considerable variation in energy and electricity consumption among paper mills has previously been attributed to differences in product grade, process configuration, equipment efficiency, production scale, and operational practices (Farla et al. 1997; Laurijssen et al. 2012; Kong et al. 2016).

The relationship between electricity intensity and electricity-related CO_2e emissions provides an important additional finding. The anonymized plant had an estimated electricity-related emission intensity of 141 kg CO_2e/ton. For the product-matched European comparison, combining the indicative electricity-intensity range of 350–450 kWh/ton with the European grid emission factor of 0.251 kg CO_2e/kWh yields an illustrative electricity-related CO_2e emission-intensity range of approximately 88–113 kg CO_2e/ton. Thus, although the analyzed plant consumed less electricity per ton than the product-matched European reference range, its electricity-related CO_2e emission intensity was higher than the corresponding European-grid scenario. This difference results from the substantially higher grid emission factor applied for Türkiye (0.442 kg CO_2e/kWh) relative to Europe (0.251 kg CO_2e/kWh). The comparison demonstrates that improvements in plant-level electricity efficiency do not necessarily translate directly into lower electricity-related CO_2e emissions when the carbon intensity of electricity generation differs substantially. Energy consumption has been identified as an important contributor to the environmental burden of pulp and paper production, while both energy-efficiency improvements and lower-carbon energy supply can contribute to emission reduction (Worrell et al. 2009; Sun et al. 2018).

The decomposition analysis further clarified this interaction. Across the product-matched European electricity-intensity range of 350–450 kWh/ton, the higher Turkish grid emission factor contributed approximately +67 to +86 kg CO_2e/ton, whereas the lower electricity intensity of the analyzed plant reduced emissions by approximately 13 to 57 kg CO_2e/ton relative to the corresponding reference values. The resulting net difference was approximately +29 to +54 kg CO_2e/ton. Therefore, the electricity-efficiency advantage of the analyzed plant partially offset, but did not fully overcome, the disadvantage associated with the more carbon-intensive Turkish electricity grid. In the comparison with the estimated Türkiye sector-level reference, the grid effect was zero because the same national emission factor was applied to both systems; consequently, the approximately 242 kg CO_2e/ton difference was entirely associated with lower electricity intensity. These findings illustrate the complementary importance of plant-level electricity efficiency and electricity-supply decarbonization in reducing electricity-related industrial emissions.

The process indicators provide additional context beyond electricity performance. Recycled pulp accounted for approximately 85% of the plant's pulp input, indicating substantial utilization of secondary fiber resources. Recovered fiber plays an important role in circular material use in the paper sector, although its overall environmental benefit depends on collection, processing, energy requirements, and the alternative treatment of recovered paper (Villanueva and Wenzel 2007). The plant generated approximately 1,400

ton/day of steam, of which 900 ton/day was utilized, corresponding to a steam-utilization ratio of 64.3%. The remaining 35.7% indicates a potentially important stream for further investigation, although it should not automatically be interpreted as an energy loss because the available dataset does not establish whether this steam is recovered, exported, condensed, or otherwise utilized. Similarly, wastewater generation was approximately 0.104 ton per ton of paper produced. Water and wastewater management are important components of pulp and paper manufacturing, and opportunities for recirculation and recovery depend strongly on the specific production process and required water quality (Pokhrel and Viraraghavan 2004; Hubbe et al. 2016).

Several limitations should be considered when interpreting these results. Most importantly, the analysis focuses on electricity consumption and associated electricity-related CO_2e emissions rather than total plant energy consumption or a complete carbon footprint. Thermal energy inputs, including steam generated from fuels, as well as direct fuel combustion emissions, upstream emissions, transportation, raw-material production, and other life-cycle contributions are outside the present system boundary. Although the European RCF packaging-paper reference provides a more directly comparable electricity-intensity benchmark, differences in individual mill configuration and operating conditions may still affect comparability. In addition, the Türkiye electricity-intensity reference was estimated by combining sectoral electricity-consumption and paper-production statistics with different statistical boundaries and should consequently be regarded as an approximate sector-level reference rather than an official national benchmark. The aggregate European and U.S. values are similarly affected by differences in product mix, mill integration, technologies, and reporting methodologies and are therefore used primarily to provide broader sectoral context. Overall, the results indicate that the analyzed plant combines comparatively low electricity consumption with a relatively carbon-intensive electricity supply. Further reductions in electricity-related CO_2e emissions could therefore be achieved not only through continued plant-level efficiency improvements but also through lower-carbon electricity supply, while more detailed energy and material-flow measurements would enable future studies to extend the assessment to total energy use and life-cycle environmental performance.

CONCLUSION

This study evaluated the electricity-related and process performance of an anonymized paper-production facility in Türkiye using an integrated benchmarking and decomposition framework. The analyzed plant exhibited an electricity intensity of 320 kWh/ton, which was below the product-matched European RCF packaging-paper reference range of 350–450 kWh/ton. The plant also exhibited lower electricity intensity than Kartonsan, while the substantially higher aggregate values estimated for Türkiye, Europe, and the United States were retained as broader sector-level contextual references rather than directly product-matched benchmarks.

Despite its comparatively low electricity intensity, the plant's electricity-related CO_2e emission intensity of approximately 141 kg CO_2e/ton was higher than the illustrative product-matched European-grid scenario of approximately 88–113 kg CO_2e/ton. The decomposition analysis showed that the electricity-efficiency advantage of the plant reduced emissions relative to the product-matched European reference, but this benefit was more than offset by the higher carbon intensity of the Turkish electricity grid. In the comparison with the estimated Türkiye sector-level reference, where the same grid emission factor was applied to both systems, the difference in electricity-related CO_2e intensity was entirely attributable to electricity intensity. These findings demonstrate the importance of considering plant-level electricity efficiency and electricity-grid carbon intensity together when evaluating electricity-related industrial emissions.

Process-level indicators further showed an 85% recycled-pulp ratio and a 64.3% steam-utilization ratio, providing additional information on resource utilization within the facility. Overall, the results demonstrate that benchmarking combined with decomposition analysis can provide a practical framework for distinguishing the effects of electricity consumption and electricity-supply carbon intensity. Future studies incorporating direct fuel consumption, detailed steam and heat balances, renewable-energy contributions, and life-cycle emissions could extend the present framework toward a more comprehensive assessment of the overall energy and environmental performance of paper-production systems.

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Competing interests

The authors have no relevant financial or non-financial interests to disclose.

Author contributions

Ahmet Muharrem Gorunmez: Data acquisition, preliminary data analysis, and preparation of the initial manuscript draft. Esma Cetinkaya: Conceptualization, methodology, formal analysis, investigation, benchmarking framework, comparative data collection and curation, MATLAB analysis, visualization, interpretation of results, writing—original draft, and writing—review and editing. Esma Cetinkaya substantially revised and restructured the initial draft and prepared the final version of the manuscript. Both authors reviewed and approved the final manuscript.

Data availability

The industrial data analyzed in this study are not publicly available due to confidentiality restrictions associated with the anonymized industrial facility. Aggregated data supporting the findings are provided within the manuscript.