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Grid-Aware Industrial Decarbonization: A Techno-Economic Assessment of Electrification, Hydrogen, and Carbon Capture Pathways for Energy-Intensive Industries

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Abstract

The decarbonization of energy-intensive continuous process industries remains a major challenge due to the simultaneous dependence on high-temperature thermal energy, continuous operation requirements, and increasing pressure to meet net-zero emission targets. While electrification, hydrogen utilization, renewable energy integration, and carbon capture technologies have been extensively investigated, most existing studies evaluate these solutions under static electricity-grid assumptions. However, the carbon intensity of electricity systems is changing rapidly, fundamentally altering the long-term effectiveness of industrial electrification pathways. This approach may lead to suboptimal investment decisions as the carbon intensity of electricity systems is rapidly decreasing in many countries. This study proposes an integrated techno-economic framework for evaluating industrial decarbonization pathways under a transitioning power grid. An anonymized industrial case representing a large-scale energy-intensive continuous manufacturing facility was analyzed using real operational data, energy performance indicators, and technology deployment scenarios. The assessment includes operational optimization measures, process electrification, photovoltaic-supported electricity supply, hydrogen fuel substitution, oxy-fuel combustion, and carbon capture technologies. For each scenario, carbon emission reduction potential, capital expenditure (CAPEX), operational expenditure (OPEX), and marginal carbon abatement cost were evaluated and compared. The results indicate that electrification-based solutions provide one of the most cost-effective early-stage decarbonization pathways, achieving greenhouse-gas emission reductions ranging from 51.2% under current grid conditions to 58.8% under the 2035 grid decarbonization scenario. Hydrogen scenarios demonstrate substantial technical potential but exhibit considerably higher carbon avoidance costs. Carbon capture technologies become increasingly important in deep-decarbonization stages where residual process emissions cannot be eliminated through fuel switching or electrification alone. Furthermore, the study shows that the effectiveness of electrification increases as the electricity grid becomes progressively decarbonized, highlighting the critical interaction between industrial transition strategies and national energy-system evolution. The findings demonstrate that cost-optimal industrial decarbonization cannot be achieved through a single technology pathway. Instead, a phased strategy combining operational excellence, electrification, renewable energy integration, alternative fuels, and carbon capture provides the most practical route toward net-zero

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emissions. The proposed framework offers a replicable decision-support methodology for energy-intensive continuous process industries seeking economically viable decarbonization roadmaps. A key finding is that industrial electrification should be assessed under future electricity-grid conditions rather than current grid-carbon-intensity assumptions. Consequently, decarbonization decisions become increasingly dependent on the evolution of the power system supplying industrial electricity.

Keywords: industrial decarbonization; electrification; hydrogen; carbon capture; renewable energy integration; carbon abatement cost; continuous process industries; techno-economic assessment

1. Introduction

1.1. Industrial Decarbonization Challenges and Literature Review

The industrial sector is responsible for a significant share of global energy consumption and greenhouse-gas (GHG) emissions, making it one of the most challenging sectors to decarbonize in the transition toward net-zero economies. Energy-intensive industries, including glass, cement, steel, ceramics, and chemicals, rely heavily on high-temperature thermal processes that require continuous operation and large quantities of energy. Unlike many other sectors, industrial emissions originate not only from energy consumption but also from process-related sources, further increasing the complexity of decarbonization efforts.

In recent years, governments and international organizations have introduced increasingly ambitious climate policies aiming to reduce industrial emissions and accelerate the transition toward low-carbon manufacturing systems. The implementation of carbon pricing mechanisms, emissions trading systems, carbon border adjustment mechanisms, and national net-zero commitments has significantly increased the pressure on industrial facilities to adopt effective decarbonization strategies. Consequently, identifying technically feasible and economically viable pathways for deep emission reduction has become a strategic priority for both industries and policymakers.

Several technological pathways have been proposed to reduce industrial greenhouse-gas emissions. Energy-efficiency improvements continue to be recognized as the first and most cost-effective step in industrial decarbonization. Process optimization, waste heat recovery, combustion control, digital energy-management systems, and advanced monitoring platforms can provide substantial reductions in fuel consumption while requiring relatively modest investments. However, the potential of efficiency measures alone is limited and generally insufficient to achieve long-term net-zero targets.

Industrial electrification has therefore emerged as one of the most promising decarbonization strategies. Electrification can reduce direct fossil-fuel consumption by replacing combustion-based heating systems with electrically driven technologies or by introducing electric boosting into existing thermal processes. In high-temperature industries, hybrid electric-fuel configurations have attracted increasing attention due to their ability to achieve significant emission reductions while maintaining operational flexibility and product quality. Recent technological developments in electric melting, electric boosting, heat pumps, and power-electronics systems have further strengthened the role of electrification in industrial transition pathways.

Hydrogen-based fuels represent another major area of interest. Green hydrogen produced from renewable electricity has been widely promoted as a potential substitute for fossil fuels in applications requiring high-temperature heat. Similarly, oxy-fuel combustion systems have been proposed to improve thermal efficiency and facilitate carbon capture by

increasing the concentration of carbon dioxide in the flue gas. In parallel, carbon capture, utilization, and storage (CCUS) technologies are increasingly considered essential for eliminating residual emissions that cannot be economically reduced through electrification or fuel switching alone.

Although these technologies have demonstrated varying degrees of technical maturity and decarbonization potential, the majority of existing studies evaluate them individually. Electrification, hydrogen utilization, carbon capture, renewable energy integration, and process efficiency improvements are frequently assessed as separate technological options. This fragmented approach provides limited support for industrial decision-making because real-world decarbonization strategies are typically implemented through combinations of multiple technologies rather than through a single solution.

An additional limitation of current industrial decarbonization literature is the widespread assumption of a static electricity system. The effectiveness of industrial electrification depends directly on the carbon intensity of the power grid supplying the electricity. However, electricity systems are undergoing rapid structural transformation worldwide due to large-scale deployment of renewable energy sources such as solar photovoltaic and wind power. As electricity generation becomes progressively decarbonized, the environmental benefits of electrification increase correspondingly. Consequently, decarbonization strategies that may appear marginally beneficial under present grid conditions can become substantially more effective under future electricity-system configurations. This limitation creates a systematic bias in investment evaluation because technologies that rely on electricity may appear less attractive under present grid conditions than they will be under future low-carbon electricity systems. As a result, the long-term value of electrification may be underestimated.

The issue is particularly relevant for Türkiye, where the National Energy Plan foresees a substantial transformation of the electricity sector by 2035. According to official projections, renewable energy sources are expected to account for 54.8% of electricity generation and 64.7% of installed electricity capacity by 2035, supported by significant expansion of solar and wind generation capacities. Such structural changes are expected to reduce the carbon intensity of grid electricity and consequently enhance the environmental benefits of industrial electrification pathways over time. Therefore, industrial decarbonization strategies should be evaluated in conjunction with the projected evolution of the national electricity system rather than under static grid assumptions [1].

Recent national energy balance statistics indicate a rapid transformation of the Turkish electricity sector. Total electricity generation increased from approximately 328 TWh in 2022 to more than 354 TWh in 2024, while installed solar capacity expanded from approximately 9.4 GW to over 20 GW during the same period. These developments are expected to progressively reduce the carbon intensity of electricity generation and increase the effectiveness of industrial electrification measures over time. Consequently, industrial decarbonization strategies should be evaluated under dynamic electricity-grid conditions rather than assuming constant grid carbon intensity.

Furthermore, many published analyses rely on theoretical assumptions, simplified process representations, or generic industrial datasets. Comparatively fewer studies combine real operational data, process-performance indicators, energy consumption characteristics, investment requirements, operating expenditures, and carbon-abatement metrics within a unified assessment framework. This gap limits the practical applicability of existing research and creates uncertainty regarding the prioritization of competing decarbonization investments.

Against this background, the present study investigates cost-optimal decarbonization pathways for energy-intensive continuous process industries under a progressively decarbonizing power grid. The research is based on an anonymized large-scale industrial

case study derived from actual operational data and evaluates multiple decarbonization scenarios including operational optimization, electrification, renewable electricity integration, hydrogen utilization, oxy-fuel combustion, and carbon capture technologies. The study aims to determine not only the emission-reduction potential of individual technologies but also their economic performance and marginal carbon-abatement costs. By explicitly incorporating electricity-grid evolution into the assessment framework, the study seeks to provide a more realistic and decision-oriented perspective on industrial decarbonization planning.

The research gaps addressed and the specific contributions of this study are presented in the following section.

1.2. Literature Gaps

Although significant progress has been made in the development of industrial decarbonization technologies, several important research gaps remain.

Most industrial decarbonization studies evaluate electrification under static grid-carbon-intensity assumptions, despite the rapid decarbonization of electricity systems.

First, most studies investigate individual decarbonization technologies separately. Electrification, hydrogen substitution, renewable energy integration, oxy-fuel combustion, and carbon capture systems are typically assessed as standalone solutions [2–4]. However, industrial decarbonization is inherently a system-level challenge requiring the simultaneous evaluation of multiple interacting technologies. As a result, the comparative effectiveness and economic performance of integrated technology portfolios remain insufficiently understood [5].

Second, most current studies evaluate industrial decarbonization under static electricity-grid assumptions [2]. This approach neglects the ongoing transformation of electricity systems driven by the large-scale deployment of renewable energy technologies [6,7]. Since the carbon intensity of electricity directly affects the environmental performance of industrial electrification, decarbonization pathways assessed under current grid conditions may not accurately represent their future performance.

Third, limited attention has been given to the interaction between operational improvements and capital-intensive decarbonization technologies. Operational excellence measures such as combustion optimization, excess-air reduction, advanced monitoring systems, and process control strategies are often treated independently from electrification, hydrogen, or carbon-capture solutions [5,8]. Consequently, the role of low-cost operational measures as enabling technologies for deeper decarbonization remains underexplored.

Fourth, many published studies rely on theoretical assumptions or generic industrial datasets. Comparatively few investigations employ real industrial operating data that simultaneously incorporates process performance, energy consumption, emissions, investment requirements, and operating costs. This limitation reduces the practical applicability of existing research and creates uncertainty in investment prioritization.

Finally, relatively few studies evaluate industrial decarbonization strategies using a carbon-abatement-cost perspective. While emission-reduction potentials are widely reported, decision-makers ultimately require information regarding the economic efficiency of competing technologies, particularly under increasing carbon-pricing mechanisms and carbon-border adjustment regulations [9–11]. Carbon-abatement-cost methodologies have been widely applied in energy-policy analysis; however, their application to integrated industrial decarbonization pathways remains limited.

The need for integrated assessment frameworks is further reinforced by recent national policy documents. Türkiye's National Energy Plan, Energy Efficiency Strategy 2030, and the Ministry of Energy and Natural Resources Strategic Plan all emphasize simultaneous progress in renewable energy deployment, industrial energy efficiency, electrification,

hydrogen development, grid flexibility, and low-carbon technologies. Nevertheless, few studies have assessed these transition pathways within a single techno-economic framework that explicitly considers the interaction between industrial transformation and electricity-grid decarbonization.

These limitations indicate the need for an integrated, techno-economic, and grid-aware assessment framework capable of supporting practical industrial decarbonization decisions. The identified literature gaps and corresponding contributions of the present study are summarized in Table 1.

Table 1. Literature gaps and contributions of the present study.

Research Area	Common Approach in Literature	Limitation	Contribution of This Study
Electrification	Evaluated independently	Ignores future grid evolution	Evaluates electrification under decarbonizing grid scenarios
Hydrogen	Focus on technical feasibility	Limited economic comparison	Includes techno-economic assessment and MACC analysis
Carbon Capture	Analyzed as stand-alone technology	Limited system integration	Evaluates CCUS within integrated roadmap
Renewable Energy	Often disconnected from process transformation	Scope-1 emissions not fully addressed	Links renewable energy with industrial process electrification
Industrial Decarbonization	Technology-specific studies	Lack of integrated assessment	Simultaneous evaluation of all major pathways
Economic Assessment	CAPEX and OPEX often reported separately	Limited investment prioritization	Uses Marginal Carbon Abatement Cost framework
Electrification Assessment	Current grid emission factor	Static evaluation	Grid-aware assessment under future power-system scenarios

1.3. Research Objectives

The objective of this study is to develop and apply an integrated techno-economic framework for evaluating cost-optimal decarbonization pathways in energy-intensive continuous process industries operating under a progressively decarbonizing electricity grid. The proposed framework is aligned with Türkiye's long-term net-zero transition objectives, including renewable-energy expansion, industrial energy-efficiency improvements, electrification, hydrogen deployment, and low-carbon industrial transformation targets outlined in national policy documents [6,7].

More specifically, the study aims to:

1. Establish a baseline assessment of industrial energy consumption and greenhouse-gas emissions.
2. Quantify the emission-reduction potential of operational optimization, electrification, renewable electricity integration, hydrogen utilization, oxy-fuel combustion, and carbon capture technologies.
3. Evaluate the influence of electricity-grid decarbonization on the environmental performance of industrial electrification pathways.
4. Compare alternative decarbonization scenarios using technical, environmental, and economic performance indicators.
5. Determine marginal carbon abatement costs for competing technologies and identify cost-optimal transition pathways.

6. Develop a phased roadmap supporting long-term net-zero transformation in energy-intensive continuous process industries.

1.4. Novelty and Contributions of the Study

To address the identified research gaps, this study proposes a comprehensive assessment framework integrating process performance, energy systems, decarbonization technologies, and electricity-grid evolution within a single analytical platform, addressing major limitations identified in previous industrial decarbonization studies [2,4].

The main contributions of this work are summarized as follows:

Contribution 1

An integrated industrial decarbonization framework is developed that simultaneously evaluates the following:

- Operational optimization;
- Process electrification;
- Renewable electricity integration;
- Hydrogen utilization;
- Oxy-fuel combustion;
- Carbon capture technologies.

Unlike most previous studies, all technology options are assessed using consistent technical, environmental, and economic metrics.

Contribution 2

A grid-aware industrial decarbonization framework is introduced, explicitly incorporating future electricity-grid evolution into the evaluation of electrification pathways. The results demonstrate that electrification performance is dynamic rather than static and depends on the projected carbon intensity of future electricity systems [2,6].

Contribution 3

A realistic techno-economic evaluation is performed using real operational data derived from an anonymized large-scale continuous process manufacturing facility.

This approach enables a more representative assessment of industrial decarbonization pathways than studies based solely on theoretical assumptions.

Contribution 4

Marginal Carbon Abatement Costs (MACC) are calculated for all investigated scenarios [9,10].

This allows direct comparison of competing technologies based on both of the following:

- Emission reduction potential;
- Economic efficiency.

Consequently, investment decisions can be evaluated using EUR/tCO_2 avoided rather than technology attractiveness alone.

Contribution 5

A phased and cost-optimal decarbonization roadmap is proposed, demonstrating that net-zero industrial transformation is most effectively achieved through a sequential transition from operational excellence and electrification toward alternative fuels and carbon capture technologies.

In this study, a grid-aware decarbonization approach refers to the explicit consideration of future electricity-grid carbon-intensity evolution when evaluating industrial decarbonization technologies and investment decisions.

1.5. Research Hypotheses

The proposed hypotheses and validation metrics are presented in Table 2.

Table 2. Research hypotheses and validation metrics.

Hypothesis	Description	Validation Metric
H1	Operational optimization and electrification provide the lowest early-stage decarbonization costs	MACC comparison
H2	Electrification becomes more effective as the grid decarbonizes	Emission reduction under G1–G4 grid scenarios
H3	Hydrogen pathways have higher abatement costs than electrification	EUR/tCO_2 avoided
H4	Net-zero transformation requires multiple technologies rather than a single solution	Integrated roadmap performance

Based on the literature review and identified research gaps, the following hypotheses are proposed:

H1. *Operational optimization and electrification provide the lowest carbon-abatement costs during the early stages of industrial decarbonization.*

H2. *The carbon-reduction effectiveness of industrial electrification increases as the electricity grid becomes progressively decarbonized* [6,7].

H3. *Hydrogen-based pathways offer substantial emission-reduction potential but are associated with significantly higher carbon-abatement costs than electrification-based solutions* [7,12,13].

H4. *Net-zero industrial transformation cannot be achieved through a single technology and requires the integration of operational improvements, electrification, renewable energy, alternative fuels, and carbon capture technologies* [6].

Although the detailed quantitative assessment was based on one anonymized facility, comparable trends were observed across multiple industrial sites operated in different regions of Türkiye. Due to confidentiality constraints, these additional datasets are not reported in detail [14,15].

2. Methodology

This study develops an integrated techno-economic assessment framework to evaluate alternative decarbonization pathways for energy-intensive continuous process industries operating under a progressively decarbonizing electricity grid. The methodological approach combines industrial operational data, energy performance analysis, greenhouse-gas emissions accounting, electricity-grid evolution scenarios, and economic evaluation metrics within a unified assessment platform.

The overall methodology consists of seven sequential stages: industrial operational data collection, baseline assessment, greenhouse-gas inventory development, grid decarbonization scenario construction, technology pathway modeling, techno-economic assessment including MACC analysis, and development of the cost-optimal decarbonization roadmap. The methodological framework is illustrated in Figure 1.

As illustrated in Figure 1, the proposed methodology consists of seven sequential stages, beginning with industrial operational data collection and baseline assessment, followed by electricity-grid decarbonization scenarios, technology pathway evaluation, techno-economic assessment, MACC analysis, and finally, the development of a cost-optimal industrial decarbonization roadmap.

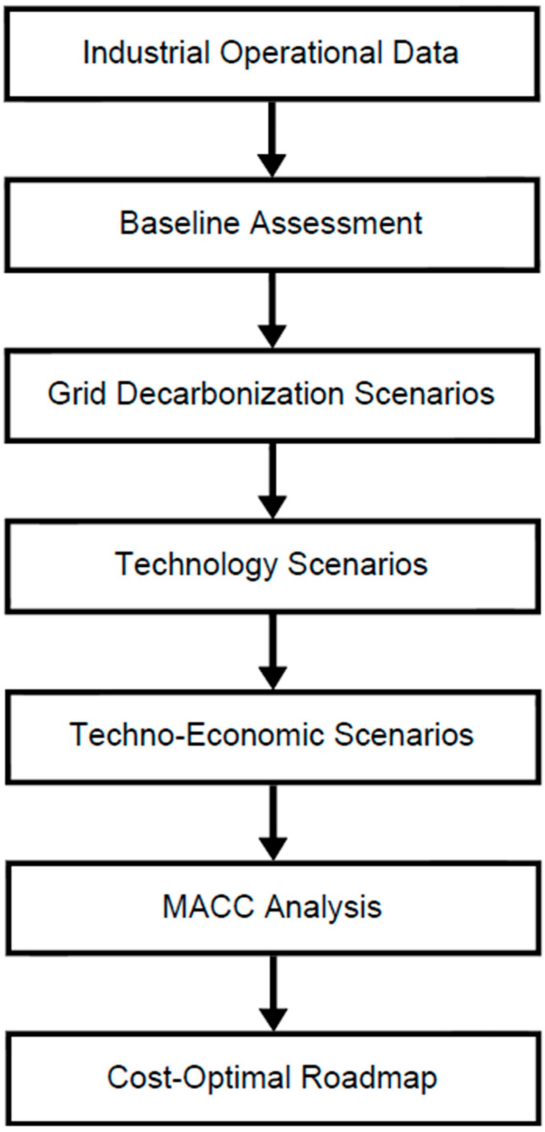


Figure 1. Overall methodological framework adopted for the evaluation of industrial decarbonization pathways.

Overall methodological framework of the study.

Industrial operational data → Energy and emissions baseline → Grid decarbonization scenarios → Decarbonization technology scenarios → Techno-economic assessment → Cost-optimal roadmap.

2.1. Baseline Industrial System Assessment

An anonymized large-scale energy-intensive continuous process manufacturing facility was selected as the reference case. The facility represents a typical high-temperature industrial operation characterized by the following:

- Continuous 24/7 production;
- High thermal energy demand;
- Significant natural-gas consumption;
- Electricity-intensive auxiliary systems;
- Long production campaigns;
- Stringent product-quality requirements.

The baseline assessment included the following:

- Annual fuel consumption;
- Electricity consumption;
- Thermal energy demand;
- Specific energy consumption;
- Production rate;
- Operational performance indicators.

The collected data were used to establish the reference operating conditions against which all decarbonization scenarios were evaluated.

2.2. Greenhouse-Gas Emission Assessment

Greenhouse-gas emissions were calculated according to a Scope 1 and Scope 2 accounting framework.

2.2.1. Scope 1 Emissions

Scope 1 emissions include direct emissions resulting from on-site fuel combustion and process-related emissions.

Direct emissions were calculated as:

$$E_{S1} = \sum_{i} FC_i \times EF_i \quad (1)$$

where:

- E_{S1} = Scope 1 emissions (kg CO_2);
- FC_i = fuel consumption of fuel i;
- EF_i = emission factor of fuel i.

Process-related emissions associated with raw-material decomposition were incorporated where applicable.

2.2.2. Scope 2 Emissions

Scope 2 emissions were calculated from purchased electricity consumption:

$$E_{S2} = EC \times GEF \quad (2)$$

where:

- E_{S2} = Scope 2 emissions (kg CO_2);
- EC = electricity consumption (kWh);
- GEF = grid emission factor (kg CO_2/kWh).

The grid emission factor varied across different electricity-grid scenarios in order to account for future power-system decarbonization.

2.2.3. Total Emissions

Total emissions were calculated as:

$$E_{Total} = E_{S1} + E_{S2} \quad (3)$$

The baseline emissions served as the reference for all emission-reduction calculations.

2.3. Electricity-Grid Decarbonization Scenarios

A key feature of this study is the explicit incorporation of electricity-grid evolution into the decarbonization assessment. The grid scenarios were developed in accordance with the long-term projections presented in Türkiye's National Energy Plan, which foresees rapid

increases in solar, wind, storage, and hydrogen-production capacities through 2035. The projected increase in renewable-energy penetration provides the basis for evaluating how electrification performance evolves under progressively lower-carbon electricity systems.

Four different grid scenarios were defined:

For each scenario, the grid emission factor was adjusted according to the projected evolution of the following:

- Solar generation;
- Wind generation;
- Hydroelectric generation;
- Fossil-fuel generation;
- Overall renewable-energy penetration.

This approach allows quantification of the changing environmental effectiveness of electrification pathways over time.

As presented in Table 3, the environmental performance of industrial electrification improves as the electricity grid becomes progressively decarbonized. Under current grid conditions (G1), process electrification reduced total greenhouse-gas emissions by 51.2%. This value increased to 53.6%, 56.1%, and 58.8% under the G2, G3, and G4 scenarios, respectively. These findings confirm that the effectiveness of industrial electrification is strongly dependent on the carbon intensity of the electricity supply and therefore should be assessed using future grid conditions rather than static present-day assumptions.

Table 3. Electricity grid decarbonization scenarios.

Scenario	Target Year	Renewable Electricity Share (%)	Grid Emission Factor (kg CO_2/kWh)	Total GHG Emission Reduction (%)	Description	Basis
G1	2024	42	0.42	51.2	Current Grid Conditions	National Energy Balance
G2	2027	48	0.36	53.6	Near-Term Grid Transition	Renewable Capacity Expansion
G3	2030	55	0.30	56.1	Intermediate Decarbonization Scenario	National Energy Plan
G4	2035	65	0.23	58.8	Advanced Decarbonization Scenario	National Energy Plan

The electricity-grid emission factors summarized in Table 3 were derived from current national electricity-generation statistics and future electricity-sector projections presented in Türkiye's National Energy Plan [1]. As shown in Table 3, the grid emission factor decreases from 0.42 kg CO_2/kWh under current conditions (G1) to 0.23 kg CO_2/kWh under the long-term decarbonization scenario (G4). This reduction is driven by increasing renewable-electricity penetration, energy-storage deployment, and reduced dependence on fossil-fuel-based power generation [1,6,7]. Consequently, the decarbonization benefit of industrial electrification increases progressively as the national power system evolves toward a lower-carbon generation mix.

2.4. Decarbonization Technology Scenarios

Seven decarbonization pathways were evaluated.

S1—Operational Optimization

The first scenario considers low-capex operational improvements including the following:

- Combustion optimization;
- Excess-air reduction;
- Burner tuning;
- Process-control improvements;
- Digital monitoring systems;
- NO_x reduction measures.

The objective is to quantify the emission-reduction potential achievable through operational excellence before major capital investments. Scenario S1 is also consistent with the objectives of Türkiye's Energy Efficiency Strategy 2030 and the Second National Energy Efficiency Action Plan, which promote industrial energy-management systems, advanced monitoring infrastructure, digitalization, energy-consumption tracking, and reductions in specific energy consumption and carbon intensity across industrial facilities.

S2—Process Electrification

This scenario evaluates the introduction of electrical energy into the thermal process through electrification technologies.

The assessment includes the following:

- Electric boosting;
- Hybrid furnace operation;
- Increased electrical energy share.

Both energy performance and emission reductions are evaluated under different grid scenarios.

S3—Renewable Electricity Integration

This scenario combines process electrification with renewable electricity supply.

Alternative supply structures include the following:

- Photovoltaic systems;
- Power purchase agreements (PPAs);
- Renewable electricity contracts.

The objective is to minimize Scope 2 emissions associated with electrification.

S4—Hydrogen Utilization

Hydrogen substitution scenarios are evaluated by partially replacing natural gas with green hydrogen.

The assessment considers:

$$H_2\ blends \rightarrow Hybrid\ fuel\ operation$$

and examines both technical and economic performance.

Hydrogen production requirements, renewable electricity needs, and electrolyzer capacities are included in the analysis.

S5—Oxy-Fuel Combustion

The oxy-fuel scenario evaluates the replacement of air–fuel combustion with oxygen-based combustion systems.

The analysis considers the following:

- Thermal efficiency improvements;
- Fuel savings;
- Oxygen consumption;
- Emission reductions.

S6—Carbon Capture

Carbon capture technologies are introduced as deep-decarbonization options.

The scenario evaluates the following:

- Capture efficiency;
- Captured CO_2 quantity;
- Additional energy demand;
- Capital and operating expenditures.

S7—Integrated Decarbonization Pathway

The final scenario represents a phased decarbonization roadmap combining the following:

- Operational optimization;
- Electrification;
- Renewable electricity;
- Alternative fuels;
- Carbon capture.

This scenario is intended to represent a realistic net-zero transition pathway.

2.5. Techno-Economic Assessment

For each scenario, both technical and economic performance indicators were calculated.

2.5.1. Capital Expenditure (CAPEX)

The investigated decarbonization pathways were evaluated using an integrated techno-economic assessment framework combining investment requirements, operational expenditures, greenhouse-gas reduction potential, and marginal carbon abatement costs. The objective of the assessment was to identify not only the technical effectiveness of alternative decarbonization measures but also their economic viability under industrial operating conditions.

The economic evaluation was conducted using representative industrial-scale assumptions derived from recent industrial decarbonization studies and publicly available energy market data. A project lifetime of 20 years and a real discount rate of 8% were assumed throughout the analysis. Energy prices and carbon costs were selected to reflect current and near-term industrial market conditions.

Table 4 summarizes the principal economic assumptions used in the assessment.

The economic performance of each scenario was evaluated using four principal indicators: capital expenditure (CAPEX), operational expenditure (OPEX), carbon abatement potential, and marginal carbon abatement cost (MACC).

Capital expenditure represents the total investment required for the implementation of a specific decarbonization technology. CAPEX includes equipment procurement, engineering services, installation activities, infrastructure modifications, utility integration, auxiliary systems, and commissioning requirements.

The total capital expenditure was calculated as:

$$CAPEX = C_{equipment} + C_{installation} + C_{infrastructure} + C_{engineering} \quad (4)$$

where:

CAPEX = total capital expenditure (EUR);

$C_{equipment}$ = equipment procurement cost (EUR);

$C_{installation}$ = installation and commissioning cost (EUR);

$C_{infrastructure}$ = infrastructure modification and utility integration cost (EUR);

$C_{engineering}$ = engineering and project development cost (EUR).

For confidentiality reasons, detailed technology-specific investment values are not disclosed. Instead, technologies are compared using relative investment levels and carbon-abatement performance.

Table 4. Economic assumptions used in the techno-economic assessment.

Parameter	Value
Project Lifetime	20 years
Discount Rate	8%
Natural Gas Price	35 EUR/MWh
Industrial Electricity Price	90 EUR/MWh
Green Hydrogen Price	4.5 EUR/kg
Carbon Price	75 EUR/tCO_2
Annual Operation and Maintenance Cost	3% of CAPEX
Carbon Capture Cost	100 EUR/tCO_2 captured

2.5.2. Operational Expenditure (OPEX)

Operational expenditure includes all recurring annual costs associated with plant operation after implementation of the decarbonization measure.

$$OPEX = C_{fuel} + C_{electricity} + C_{maintenance} + C_{carbon} \quad (5)$$

where:

OPEX = annual operational expenditure (EUR/year);

C_{fuel} = annual fuel cost (EUR/year);

$C_{electricity}$ = annual electricity cost (EUR/year);

$C_{maintenance}$ = annual maintenance expenditure (EUR/year);

C_{carbon} = annual carbon-emission cost (EUR/year).

Changes in OPEX relative to baseline operation were calculated for each scenario to determine the long-term economic implications of the investigated technologies.

2.5.3. Carbon Abatement Potential

The environmental performance of each scenario was evaluated by comparing annual greenhouse-gas emissions against baseline plant operation.

$$ER = \frac{E_{baseline} - E_{scenario}}{E_{baseline}} \times 100 \quad (6)$$

where:

ER = greenhouse-gas emission reduction (%);

$E_{baseline}$ = baseline annual emissions (tCO_2/year);

$E_{scenario}$ = annual emissions after implementation of the considered scenario (tCO_2/year).

This indicator enables direct comparison of decarbonization pathways irrespective of facility size or production volume.

2.5.4. Marginal Carbon Abatement Cost

The Marginal Carbon Abatement Cost (MACC) was selected as the principal economic indicator for comparing alternative decarbonization pathways. MACC quantifies the cost required to avoid one tonne of carbon dioxide emissions and enables simultaneous assessment of economic efficiency and environmental benefit.

The MACC was calculated according to:

$$MACC = \frac{Annualized\ CAPEX + \Delta OPEX}{CO_{2,avoided}} \quad (7)$$

where:

MACC = marginal carbon abatement cost (EUR/tCO_2 avoided);

Annualized CAPEX = annualized investment expenditure (EUR/year);

ΔOPEX = change in annual operational expenditure relative to baseline operation (EUR/year);

$CO_{2,avoided}$ = annual avoided carbon dioxide emissions (tCO_2/year).

Lower MACC values indicate more economically attractive decarbonization pathways because they provide greater emission reductions per unit of invested capital. Consequently, MACC analysis allows direct ranking of alternative technologies according to both environmental effectiveness and economic performance.

The MACC methodology adopted in this study is consistent with approaches widely applied in industrial decarbonization and climate-policy assessments and has been extensively used to support technology prioritization and investment decision-making.

2.6. Development of the Cost-Optimal Decarbonization Roadmap

Finally, all scenarios were ranked according to the following:

1. Greenhouse-gas reduction potential;
2. CAPEX requirement;
3. OPEX impact;
4. Marginal carbon-abatement cost;
5. Implementation complexity;
6. Technology maturity.

A phased implementation roadmap was then developed to identify the most cost-effective transition pathway from the baseline state toward net-zero industrial operation.

3. Case Study Description and Baseline Assessment

3.1. Industrial Facility Description

The case study considered in this research represents a large-scale energy-intensive continuous process manufacturing facility operating under 24 h production conditions. To preserve industrial confidentiality, all company-specific information, plant identities, production locations, and commercially sensitive operational parameters have been anonymized.

The selected facility is characterized by the following:

- Continuous production operation;
- High-temperature thermal processing;
- Significant natural gas consumption;
- Electricity-intensive auxiliary systems;
- Long operating campaigns;
- Centralized energy management infrastructure.

The facility employs multiple thermal units supported by advanced energy-monitoring and process-control systems. Energy performance data, fuel consumption records, production statistics, and operational indicators were collected and consolidated to establish a representative baseline for the decarbonization assessment.

The industrial process requires stable thermal conditions and uninterrupted operation, making the facility representative of energy-intensive continuous process industries such as glass, ceramics, cement, chemicals, and similar manufacturing sectors.

3.2. Baseline Energy Consumption Structure

The first step of the assessment consisted of establishing the energy consumption profile of the facility.

The analysis revealed that thermal energy constitutes the dominant share of total energy demand. Natural gas is the primary energy source, while electricity is mainly used for the following:

- Process auxiliaries;
- Production equipment;
- Material handling systems;
- Cooling systems;
- Compressed-air systems;
- Digital infrastructure and monitoring systems.

Figure 2 presents the baseline energy distribution.

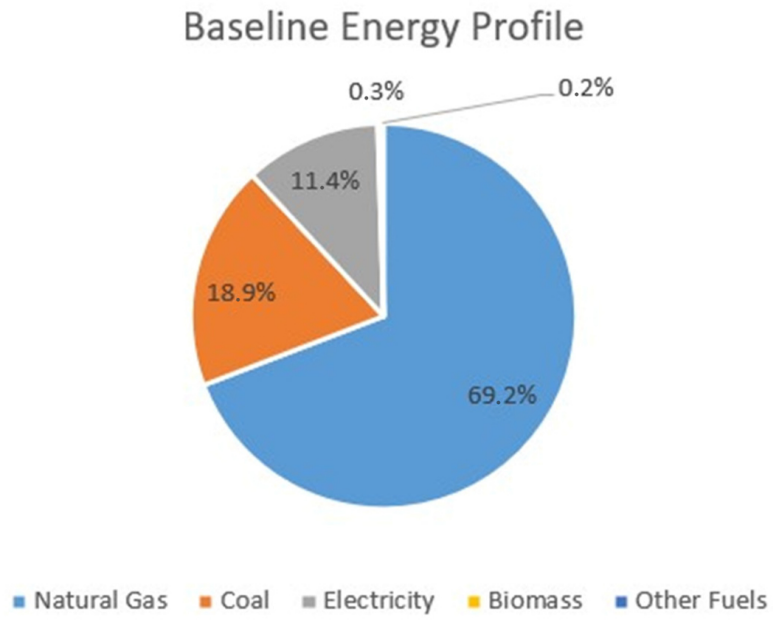


Figure 2. Baseline energy profile.

As illustrated in Figure 2, the baseline energy profile is dominated by fossil fuels, with natural gas representing approximately 69% of total energy demand, followed by coal (19%) and electricity (11%). This heavy dependence on carbon-intensive energy sources confirms that decarbonization of energy-intensive continuous process industries remains primarily a thermal decarbonization challenge. Therefore, meaningful progress toward net-zero operation will require the integration of electrification, renewable-energy deployment, alternative fuels, and carbon-capture technologies in addition to conventional energy-efficiency improvements.

The results indicate that fossil fuels account for the majority of total energy consumption, highlighting the importance of thermal-process decarbonization strategies alongside electricity-related measures.

3.3. Specific Energy Consumption Analysis

Specific energy consumption (SEC) was selected as a key performance indicator because it directly relates energy use to productive output.

The specific energy consumption was calculated as:

$$SEC = \frac{E_{total}}{P} \quad (8)$$

where:

- SEC = specific energy consumption;
- E_{total} = total annual energy consumption;
- P = annual production.

This indicator allows the comparison of different operational scenarios independently from production volume and serves as a benchmark for evaluating future decarbonization measures.

Historical operational data demonstrate that continuous process optimization and technology upgrades have already provided measurable improvements in energy efficiency over time. However, the remaining improvement potential from efficiency measures alone appears insufficient for achieving long-term net-zero targets, thereby necessitating additional decarbonization actions.

3.4. Baseline Greenhouse-Gas Emissions

The baseline greenhouse-gas inventory was established according to the methodology described in Section 2.

Total emissions were divided into:

Scope 1

Direct emissions:

- Fuel combustion;
- Thermal process emissions;
- Combustion-related CO_2 generation.

Scope 2

Indirect emissions:

- Purchased electricity consumption.

The results demonstrate that Scope 1 emissions dominate the overall carbon footprint due to the large thermal energy requirements of continuous high-temperature industrial processes.

Consequently, decarbonization strategies focusing exclusively on renewable electricity procurement are unlikely to achieve deep emission reductions unless accompanied by thermal-process transformation measures.

3.5. Decarbonization Levers Within the Baseline System

Before evaluating future scenarios, the major decarbonization opportunities within the baseline system were identified.

These opportunities were grouped into five categories:

Operational Improvements

- Combustion optimization;
- Excess-air reduction;
- Process control improvements;
- NOx reduction measures;
- Digital energy management.

Electrification

- Electric boosting;
- Hybrid thermal systems;
- Expanded electric process capacities.

Renewable Electricity Integration

- Photovoltaic generation;
- Power purchase agreements;
- Renewable electricity sourcing.

Alternative Fuels

- Hydrogen blending;

- Low-carbon fuel substitution;
- Oxy-fuel combustion systems.

Carbon Capture

- Post-combustion carbon capture;
- Integrated carbon management solutions.

Figure 3 summarizes the identified decarbonization pathways.

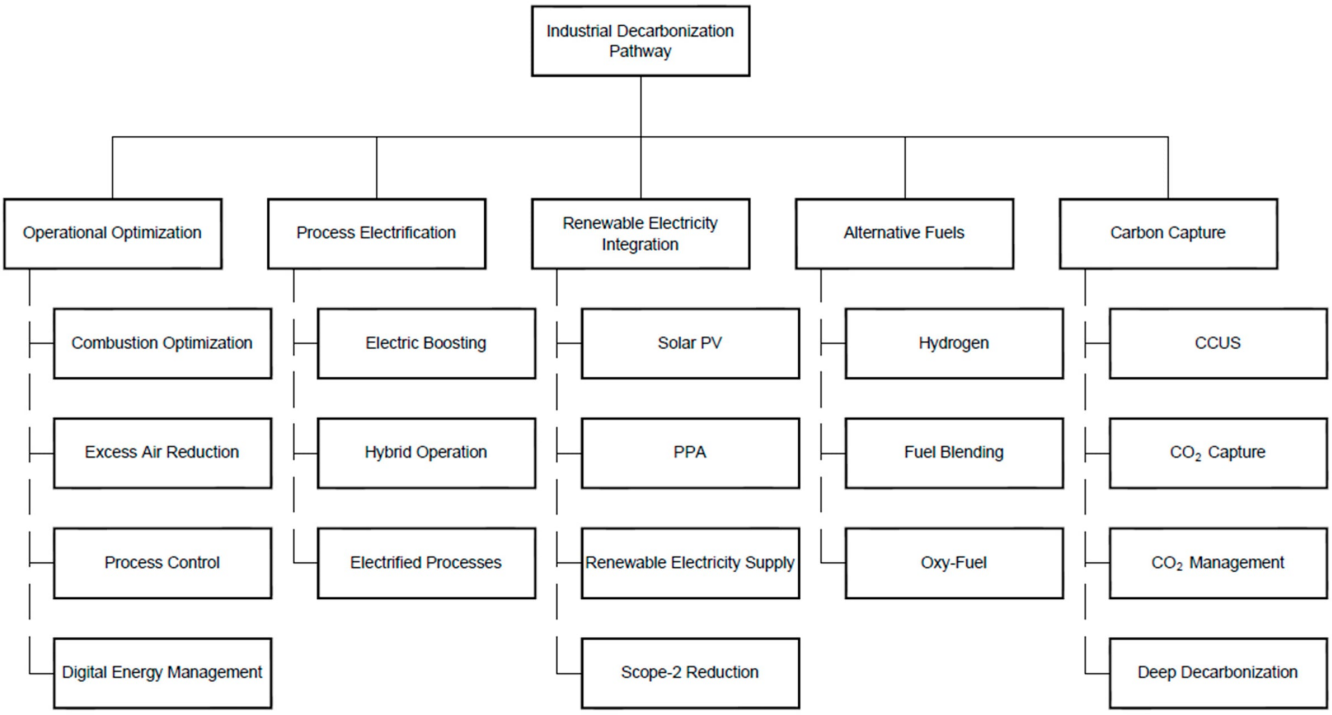


Figure 3. Industrial decarbonization pathways considered in the study.

As illustrated in Figure 3, the identified decarbonization opportunities can be grouped into five principal categories: operational optimization, process electrification, renewable electricity integration, alternative fuels, and carbon-capture technologies. These pathways collectively address both direct and indirect emissions and constitute the foundation of the integrated decarbonization scenarios evaluated in this study.

3.6. Baseline Assessment Summary

The baseline analysis highlights three critical observations.

First, the industrial system remains predominantly dependent on fossil-fuel-based thermal energy.

Second, Scope 1 emissions constitute the largest share of total greenhouse-gas emissions, indicating that thermal-process transformation is essential for achieving deep decarbonization.

Third, although operational improvements can provide meaningful energy savings and emission reductions, long-term net-zero targets require the deployment of additional measures such as electrification, renewable electricity integration, alternative fuels, and carbon capture technologies.

Accordingly, the baseline assessment establishes the reference framework for evaluating the decarbonization scenarios presented in the following section.

4. Decarbonization Scenarios

To identify cost-optimal pathways toward deep industrial decarbonization, a series of technology scenarios were developed and evaluated. The scenarios were designed to represent both incremental and transformative decarbonization measures that can be implemented throughout different stages of the industrial transition process. As summarized in Table 5, the evaluated pathways range from low-cost operational optimization measures to advanced decarbonization technologies including electrification, hydrogen utilization, oxy-fuel combustion, carbon capture, and integrated net-zero transition strategies.

Table 5. Decarbonization scenarios.

Scenario	Description	Main Objective
S1	Operational Optimization	Improve efficiency and reduce fuel consumption
S2	Process Electrification	Reduce fossil fuel dependency
S3	Renewable Electricity Integration	Reduce Scope-2 emissions
S4	Hydrogen Utilization	Replace fossil fuels with low-carbon fuels
S5	Oxy-Fuel Combustion	Improve thermal efficiency
S6	Carbon Capture	Eliminate residual emissions
S7	Integrated Pathway	Develop cost-optimal net-zero roadmap

The evaluated pathways range from low-capital operational improvements to large-scale technology transformations involving electrification, renewable energy integration, alternative fuels, oxy-fuel combustion systems, and carbon capture technologies. The scenarios were constructed to reflect realistic industrial implementation strategies and were assessed using the methodology described in Section 2.

As illustrated in Figure 4, seven decarbonization scenarios were evaluated, ranging from operational optimization and process electrification to hydrogen utilization, oxy-fuel combustion, and carbon capture. The final integrated pathway (S7) combines the most promising elements of the individual scenarios and serves as the basis for the proposed cost-optimal roadmap toward near net-zero industrial operation.

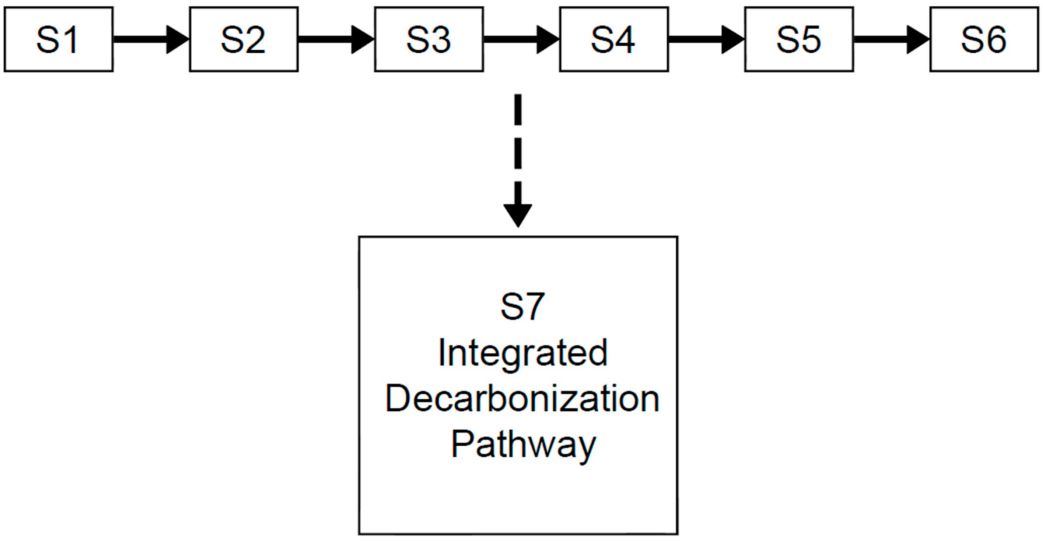


Figure 4. Decarbonization scenarios evaluated in the study.

4.1. Scenario S1: Operational Optimization

Operational optimization represents the first stage of industrial decarbonization and focuses on improving process efficiency without major equipment replacement.

The scenario includes the following:

- Combustion optimization;
- Excess-air reduction;
- Burner tuning;
- Furnace pressure stabilization;
- Digital energy management;
- Advanced process monitoring;
- NOx reduction measures;
- Operator-driven performance optimization.

These measures primarily target fuel savings and emission reductions through improved operational performance. Since implementation typically requires relatively low capital investment compared to other decarbonization options, operational optimization is treated as the baseline improvement pathway.

The objective of Scenario S1 is to quantify the maximum achievable decarbonization potential through operational excellence alone.

4.2. Scenario S2: Process Electrification

Electrification is widely considered one of the most promising solutions for industrial decarbonization.

In this scenario, part of the thermal energy demand is replaced by electricity through the introduction of electric boosting technologies.

The assessment considers the following:

- Hybrid thermal–electric operation;
- Increased electrical energy contribution;
- Reduced fossil fuel consumption;
- Modified energy balances;
- Changes in thermal efficiency.

Unlike conventional fuel-driven systems, electrification enables direct energy transfer into the process and therefore improves overall energy-utilization efficiency.

However, the resulting carbon reductions depend strongly on the carbon intensity of the electricity supply. Consequently, Scenario S2 is evaluated under all electricity-grid evolution scenarios defined in Section 2. The increasing strategic importance of electrification is further supported by national energy-transition policies. Türkiye's National Energy Plan projects that electricity consumption will increase significantly by 2035 while the share of electricity in final energy consumption continues to rise. These developments indicate that industrial electrification is likely to become an increasingly important component of the national decarbonization strategy.

4.3. Scenario S3: Electrification with Renewable Electricity Integration

Although electrification reduces direct fuel consumption, indirect emissions may remain significant when electricity is supplied from carbon-intensive power systems.

Therefore, Scenario S3 combines process electrification with renewable electricity procurement strategies.

The evaluated options include the following:

- Photovoltaic (PV) generation;
- Renewable power purchase agreements (PPA);
- Grid-connected renewable electricity supply;
- Partially self-generated renewable electricity.

The objective is to reduce Scope 2 emissions while maximizing the environmental benefit of electrification.

Special attention is given to the interaction between renewable electricity penetration and industrial decarbonization performance.

4.4. Scenario S4: Hydrogen Fuel Substitution

Hydrogen is increasingly considered a potential long-term replacement for fossil fuels in high-temperature industrial applications.

Scenario S4 evaluates partial substitution of natural gas by green hydrogen produced using renewable electricity.

The analysis includes the following:

- Hydrogen blending ratios;
- Fuel replacement potential;
- Additional electricity demand;
- Electrolyzer requirements;
- Renewable generation requirements;
- Hydrogen production infrastructure.

The scenario assesses both the technical feasibility and economic implications of hydrogen deployment.

Particular attention is given to the relationship between hydrogen production costs and resulting carbon-abatement performance. Hydrogen deployment is also identified as a strategic priority within national energy policy. Türkiye's National Energy Plan projects the development of approximately 5 GW of electrolyzer capacity by 2035 and considers hydrogen primarily as a decarbonization solution for industrial applications and fuel substitution. These projections reinforce the relevance of evaluating hydrogen pathways within long-term industrial transition strategies.

4.5. Scenario S5: Oxy-Fuel Combustion

Oxy-fuel combustion has emerged as an attractive option for reducing thermal losses and facilitating carbon capture.

In this scenario, conventional air–fuel combustion is replaced by oxygen-enriched combustion systems.

The following effects are evaluated:

- Reduced nitrogen dilution;
- Improved flame efficiency;
- Lower flue-gas volumes;
- Increased heat-transfer efficiency;
- Reduced overall fuel demand.

In addition to energy benefits, oxy-fuel operation can significantly increase flue–gas CO_2 concentration, thereby improving the feasibility of downstream carbon-capture technologies.

4.6. Scenario S6: Carbon Capture and Utilization

Carbon capture technologies become increasingly relevant when deep decarbonization targets are pursued.

Scenario S6 evaluates technologies capable of capturing carbon dioxide from industrial exhaust streams.

The assessment includes the following:

- Capture efficiency;
- Annual CO_2 capture potential;
- Additional energy consumption;
- Carbon compression and handling requirements;

- Operating expenditures;
- Infrastructure investment requirements.

Unlike fuel-switching technologies, carbon capture directly addresses residual emissions that remain unavoidable even after significant process improvements and electrification.

This scenario therefore represents a potential pathway toward near-zero or net-zero industrial operation.

For assessment purposes, captured CO_2 was assumed to be compressed to approximately 110 bar for transport and storage applications. The overall energy penalty associated with capture, compression, and auxiliary systems was assumed to be in the range of 15–20% of baseline plant energy consumption based on published industrial CCS studies.

4.7. Scenario S7: Integrated Decarbonization Pathway

Real-world industrial transformation rarely occurs through the implementation of a single technology.

For this reason, Scenario S7 combines the most effective measures from the previous scenarios into a phased integrated roadmap.

The integrated pathway includes the following:

Stage 1

Operational Excellence

- Process optimization;
- Combustion improvements;
- Digitalization.

Stage 2

Electrification

- Electric boosting;
- Hybrid operation.

Stage 3

Renewable Energy Integration

- Photovoltaic generation;
- Renewable electricity sourcing.

Stage 4

Alternative Fuels

- Hydrogen utilization;
- Advanced combustion systems.

Stage 5

Deep Decarbonization

- Oxy-fuel technologies;
- Carbon capture systems.

This scenario aims to identify the most practical and economically feasible route toward net-zero emissions while minimizing transition risks and avoiding premature investment in high-cost technologies. The proposed phased roadmap is broadly consistent with the strategic priorities defined by the Ministry of Energy and Natural Resources, including industrial energy efficiency, renewable-energy expansion, electrification, hydrogen development, grid flexibility enhancement, and long-term net-zero carbon transition objectives.

4.8. Scenario Evaluation Criteria

All scenarios were evaluated using a common set of performance indicators.

Environmental Indicators

- Scope 1 emissions;
- Scope 2 emissions;
- Total GHG emissions;
- Relative emission reduction;
- Absolute emission reduction.

Technical Indicators

- Specific energy consumption;
- Fuel consumption;
- Electricity demand;
- Renewable energy requirement.

Economic Indicators

- Capital expenditure (CAPEX);
- Operational expenditure (OPEX);
- Carbon costs;
- Marginal Carbon Abatement Cost (MACC).

Strategic Indicators

- Technology maturity;
- Implementation complexity;
- Scalability;
- Compatibility with net-zero pathways.

These indicators provide a consistent basis for comparing alternative decarbonization strategies and identifying cost-optimal transition pathways.

5. Results and Discussion

5.1. Baseline Energy and Emission Performance

Table 6 presents the baseline energy consumption profile of the reference industrial system. Natural gas represents the dominant energy source, accounting for approximately 69% of total energy demand, followed by coal (19%) and electricity (11%). The results indicate that fossil fuels account for nearly 88% of total energy consumption, highlighting the need for fuel substitution, process electrification, renewable-energy integration, and carbon-management strategies to achieve deep decarbonization.

Table 6. Baseline energy consumption profile of the reference industrial system.

Energy Source	Annual Consumption (10^6 GJ)	Share (%)
Natural Gas	64.7	69.2
Coal	17.7	18.9
Electricity	10.7	11.4
Biomass	0.3	0.3
Other Fuels	0.2	0.2
Total	93.6	100.0

The baseline energy profile reveals a strong dependence on fossil fuels, particularly natural gas and coal, which together account for approximately 88% of total energy consumption. Consequently, significant emission reductions cannot be achieved solely through renewable electricity procurement and require the parallel deployment of electrification, fuel-switching, hydrogen, and carbon-capture technologies.

Combined heat and power systems, steam turbines, and waste-heat recovery units collectively contribute approximately 98.5% of internal power generation, indicating that many conventional energy-efficiency opportunities have already been captured.

Table 7 shows the on-site electricity generation portfolio of reference industrial system. Cogeneration systems account for approximately 77% of internal electricity generation, followed by steam turbines (18%), waste-heat recovery systems (4%), and solar photovoltaic installations (1.5%). The results indicate that the facility already incorporates several energy-efficiency and energy-recovery measures; however, the contribution of renewable electricity remains limited, suggesting significant potential for further renewable-energy integration.

Table 7. Internal energy generation portfolio of the reference industrial system.

Generation Technology	Annual Generation (GWh)	Share (%)
Cogeneration	1148	76.7
Steam Turbines	264	17.6
Waste Heat Recovery	63	4.2
Solar PV	22	1.5
Total	1497	100.0

Although the facility already benefits from extensive cogeneration and waste-heat recovery systems, solar PV currently contributes only 1.5% of total internal electricity generation. This finding supports the inclusion of renewable-electricity expansion and electrification pathways among the evaluated decarbonization scenarios.

This finding confirms that decarbonization of energy-intensive continuous process industries should be considered primarily as a thermal decarbonization challenge rather than solely an electricity decarbonization problem. Although renewable electricity procurement contributes to emission reduction, deep decarbonization requires substantial transformation of high-temperature thermal processes.

Furthermore, the baseline analysis indicated that previous energy-efficiency improvements had already reduced specific energy consumption over time. This suggests that a significant portion of conventional efficiency opportunities have already been captured, thereby limiting the potential for further emission reductions through operational measures alone. Based on these findings, a comprehensive set of environmental, technical, and economic indicators was established to ensure a consistent comparison of all decarbonization scenarios. These evaluation criteria are presented in Table 8.

Table 8. Evaluation criteria used for decarbonization scenario assessment.

Category	Indicator	Unit
Environmental	Scope-1 Emissions	tCO_2/year
Environmental	Scope-2 Emissions	tCO_2/year
Environmental	Total Emissions	tCO_2/year
Environmental	Emission Reduction	%
Technical	Specific Energy Consumption	kcal/kg-product
Technical	Fuel Consumption	Nm^3/h
Technical	Electricity Consumption	MWh/year
Economic	CAPEX	EUR
Economic	OPEX	EUR/year
Economic	Carbon Cost	EUR/year
Economic	MACC	EUR/tCO_2 avoided

5.2. Impact of Operational Optimization

Scenario S1 demonstrated that operational optimization provides the lowest-risk and lowest-cost pathway for initial decarbonization efforts.

Measures such as the following resulted in measurable reductions in fuel consumption and associated emissions:

- Combustion optimization;
- Excess-air reduction;
- Burner balancing;
- Process stabilization;
- Digital monitoring and control.

The results indicate that operational excellence can generate meaningful carbon reductions without major capital investments. However, the achievable emission reduction remains inherently limited because the fundamental fossil-fuel dependency of the thermal process is not eliminated.

Therefore, operational optimization should be viewed as an enabling technology that improves the effectiveness of subsequent decarbonization investments rather than as a standalone pathway toward net-zero emissions.

From an investment perspective, Scenario S1 exhibited the lowest carbon-abatement cost among all evaluated measures and therefore represents an attractive first-stage transition strategy.

The calculated MACC for Scenario S1 was approximately 5 EUR/tCO_2, making it the most economically attractive short-term decarbonization option.

5.3. Electrification Under Different Grid Scenarios

Electrification emerged as one of the most effective decarbonization measures evaluated in this study.

A key outcome of the analysis is that electrification should not be interpreted as a fixed-emission-reduction technology. Its environmental performance improves progressively as the electricity grid becomes increasingly decarbonized. Consequently, the attractiveness of electrification depends not only on industrial process characteristics but also on the future evolution of the electricity system.

The introduction of electric boosting significantly reduced natural-gas demand while simultaneously improving overall energy-transfer efficiency. Because electrical energy is transferred directly into the process, lower total energy consumption was required to achieve comparable production performance.

However, one of the most important findings of this study is that the environmental effectiveness of electrification is not constant.

Under present electricity-grid conditions, electrification produced substantial greenhouse-gas reductions. Nevertheless, the carbon-reduction performance improved further under future grid scenarios characterized by increasing shares of renewable electricity generation.

Figure 5 illustrates the relationship between grid emission factors and electrification performance.

The projected increase in solar and wind generation capacity is expected to reduce electricity-grid carbon intensity and improve the emission-reduction performance of industrial electrification pathways over time.

The observed improvement in electrification performance under future grid scenarios is consistent with projections presented in Türkiye's National Energy Plan. The projected expansion of solar and wind generation capacity and the increasing share of renewable electricity generation are expected to lower grid emission factors and amplify the carbon-reduction benefits associated with industrial electrification.

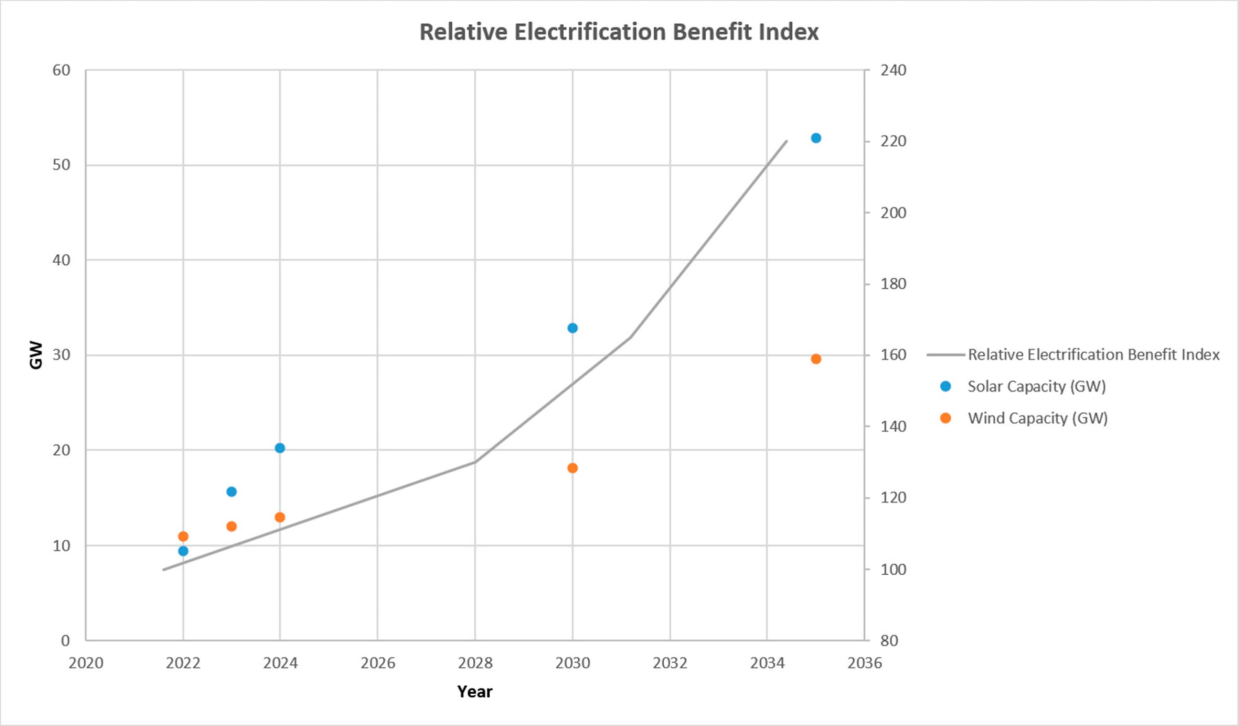


Figure 5. Impact of electricity-grid decarbonization on the emission-reduction performance of industrial electrification pathways.

Impact of electricity-grid carbon intensity on electrification-based emission reductions.

The results demonstrate that electrification should not be evaluated independently from power-system evolution. As electricity systems become progressively decarbonized, the environmental benefits of industrial electrification increase considerably. This finding supports Hypothesis H2 and represents one of the principal contributions of the current work.

From an economic perspective, electrification exhibited one of the lowest marginal carbon-abatement costs among all investigated technology pathways.

As summarized in Table 3, the emission-reduction performance of process electrification improves as the electricity grid becomes progressively decarbonized. Total greenhouse-gas emissions were reduced by 51.2%, 53.6%, 56.1%, and 58.8% under grid scenarios G1, G2, G3, and G4, respectively. The progressive improvement reflects the declining carbon intensity of the electricity supply and confirms that the environmental benefits of industrial electrification increase as the power system becomes more decarbonized. These findings support Hypothesis H2 and demonstrate the importance of evaluating electrification pathways under future grid conditions rather than relying solely on present-day electricity carbon factors.

5.4. Renewable Electricity Integration

The integration of renewable electricity provided additional emission reductions by decreasing indirect emissions associated with purchased electricity.

Photovoltaic systems and renewable power procurement mechanisms enhanced the carbon benefits of electrification pathways while reducing long-term exposure to carbon pricing and electricity-market volatility.

The analysis shows that renewable electricity integration becomes increasingly valuable when combined with process electrification. In contrast, renewable electricity projects implemented without significant process transformation generate smaller overall decarbonization benefits because Scope 1 emissions continue to dominate the total carbon footprint.

This result demonstrates the importance of coordinated implementation strategies rather than isolated energy-transition initiatives.

5.5. Hydrogen-Based Decarbonization Pathways

Hydrogen substitution scenarios demonstrated significant technical decarbonization potential.

Partial replacement of natural gas with green hydrogen reduced direct fossil-fuel-related emissions and contributed to substantial reductions in the carbon footprint of thermal operations.

Despite these environmental benefits, hydrogen pathways exhibited considerably higher costs than electrification-based alternatives.

The primary economic challenges were associated with the following:

- Electrolyzer investments;
- Renewable electricity requirements;
- Hydrogen production costs;
- Hydrogen storage infrastructure.

As a consequence, the marginal carbon-abatement cost of hydrogen scenarios was significantly higher than the values observed for electrification pathways.

These findings support Hypothesis H3 and suggest that hydrogen is more likely to become relevant in the later stages of industrial decarbonization after economically attractive electrification opportunities have already been deployed.

5.6. Oxy-Fuel and Carbon Capture Pathways

The oxy-fuel scenarios produced notable improvements in thermal efficiency and reduced overall fuel demand.

In addition to direct energy benefits, oxy-fuel operation increased CO_2 concentration in flue gases, thereby improving the effectiveness of downstream carbon-capture processes.

Carbon capture technologies delivered the highest absolute emission reductions among the investigated options, particularly when combined with oxy-fuel combustion systems.

However, these technologies were accompanied by the following:

- Substantial capital expenditures;
- Additional operating costs;
- Increased process complexity.

The results indicate that carbon capture becomes most attractive when low-cost opportunities such as operational improvements and electrification have already been exhausted.

Hence, carbon capture should be regarded as a deep-decarbonization technology rather than an early-stage emission-reduction measure.

Table 9 presents a comparative assessment of the investigated decarbonization pathways. Operational optimization represents the lowest-cost short-term option and serves as the foundation for subsequent investments. Process electrification emerges as one of the most attractive medium-term strategies due to its high decarbonization potential under an increasingly renewable electricity grid. Renewable electricity integration further enhances the benefits of electrification by reducing Scope-2 emissions. Hydrogen, oxy-fuel combustion, and carbon-capture technologies provide deeper emission reductions but require substantially higher investments and longer implementation timeframes. Consequently, a phased and integrated transition pathway is identified as the most suitable approach for achieving near net-zero industrial operation.

Table 9. Comparative assessment of decarbonization scenarios.

Scenario	Main Technology	Emission Reduction Potential (%)	Relative CAPEX	Relative MACC (EUR/tCO_2)	Implementation Priority
S1	Operational Optimization	5–10	Very Low	5	1
S2	Process Electrification	50–55	Medium	25	2
S3	Renewable Electricity Integration	10–15	Medium	15	3
S4	Hydrogen Utilization	55–65	High	450	5
S5	Oxy-Fuel Combustion	65–75	High	60	4
S6	Carbon Capture (CCUS)	85–95	Very High	120	6
S7	Integrated Pathway	>95	Integrated	Optimized	Final

5.7. Marginal Carbon Abatement Cost Analysis

A key objective of this study was to evaluate decarbonization technologies not only in terms of emission reduction potential but also in terms of economic efficiency.

Figure 6 presents the Marginal Carbon Abatement Cost Curve (MACC) developed for the investigated scenarios.

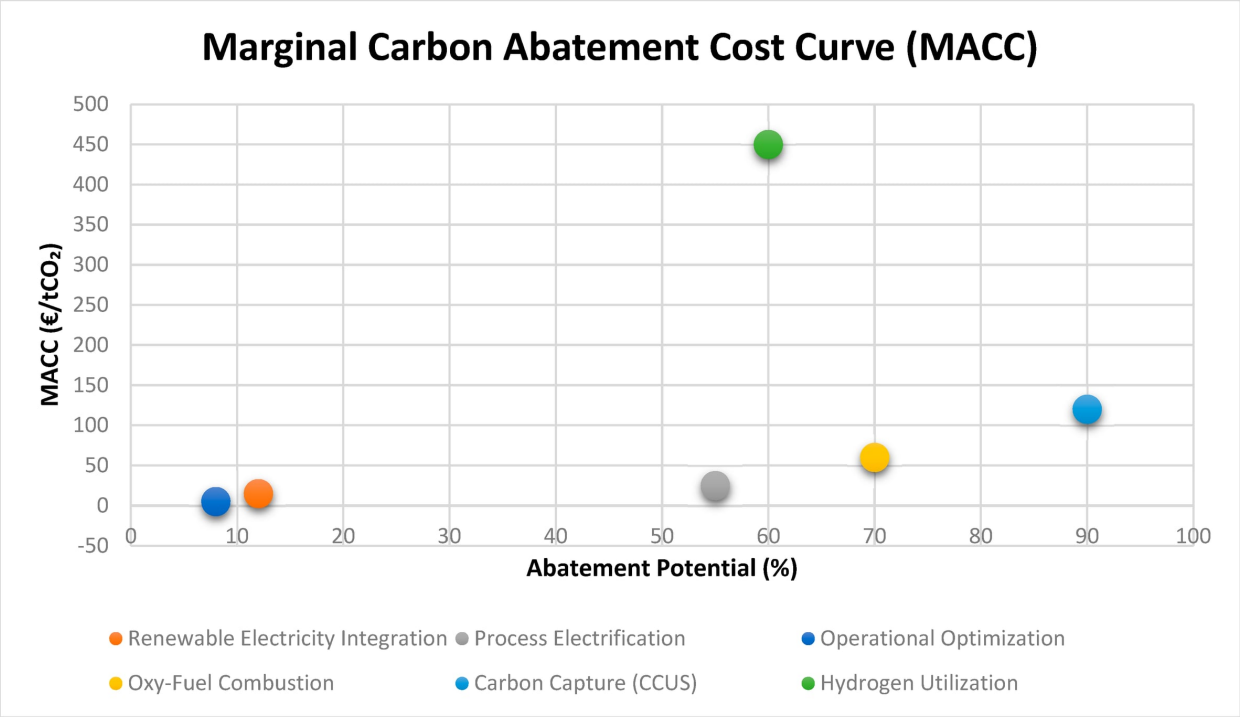


Figure 6. Marginal Carbon Abatement Cost Curve (MACC) for the evaluated decarbonization pathways.

Operational optimization and renewable electricity integration exhibit the lowest carbon-abatement costs, while process electrification provides a favorable balance between economic performance and emission-reduction potential. Hydrogen utilization offers substantial decarbonization benefits but is associated with the highest carbon-abatement cost. Carbon capture technologies deliver deep emission reductions at higher investment requirements, supporting their deployment during later stages of industrial decarbonization.

As shown in Figure 6, the economic attractiveness of decarbonization technologies varies significantly. Operational optimization and electrification represent the most cost-effective near-term measures, while hydrogen and carbon-capture technologies are associated with considerably higher carbon-abatement costs. The results therefore support a phased implementation strategy in which low-cost opportunities are prioritized before deploying capital-intensive deep-decarbonization technologies.

Marginal Carbon Abatement Cost Curve for evaluated decarbonization pathways.

The MACC analysis highlights three important observations.

First, operational optimization and electrification exhibited the lowest carbon-abatement costs, making them economically attractive early-stage investments.

Second, hydrogen technologies delivered meaningful emission reductions but at substantially higher carbon-abatement costs.

Third, carbon capture technologies achieved very high emission reductions but generally required larger investments and therefore occupied the upper end of the cost spectrum.

These findings indicate that the most effective decarbonization strategy is not necessarily the technology with the greatest emission-reduction potential, but rather the technology that achieves the greatest reduction per unit of invested capital.

5.8. Development of a Cost-Optimal Decarbonization Roadmap

Based on the combined environmental and economic assessment, a phased decarbonization roadmap was developed.

The proposed transition sequence is illustrated in Figure 7. The proposed transition pathway prioritizes operational optimization and process electrification during the early stages of industrial transformation, followed by renewable-electricity integration, hydrogen deployment, and deep-decarbonization technologies such as oxy-fuel combustion and carbon capture. The phased approach minimizes transition costs while supporting long-term near net-zero industrial operation.

Cost-optimal industrial decarbonization roadmap.

The results suggest the following implementation hierarchy:

Phase 1: Operational Excellence

- Process optimization;
- Energy monitoring;
- Combustion improvements;
- Digitalization.

Phase 2: Electrification

- Electric boosting;
- Hybrid thermal–electric operation.

Phase 3: Renewable Integration

- Solar PV deployment;
- Renewable electricity procurement.

Phase 4: Alternative Fuels

- Hydrogen integration;
- Advanced combustion systems.

Phase 5: Deep Decarbonization

- Oxy-fuel technologies;
- Carbon capture systems.

This phased approach minimizes overall decarbonization cost while maintaining operational reliability and production continuity.

The findings therefore support Hypothesis H4 and demonstrate that industrial net-zero transformation cannot be achieved through a single technology pathway. Instead, the most practical and economically viable solution is a sequential transition strategy that combines operational excellence, electrification, renewable energy integration, alternative fuels, and carbon capture technologies within a unified roadmap, as seen at Table 10.

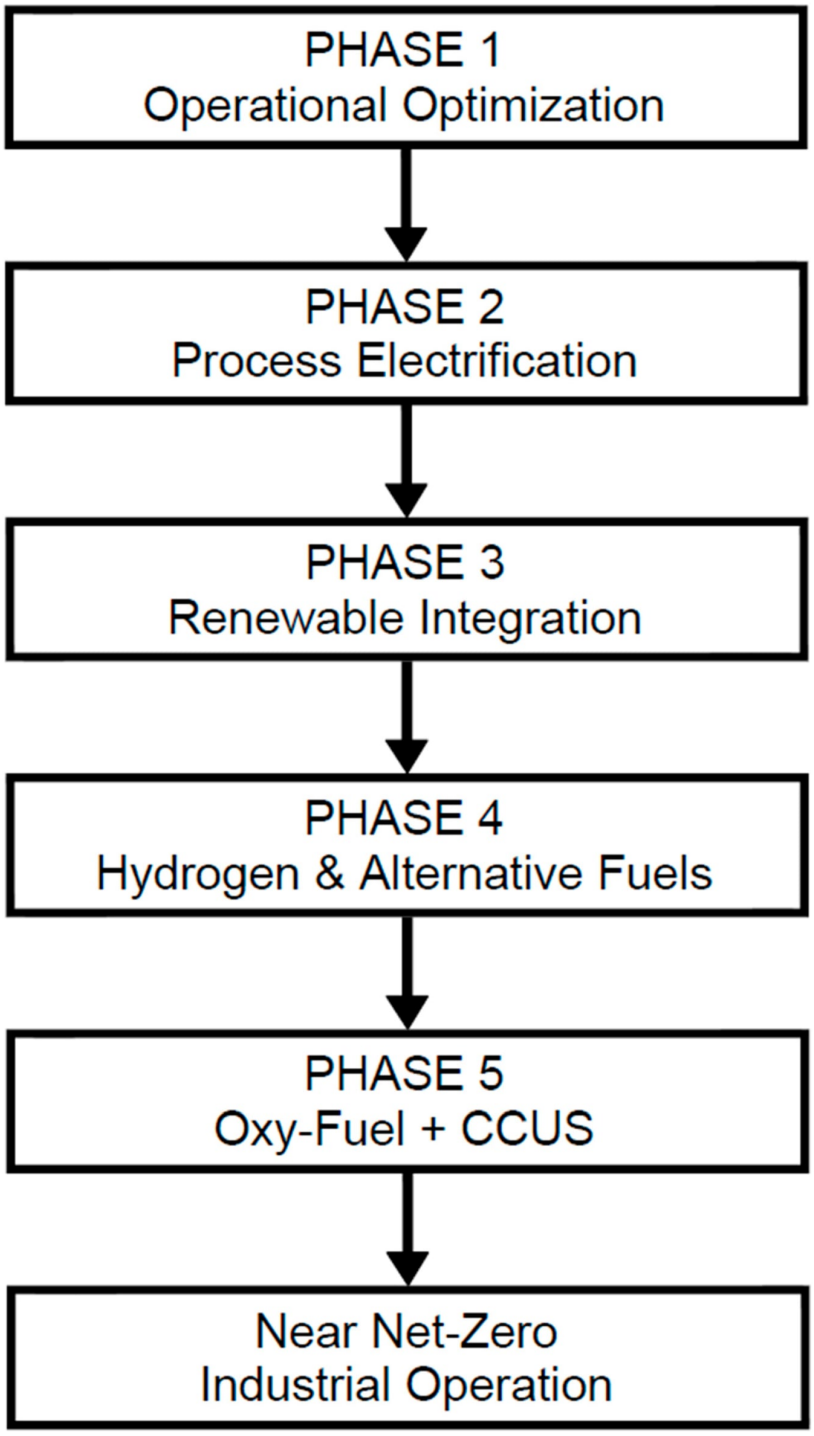


Figure 7. Cost-optimal industrial decarbonization roadmap.

Table 10. Proposed cost-optimal industrial decarbonization roadmap.

Phase	Time Horizon	Primary Measures	Expected Outcome
Phase 1	Short-Term	Operational Optimization, Digital Monitoring	5–10% emission reduction
Phase 2	Short–Medium Term	Electrification and Boosting	Additional 50–55% reduction
Phase 3	Medium Term	Renewable Electricity Integration	Additional 10–15% Scope-2 reduction
Phase 4	Medium–Long Term	Hydrogen and Alternative Fuels	55–65% fossil fuel replacement potential
Phase 5	Long Term	Oxy-Fuel and CCUS	>90% total emission reduction

In addition to its economic and environmental advantages, the proposed roadmap aligns closely with national energy-transition priorities, including renewable-energy deployment, industrial energy efficiency, electrification, hydrogen development, and long-term net-zero transformation objectives identified in multiple strategic policy documents.

5.9. Sensitivity Analysis

To evaluate the robustness of the proposed decarbonization pathways, a sensitivity analysis was conducted for the parameters associated with the highest degree of uncertainty. Three key variables were selected based on their expected influence on both the environmental and economic performance of the investigated technologies: electricity-grid emission factor, green hydrogen cost, and carbon price.

The electricity-grid emission factor was varied by ±20% relative to the values adopted in the baseline assessment. This range reflects uncertainties associated with future renewable-energy deployment rates, electricity demand growth, storage-system penetration, and long-term power-sector policies. The analysis showed that lower grid-emission factors further improved the environmental performance of electrification pathways, while higher grid-carbon intensities reduced, but did not eliminate, the emission-reduction benefits of electrification.

Green hydrogen costs were varied by ±30% to capture uncertainties associated with electrolyzer investment costs, renewable-electricity prices, capacity factors, and future hydrogen-market development. The results indicated that hydrogen-based pathways are highly sensitive to fuel-production costs. A reduction in hydrogen costs significantly improved the techno-economic performance of Scenario S4, whereas higher hydrogen costs further increased the marginal carbon abatement cost relative to electrification-based pathways.

Carbon prices were varied by ±50% to account for possible future developments in emission trading systems, carbon taxes, and carbon border adjustment mechanisms. Higher carbon prices improved the economic attractiveness of deep-decarbonization technologies such as hydrogen utilization and carbon capture by increasing the value of avoided emissions. Conversely, lower carbon prices reduced the economic incentive for these technologies while having relatively limited impact on operational optimization and electrification scenarios.

Overall, the sensitivity analysis confirmed that the relative ranking of the investigated decarbonization pathways remained unchanged within the examined uncertainty ranges. Operational optimization and process electrification consistently emerged as the most economically attractive near-term decarbonization measures, while hydrogen utilization and carbon capture technologies became increasingly attractive under future low-carbon and high-carbon-price conditions.

Therefore, the principal conclusions of this study can be considered robust against reasonable variations in key economic and environmental assumptions.

The quantitative sensitivity analysis results are summarized in Table 11. Among the investigated variables, hydrogen cost exhibited the strongest influence on the economic performance of decarbonization pathways. A 30% reduction in hydrogen cost decreased the MACC of Scenario S4 from 450 EUR/tCO_2 to 315 EUR/tCO_2, whereas a 30% increase increased the MACC to 585 EUR/tCO_2. Electrification pathways were moderately affected by variations in grid emission factors, while CCUS technologies showed increasing economic attractiveness under higher carbon-price assumptions. Despite these variations, the overall ranking of the investigated decarbonization pathways remained unchanged, confirming the robustness of the proposed roadmap.

Table 11. Sensitivity of MACC values to key uncertain parameters.

Scenario	Base MACC (EUR/tCO_2)	Variable	Low Case	MACC (EUR/tCO_2)	High Case	MACC (EUR/tCO_2)
S2 Electrification	25	Grid Emission Factor	−20%	21	+20%	30
S4 Hydrogen	450	Hydrogen Cost	−30%	315	+30%	585
S6 CCUS	120	Carbon Price	−50%	145	+50%	95

6. Conclusions

This study presented an integrated techno-economic assessment of industrial decarbonization pathways for energy-intensive continuous process industries operating under a progressively decarbonizing electricity grid. Unlike conventional approaches that evaluate individual technologies independently, the proposed framework simultaneously assessed operational optimization, process electrification, renewable electricity integration, hydrogen utilization, oxy-fuel combustion, and carbon capture technologies within a unified decision-support methodology.

The baseline assessment demonstrated that the investigated industrial system remains highly dependent on fossil-fuel-based thermal energy, resulting in a greenhouse-gas emission profile dominated by Scope 1 emissions. This finding confirms that deep industrial decarbonization requires the transformation of thermal processes in addition to improvements in electricity sourcing and energy management.

The results revealed that operational optimization measures represent the most attractive entry point for industrial decarbonization due to their low investment requirements, short implementation periods, and favorable carbon-abatement costs. However, the achievable emission reductions from operational measures alone were found to be insufficient for meeting long-term net-zero objectives.

Among the technology pathways evaluated, electrification emerged as the most cost-effective medium-term decarbonization strategy. The combination of reduced fossil-fuel consumption and improved energy-transfer efficiency enabled substantial greenhouse-gas reductions while maintaining competitive carbon-abatement costs. More importantly, the analysis demonstrated that the carbon-reduction effectiveness of electrification is not constant but strongly dependent on the carbon intensity of the electricity grid. As renewable-energy penetration increases and power systems become progressively decarbonized, the environmental benefits of industrial electrification improve significantly.

Hydrogen-based pathways were found to provide considerable technical potential for reducing direct fossil-fuel consumption in high-temperature industrial applications. However, the associated investments in renewable electricity generation, electrolyzers, storage systems, and hydrogen infrastructure resulted in significantly higher carbon-abatement costs compared with electrification-based alternatives. Consequently, hydrogen appears more suitable as a later-stage decarbonization option once lower-cost opportunities have been largely exhausted.

Oxy-fuel combustion and carbon capture technologies demonstrated the highest potential for deep emission reductions and near-zero industrial operation. Nevertheless, these technologies are associated with substantial capital requirements and increased operational complexity. Therefore, their deployment is likely to be justified primarily in advanced stages of decarbonization where residual process emissions remain difficult to eliminate through efficiency improvements, electrification, or alternative fuels.

A key contribution of this study is the development of a Marginal Carbon Abatement Cost (MACC) framework enabling direct comparison of competing technologies based on both environmental and economic performance. The results indicate that the

most effective decarbonization pathway is not necessarily the technology with the highest emission-reduction potential, but rather the technology that provides the greatest emission reduction per unit of invested capital under evolving electricity-system conditions.

Based on the integrated assessment, a phased industrial decarbonization roadmap was proposed. The recommended transition sequence begins with operational excellence and digital energy management, followed by electrification and renewable electricity integration, and ultimately progresses toward alternative fuels, oxy-fuel technologies, and carbon capture systems. This phased approach minimizes overall transition costs while maintaining operational reliability and supporting long-term net-zero objectives.

The findings support the central hypothesis of this research that industrial electrification should not be evaluated independently of electricity-grid evolution. Instead, successful industrial decarbonization requires coordinated transformation of both industrial energy systems and national electricity infrastructures. Accordingly, the proposed framework provides a practical and replicable methodology for decision-makers seeking to identify cost-optimal decarbonization pathways in energy-intensive continuous process industries. Furthermore, the proposed approach is consistent with the strategic objectives outlined in Türkiye's National Energy Plan, Energy Efficiency Strategy 2030, and the Ministry of Energy and Natural Resources Strategic Plan, thereby providing a bridge between national energy-transition policies and practical industrial implementation pathways.

The principal contribution of this study is the demonstration that industrial electrification should not be evaluated under static electricity-grid assumptions. Instead, the environmental and economic value of electrification evolves together with the decarbonization of the electricity system. This finding highlights the importance of grid-aware industrial decarbonization strategies when developing long-term transition roadmaps.

Limitations and Future Research

Several limitations of the present study should be acknowledged. First, the analysis was based on a single anonymized industrial case study, although the process characteristics investigated are representative of a broader class of energy-intensive continuous manufacturing systems. Second, future energy prices, carbon prices, hydrogen costs, and technology learning rates remain subject to uncertainty. Third, electricity-grid evolution was evaluated using scenario-based assumptions that may vary depending on national energy policies and renewable-energy deployment rates.

Future research should extend the proposed framework by incorporating stochastic energy-market modeling, dynamic carbon-pricing scenarios, life-cycle assessment (LCA) methodologies, and advanced optimization techniques. In addition, the integration of artificial intelligence and machine-learning approaches for real-time energy management and decarbonization planning represents a promising area for further investigation.

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