

NET ZERO
PARTNERSHIP



NDC 3.0 Guidebook for Industrial Decarbonization:

A Structured Approach to Designing and Prioritizing Policies and Measures

VOLUME 2

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The Net Zero Partnership for Industrial Decarbonization is a global initiative led by UNIDO that supports emerging markets and developing economies (EMDEs) in their transition towards low-carbon steel, cement, and concrete. The project offers tailored policy support, promotes decarbonization solutions, and encourages international collaboration to achieve net-zero emissions by 2050.

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FOREWORD

We are living in challenging and transformative times and the global community is grappling with many challenges including geopolitical tensions, economic uncertainty, conflicts, and the impacts of climate change which are becoming more acute with each passing year.

Resources are stretched, trust in global cooperation is under pressure, and progress toward our shared goals is way too slow. Yet in moments like these cooperation and partnerships are more important than ever, and the need to act is clear.

The climate crisis is not a distant threat. It is here. Records show that last year was once again record-breaking for heat, extreme weather, and climate-induced disasters such as both floods and droughts. Nowhere is the need for action more critical, and more complex, than in heavy industry.

Heavy industry, including steel, cement, and chemicals, accounts for the largest share of industrial emissions. They are central to our economies and development, but they are also responsible for more than 25 percent of global greenhouse gas emissions. Decarbonizing these heavily-emitting sectors is both an immense challenge and a great opportunity.

Without considerable emissions cuts from heavy industry, the world cannot reach its climate goals.

Emissions from these sectors must fall by at least 20 percent by 2030 and 90 percent by mid-century. Despite this, investment in industrial decarbonization remains far below what is needed, particularly in developing countries where demand for steel and cement is growing rapidly. The stakes are enormous, but so too is the potential for transformation.

The third round of Nationally Determined Contributions, or NDCs 3.0, offers a critical chance to deliver this transformation. These are not just climate pledges. They are strategies for economic resilience, investment readiness, and sustainable industrial growth. They provide a framework for aligning national development with global climate ambition - and for attracting the financing needed to turn ideas into impact.

We can no longer simply think of heavy industry as a hard-to-abate exception.

Instead it must be a central pillar of our climate strategy. Markets are beginning to align with this necessity. Demand for low-carbon products is gaining momentum, public procurement policies are increasingly incentivizing greener materials, and the cost of clean technologies continues to decline. However, we must urgently press these positive trends forward, especially through greater international cooperation and coherent policy frameworks that send clear and consistent signals to the market.

This guidebook is a tool for that. It supports governments in identifying practical options to decarbonize their heavy industries for maximum impact. It reinforces the vital message that industrial decarbonization is not just about reducing emissions – it is about building more resilient and sustainable economies which are fit for the future.



Gerd Müller

Director General, UNIDO

TABLE OF CONTENTS

Definitions	7
Acronyms	10
1. General Introduction	12
In numbers: Why countries should integrate industries into their NDCs	14
Scope and Objectives	15
About the NDC 3.0 Guidebook for Industrial Decarbonization	16
2. Building Blocks of Industrial Decarbonization – An Implementation Guide	20
Overview of Industrial Decarbonization Building Blocks	21
Building Block 1: Material Efficiency	26
Industry Trends	26
Enabling Factors and Policy Support	28
Decision Tree for Prioritization	29
Building Block 2: Energy Efficiency	33
Industry Trends	33
Enabling Factors and Policy Support	35
Decision Tree for Prioritization	37
Building Block 3: Low-Carbon Energy and Feedstocks	41
Industry Trends	41
Enabling Factors and Policy Support	43
Decision Tree for Prioritization	44
Building Block 4: Electrification and Process Change	48
Industry Trends	48
Enabling Factors and Policy Support	50
Decision Tree for Prioritization	51
Building Block 5: Carbon Capture, Utilization, and/or Storage	55
Industry Trends	55
Enabling Factors and Policy Support	57
Decision Tree for Prioritization	58

3. Overarching Mechanisms for Advancing Industrial Decarbonization Across Building Blocks	62
Public-Private Partnerships and Voluntary Agreements	65
Green Public Procurement and Demand Signals	67
Industrial Hubs	68
Annexes	70
Annex A. Methodology for Estimating GHG Impact	72
Annex B. Measures within the Five Building Blocks of Industrial Decarbonization	76
B.1. Material Efficiency	76
B.2. Energy Efficiency	87
B.3. Low-Carbon Energy and Feedstocks	93
B.4. Electrification and Process Change	99
B.5. Carbon Capture, Utilization, and/or Storage (CCS/CCUS)	107
Annex C. Industry Specific Measures	109
Energy Industry	109
Iron and Steel Industry	109
Cement and Glass Industry	110
Chemical Industry	110
Annex D. Exploring Additional Sources of Industry Sector Measures (PAMs)	126

DEFINITIONS

Based on the [Intergovernmental Panel on Climate Change \(IPCC\) Glossary](#) [↗](#), the [modalities, procedures and guidelines \(MPGs\)](#) [↗](#) of the Paris Agreement, as well as the authors' own definitions.

Carbon capture, utilization, and storage: Refers to a set of technologies designed to capture CO₂ emissions from large-scale fossil-based energy and industry sources and either store them underground or repurpose them for useful applications.

Decarbonization: The process by which countries, individuals or other entities aim to achieve zero fossil carbon existence. Typically refers to a reduction of the carbon emissions associated with electricity, industry and transport.

Electrification: Electrification involves replacing fossil fuel-based technologies and processes with electric alternatives. Electrically powered systems are often more efficient, leading to lower overall energy demand. As electricity generation shifts to renewable and low-carbon sources, electrification plays an increasingly critical role in reducing industrial emissions.

Energy efficiency: Refers to achieving the same level of output while using less energy. In industrial settings, this involves optimizing processes and technologies to reduce energy consumption without compromising productivity. Improving energy efficiency lowers operational costs and mitigates greenhouse gas emissions.

Industrial sector: In the context of this guidance document, the industrial sector refers to economic activities related to the production and processing of goods, including fuel combustion, manufacturing, and the use of products such as chemicals, with a focus on identifying and addressing GHG emissions associated with these processes as part of industrial decarbonization efforts within NDCs.

Intergovernmental Panel on Climate Change (IPCC): The United Nations body for assessing the science related to climate change, analysing the state of scientific, technical and socio-economic knowledge on climate change, its impacts and future risks, and options for reducing the rate at which climate change is taking place.

Low-carbon energy: Refers to any energy source produced with a significantly lower carbon footprint than fossil fuels, encompassing, among other, renewable energy, bioenergy, hydrogen, and synthetic fuels with low or zero greenhouse gas emissions.

Marginal Abatement Cost Curve (MACC): A graphical representation that assesses and compares the cost-effectiveness of different mitigation measures by illustrating the cost of reducing one tonne of CO₂-equivalent emissions (USD/tonne CO₂e). MACCs help stakeholders, particularly policymakers and industry leaders, prioritize decarbonization actions by providing insights into the economic feasibility and mitigation potential of various measures.

Mitigation Policies and Measures (PAMs): All types of actions, measures, and policies that reduce emissions or enhance sinks of GHGs.

Mitigation scenario: A plausible description of the future that describes how the (studied) system responds to the implementation of mitigation policies and measures. The MPGs define three scenarios. A 'with existing measures' (WEM¹), encompasses currently implemented and adopted policies and measures. If provided, a 'with additional measures' scenario (WAM) encompasses implemented, adopted and planned policies and measures. If provided, a 'without measures' projection (WOM) excludes all policies and measures implemented, adopted and planned after the year chosen as the starting points for the projection."

Mitigation target: Specific goal or objective to reduce emissions or enhance sinks of GHGs for particular emission sources, sinks, or sectors, covering one or several gases over a defined geographical area and reference period. When these targets encompass all sectors of the economy, they are referred to as economy-wide targets. NDC targets are those outlined in the NDC, which are often mitigation targets.

Nationally Determined Contribution (NDC): A climate action plan developed by signatory countries under the Paris Agreement, outlining their intended efforts to reduce national emissions and adapt to the impacts of climate change. Each Party to the Paris Agreement is required to establish an NDC and update it every five years.

Net zero emissions: Net zero emissions are achieved when anthropogenic emissions of GHGs to the atmosphere are balanced by anthropogenic removals over a specified period. Where multiple GHGs are involved, the quantification of net zero emissions depends on the climate metric chosen to compare emissions of different gases (such as global warming potential, global temperature change potential, and others, as well as the chosen time horizon).

Paris Agreement: Legally binding international treaty on climate change under the UNFCCC, aiming to hold "the increase in the global average temperature to well below 2°C above pre-industrial levels" and pursue efforts "to limit the temperature increase to 1.5°C above pre-industrial levels".

Performance-based regulations: Regulatory mechanisms that establish specific targets for emissions or energy intensity while allowing industries flexibility in how they meet these targets. These regulations encourage innovation by gradually lowering allowable emissions, incentivizing industries to adopt cleaner technologies over time.

Plan: A detailed framework for implementing strategies, specifying concrete actions, performance metrics, and resource allocation over defined timeframes. Industry-specific action plans, for example, outline emissions reduction pathways for high-emission sectors like steel or cement, detailing measures such as energy efficiency improvements or transitions to cleaner fuels.

Policy: High-level guidelines that establish government priorities and set specific objectives, such as industrial growth or decarbonization, creating an overarching direction for sectors to follow.

¹ In alignment with the terminology used in the Modalities, Procedures, and Guidelines, the acronym for this scenario is WM. However, in this guidebook, the acronym WEM will be used.

Projection: Estimation of a potential future evolution of a quantity or set of quantities, often computed with the aid of a model. Emission projections are the estimation of future GHG emission levels based on current data, historical patterns, and assumptions about future conditions. In the MPGs of the Paris Agreement, projections are referred to as “indicative of the impact of mitigation policies and measures in future trends in GHG emissions and removals”.

Material efficiency: Material efficiency is the practice of maximizing output while minimizing the use of natural resources. By optimizing material use, it reduces overall resource consumption and associated environmental impacts. At the same time, it supports economic development by ensuring a stable resource supply. A key indicator of material efficiency at the economic level is resource productivity, the ratio of economic output to material input.

Standards and codes: Technical specifications or minimum performance requirements that set benchmarks across industries. Examples include energy efficiency standards for industrial machinery or building codes mandating low-emission materials to enhance sustainability and compliance.

Strategy: A structured approach to achieving policy goals, outlining necessary actions, timelines, and resources. Strategies often articulate long-term objectives, such as national climate or energy strategies that align emissions reduction measures across multiple sectors over decades.

United Nations Framework Convention on Climate Change (UNFCCC): An international environmental treaty adopted at the Earth Summit in Rio de Janeiro in 1992. Ratified since 1994, its objective is the ‘stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.’

ACRONYMS

AFOLU	Agriculture, Forestry and Other Land Use
BAU	Business as Usual
BMWK	German Federal Ministry for Economic Affairs and Climate Action
BTR	Biennial Transparency Report
CMA	Conference of the Parties serving as the meeting of the Parties to the Paris Agreement
COP	Conference of the Parties
CTF	Common Tabular Format
ESD	Effort Sharing Decision
ETF	Enhanced Transparency Framework
EU	European Union
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GST	Global Stocktake
ICTU	Information to Facilitate Clarity, Transparency and Understanding
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IPPU	Industrial Processes and Product Use
IRES	International Recommendations for Energy Statistics
IRIS	International Recommendations for Industrial Statistics
LDC	Least Developed Country
MACC	Marginal Abatement Cost Curve
MPGs	Modalities, Procedures and Guidelines
MRV	Monitoring, Reporting and Verification
NDC	Nationally Determined Contribution
NSO	National Statistical Office

NZP-ID	Net Zero Partnership for Industrial Decarbonization
OECD	Organisation for Economic Co-operation and Development
PAMs	Policies and Measures
SIDS	Small Island Developing States
SNA	System of National Accounts
SPACC	State Action Plan on Climate Change
TNA	Technology Needs Assessment
UN	United Nations
UNDP	United Nations Development Programme
UNFCCC	United Nations Framework Convention on Climate Change
UNFPOS	United Nations Fundamental Principles of Official Statistics
UNIDO	United Nations Industrial Development Organization
WAM	With Additional Measures
WEM	With Existing Measures
WOM	Without Measures



1. GENERAL INTRODUCTION



The industrial sector, encompassing manufacturing and its interconnected value chains, accounts for around a quarter of global energy-related carbon dioxide (CO₂) emissions.

As the global economy and population continue to grow, the demand for materials and goods will also rise, making industry a critical sector for achieving net zero emissions by 2050. Within industry, heavy sectors such as steel, cement, and chemicals are particularly carbon-intensive, representing over 15 percent of total global GHG emissions and around 70 percent of direct industrial emissions.



Decarbonizing the industrial sector is not only an environmental imperative aligned with the goals of the Paris Agreement, but also essential to safeguard long-term competitiveness and sustainable development. However, the transition faces significant challenges. Many low-carbon technologies for industrial processes are still under development or remain too expensive for widespread deployment. Industrial infrastructure often has long operational lifespans, slowing the adoption of new technologies. Furthermore, industrial processes such as chemical reactions and high-temperature heat generation cannot yet be fully decarbonized with currently available commercial technologies.

Without deep emissions cuts from heavy industry, global climate goals cannot be met. Emissions from these sectors must fall by at least 20 percent by 2030 and by 90 percent by mid-century to stay on track with net zero pathways. The next round of nationally determined contributions (NDCs) presents a vital opportunity to strengthen industrial decarbonization targets, ensuring that enhanced climate ambition supports economic resilience and industrial transformation. To support effective action, there is an urgent need for pathways to industrial decarbonization that are tailored to different national contexts, NDCs, and industrial landscapes.

In numbers: Why countries should integrate industries into their NDCs

Industrial emissions are rising fast, particularly for heavy industries

Since 2020, **INDUSTRIAL EMISSIONS** have grown faster than in any other sector and **continue to rise every year.**¹

STEEL, CEMENT and **CHEMICALS** account for

70% of industrial GHG emissions.²

65% of industrial energy is **FOSSIL-FUEL BASED.**³

To keep 1.5°C in reach, emissions from heavy industries should fall by

20% by 2030

90% by 2050.⁴

2050 NET ZERO GOAL

Transition to net-zero industries requires massive investment

DECARBONIZING STEEL

requires up to **USD 335 billion** of cumulative investment by 2050.⁵

DECARBONIZING CEMENT

requires **USD 30 billion** in additional capital expenditure and **USD 300 billion** for infrastructure by 2050.⁶

DEVELOPING COUNTRIES

will need up to **USD 2.5 trillion** annually for climate-related investments by 2030.⁷

Investment needs are not yet investment opportunities

Limited market readiness of breakthrough technologies and related infrastructure.

Long lifetime of assets, high investment costs and technology risks.

Insufficient policies and low demand for low-carbon industrial products.

66% of business executives report that investment and infrastructure are the most **urgent barriers for net-zero transition.**¹⁰

90% of businesses say they would invest more if governments **implemented policies** to address sector specific barriers.¹⁰

This decade is decisive for industry decarbonization, especially for developing countries

THE NEXT 10 YEARS ARE CRITICAL

30% of emissions-heavy assets will need upgrades or replacements by 2030.⁸

2050 IS ONLY ONE INVESTMENT CYCLE AWAY.

75% of the **GLOBAL URBAN INFRASTRUCTURE** that will exist in 2050 is yet to be built, with most of this growth in developing countries.⁹

This next round of NDCs should be powerful blueprints to build a thriving low-carbon manufacturing sector, reaping long-term national benefits.

[1] Next Generation NDCs, Opportunities in the Industry Sector in NDCs, World Resources Institute, 2024 [2] Achieving Net Zero Heavy Industry Sectors in G7 Members, IEA, 2022 [3] Direct use of energy, Energy System, Energy Supply & Transformation, IEA, 2024 [4] Steel and Cement Can Drive the Decade of Action on Climate Change, Industrial Analytics Platform, 2022 [5] Making Net-Zero Steel Possible, Mission Possible Partnership, 2022 [6] IFIs and Heavy Industry Decarbonization in Emerging and Developing Economies, LeadIT, 2023 [7] The New Collective Quantified Goal on Climate Finance, OECD, 2024 [8] Net Zero Emissions by 2050 Scenario, IEA, 2024 [9] 4th Summit Report, Global Infrastructure Basel, 2014 [10] Business Breakthrough Barometer, WBCSD, 2024

Scope and Objectives

This guide is designed to assist policymakers in identifying and prioritizing policies and measures (PAMs) to enhance the ambition of industry sector targets within their Nationally Determined Contributions (NDCs) and translate these targets into actionable strategies. Building upon the foundations established in Volume 1 of the [NDC 3.0 Guidebook for Industrial Decarbonization](#), which outlines a standardized approach for strengthening NDCs, Volume 2 supports the transition from ambition to implementation.

It presents a curated list of industrial decarbonization measures aligned with the five building blocks of industrial decarbonization and offers a structured approach to turn commitments into tangible actions. Specifically, this guide aims to:

- Support the NDC enhancement process by providing a curated list of industrial decarbonization measures.
- Assist countries in integrating industrial decarbonization measures into NDC implementation through a structured approach based on the five building blocks.
- Provide guidance on overarching frameworks and supporting mechanisms to operationalize mitigation actions at the national level.
- Equip policymakers with tools to design and implement effective industrial decarbonization policies.
- Share case studies and best practices to facilitate the grouping and scaling up of GHG reduction interventions, promoting systemic and scalable climate action.

Ultimately, this guide seeks to bridge the gap between raised ambition and practical implementation, supporting countries in achieving meaningful reductions in industrial greenhouse gas emissions in line with global climate goals under the Paris Agreement.



About the NDC 3.0 Guidebook for Industrial Decarbonization

How is the guide structured?

The guide is structured to provide a comprehensive framework for industrial decarbonization, offering practical guidance for policymakers and industry stakeholders. Section 1 sets the foundation, introducing the purpose and scope of the guide. Section 2 presents the five key building blocks of industrial decarbonization, offering structured methodologies and practical guidance to help policymakers develop effective decarbonization pathways and translate commitments into concrete actions. Section 3 outlines broader mechanisms to operationalize the design and implementation of industrial mitigation actions.

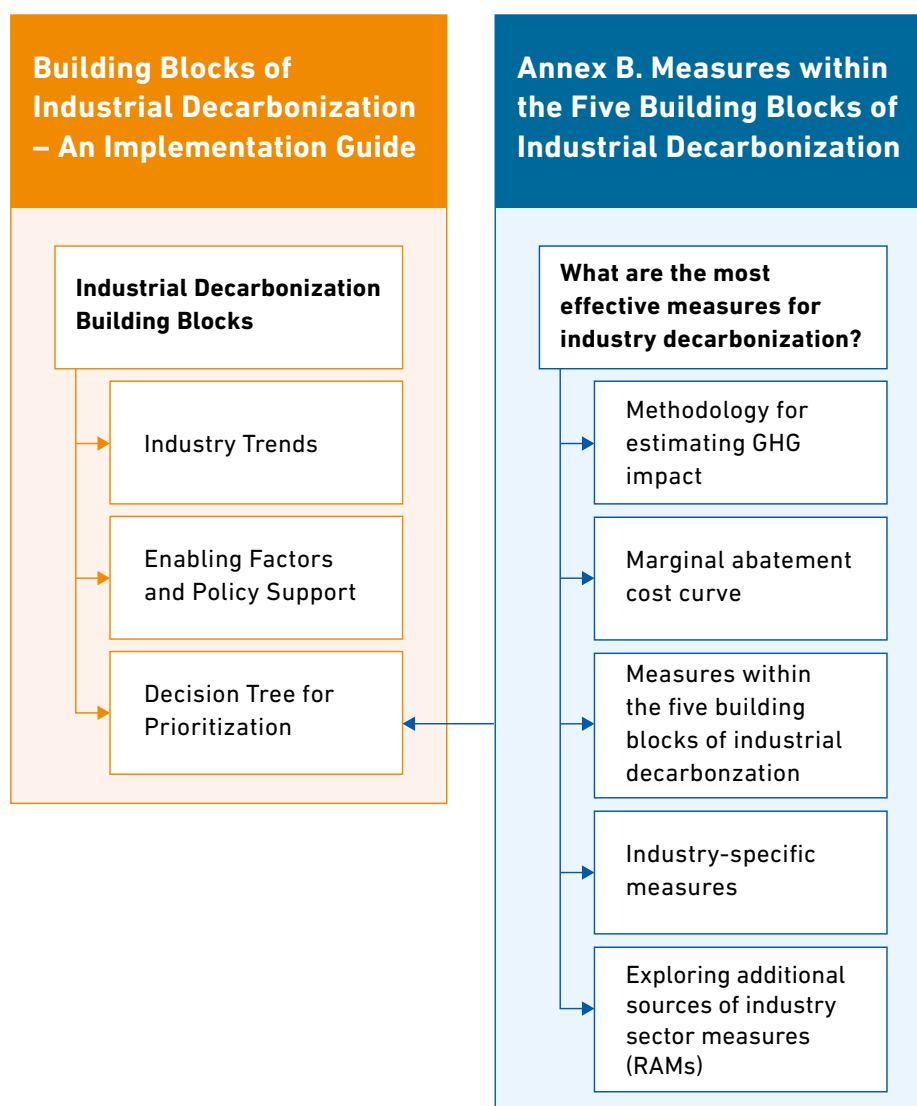


Figure 1 Overview of the guide structure.

This figure presents the structure of the implementation guide for industrial decarbonization.

Section 2 introduces the key building blocks for implementation, including industry trends, enabling factors and a decision tree for prioritizing measures. Annex B supports this process by providing a curated list of decarbonization measures that feed into the decision tree.

As the core of the guide, [Section 2. Building Blocks of Industrial Decarbonization – An Implementation Guide](#) offers a structured approach for each block, helping policymakers navigate the development of tailored decarbonization pathways. Annex B complements this by providing a comprehensive compilation of industrial decarbonization measures, enabling stakeholders to select and prioritize the most effective options.

How to navigate the guide?

To maximize the guide's effectiveness, users should first develop an understanding of the interdependence of the five industrial decarbonization building blocks, as explained in the [Overview of Industrial Decarbonization Building Blocks](#). It is also essential to assess the enabling or constraining conditions for each block in their respective national or sectoral contexts. This initial evaluation will help users identify the most appropriate block(s) for their specific situation.

Once users have selected the relevant building blocks, they can proceed through the structured approach to develop effective decarbonization pathways. The decision tree within each block provides key steps for developing effective decarbonization pathways and translating commitments into action. To support this process, [Annex B. Measures within the Five Building Blocks of Industrial Decarbonization](#) offers a comprehensive list of PAMs, allowing users to identify the most effective decarbonization measures within each block. By following this structured progression, from foundational understanding to block selection, prioritization of measures, and integration within broader policy frameworks, users will be equipped to develop and implement effective decarbonization pathways for the industrial sector, translating commitments into tangible actions.

What is the target audience?

This guidance is primarily intended for government officials, policymakers, and stakeholders involved in climate policy, particularly those responsible for the design, revision, and implementation of NDCs in the industrial sector.

It will also serve as a resource for technical experts, industry stakeholders – including industry associations, decision-makers, sector regulators, trade organizations, and major industrial operators – financial institutions, and development partners supporting industrial decarbonization efforts.

How does Volume 2 complement Volume 1 of the NDC 3.0 Guidebook for Industrial Decarbonization?

In the NDC enhancement process, Volume 2 should be considered as part of Step 5: Increasing Ambition of Targets. At this stage, countries define a framework for assessing emissions scenarios and identifying mitigation pathways to enhance their NDC targets for the next period. A key component of this process is selecting PAMs that drive emissions reductions in the industrial sector. The identification of PAMs follows a structured approach, beginning with measures that are already being implemented, followed by those that have been formally adopted for future implementation. Beyond these, countries may also consider measures that are under discussion and additional alternatives that could further support

emissions reduction efforts. Once these PAMs are identified, projections are developed based on emissions profiles, development trends, and prioritized PAMs to establish realistic and ambitious targets.

To support this step, Volume 2 of the NDC 3.0 Guidebook for Industrial Decarbonization provides a curated list of industrial decarbonization measures. This structured approach ensures that countries systematically identify and assess relevant PAMs. By integrating these measures into a projection framework, countries can evaluate their impact on future emissions, ultimately guiding the development of enhanced NDC targets.

Furthermore, Volume 2 plays a critical role in the Step 7: Country Implementation Approach, guiding the transition from NDC design to tangible action. It offers policymakers a structured methodology to develop effective decarbonization pathways for the industry sector and translate industrial decarbonization commitments into concrete steps. [Figure 2](#) illustrates how Volume 2 complements Volume 1 in the step-by-step approach for NDC enhancement.

Volume 1, in turn, also establishes the broader context by presenting a range of NDC enhancement tools, guidance on tracking and evaluating NDC progress, a clear definition of the industrial sector. By linking the ambition-raising strategies of Volume 1 with the implementation-focused guidance in Volume 2, the NDC 3.0 Guidebook provides a comprehensive roadmap to help countries achieve meaningful industrial decarbonization in the context of their NDCs.



Photo: Envato

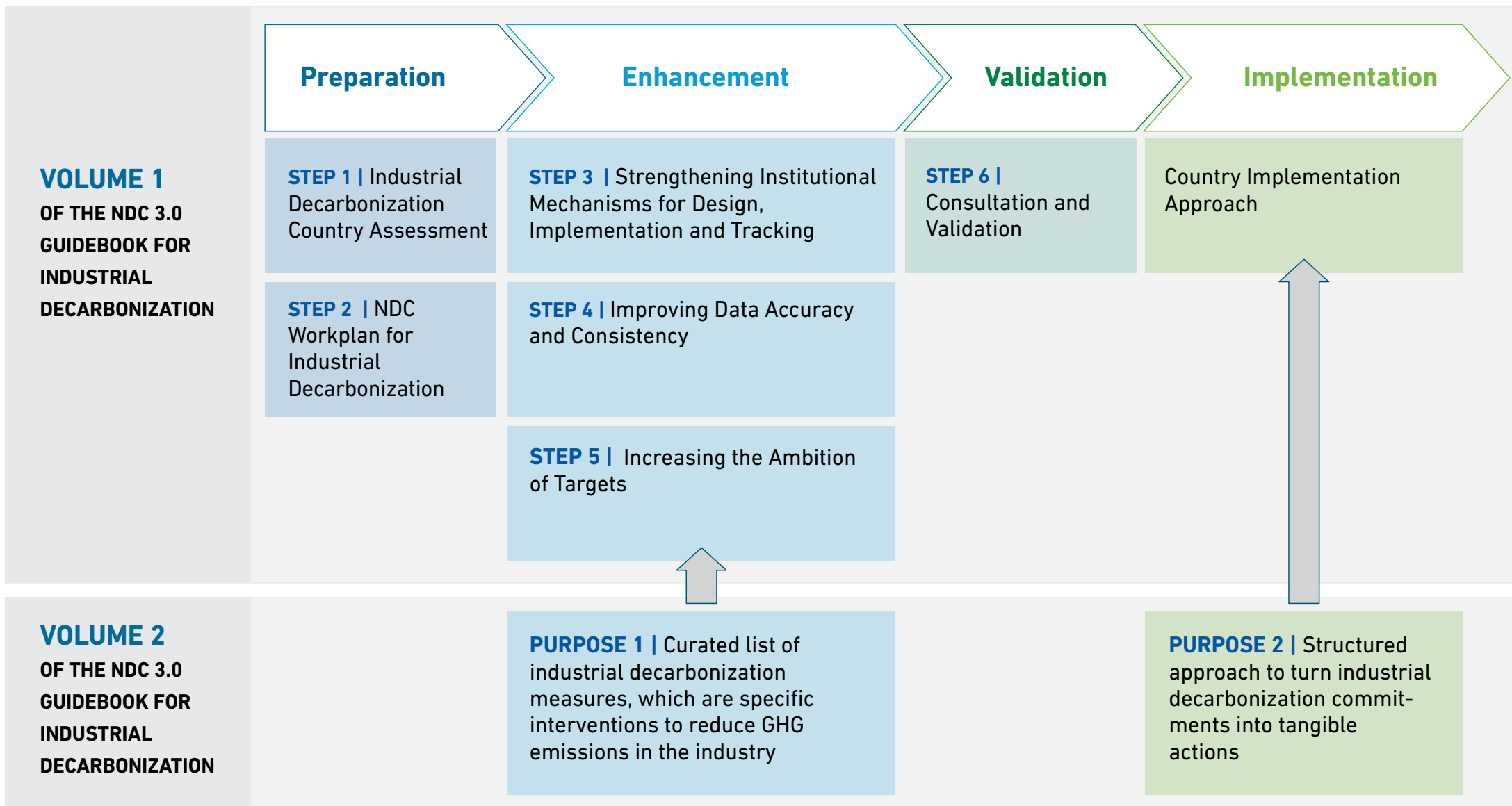


Figure 2 Linkages between Volume 1 and Volume 2 of the NDC 3.0 Guidebook for Industrial Decarbonization. Volume 1 outlines a stepwise process from assessment to implementation of industrial decarbonization within NDCs. Volume 2 supports this process by providing targeted measures to raise ambition and a structured approach to translate commitments into action.

2.

BUILDING BLOCKS OF INDUSTRIAL DECARBONIZATION – AN IMPLEMENTATION GUIDE



Overview of Industrial Decarbonization Building Blocks

This section introduces the five key building blocks of industrial decarbonization, providing a structured framework to translate national commitments into actionable strategies.

Each block is explored in detail, with practical guidance on implementing decarbonization measures. To support decision-making, the chapter includes intuitive decision trees that help policymakers and practitioners navigate key steps, such as selecting appropriate policy frameworks, analyzing case studies, and identifying effective decarbonization policies and measures (PAMs).

Industrial decarbonization is a complex but critical process to reducing GHG emissions, limiting global temperature increase, and aligning economic development with climate objectives. To facilitate this transition, five fundamental building blocks serve as the foundation for reducing emissions across industrial sectors. These building blocks – **Material Efficiency, Energy Efficiency, Low-Carbon Energy and Feedstocks, Electrification and Process Change, and Carbon Capture, Utilization, and/or Storage (CCS/CCUS)** – encompass a broad range of decarbonization measures that can be applied to different industrial contexts, from energy-intensive sectors like steel and cement to emerging industries seeking cleaner production pathways.

By leveraging these building blocks, policymakers, industry leaders, and practitioners can develop targeted PAMs that accelerate decarbonization efforts. While each block is further explored in this guide, detailing its significance both globally and within specific industries, the following box provides an initial definition of each block.

The applicability of the building blocks and the specific decarbonization measures are strongly influenced by industry-specific factors, including production processes, material use, regulatory frameworks, and economic conditions. This requires practitioners to carefully identify and prioritize options that align with national or sector-specific circumstances. In this regard, each block presents structured yet adaptable approaches that not only help identify decarbonization opportunities but also provide guidance on policy frameworks that can support effective industrial transformation.

This interdependence of the building blocks is illustrated in [Figure 3](#), encouraging practitioners to prioritize foundational options. Nonetheless, as previously noted, the applicability of the building blocks and the specific decarbonization measures depend on national and sectoral conditions. Flexibility is essential, as regional energy supply, policies, and industrial needs can shift priorities. Ultimately, all five building blocks are critical for achieving industrial decarbonization.

Box 1. Definition of the industrial decarbonization building blocks

Material Efficiency

Material efficiency is the practice of maximizing output while minimizing the use of natural resources. By optimizing material use, it reduces overall resource consumption and associated environmental impacts. At the same time, it supports economic development by ensuring a stable resource supply. A key indicator of material efficiency at the economic level is resource productivity, the ratio of economic output to material input.

Energy Efficiency

Energy efficiency refers to achieving the same level of output while using less energy. In industrial settings, this involves optimizing processes and technologies to reduce energy consumption without compromising productivity. Improving energy efficiency lowers operational costs and mitigates greenhouse gas emissions.

Low-Carbon Energy and Feedstocks

Low-carbon energy refers to any energy source produced with a significantly lower carbon footprint than fossil fuels, encompassing, among other, renewable energy, bioenergy, hydrogen, and low-carbon fuels with low or zero greenhouse gas emissions. Green hydrogen bio-based or other low-carbon feedstocks provide alternative to carbon-intensive industrial processes.

Electrification and Process Change

Electrification involves replacing fossil fuel-based technologies and processes with electric alternatives. Electrically powered systems are often more efficient, leading to lower overall energy demand. As electricity generation shifts to renewable and low-carbon sources, electrification plays an increasingly critical role in reducing industrial emissions. Process change involves introduction of new technology solutions resulting in lower carbon footprint of the final product.

Carbon Capture, Utilization, and/or Storage (CCS/CCUS)

CCS/CCUS is a technology that captures carbon dioxide (CO₂) emissions from industrial processes and either stores them underground or repurposes them for useful applications. It involves separation of CO₂ from flue gases; transport of the captured CO₂; and storage/utilization, where CO₂ is either injected into deep underground rock formations for long-term storage or repurposed to create valuable products, such as synthetic fuels and building materials.

INDUSTRIAL DECARBONIZATION: 5 BUILDING BLOCKS

These five building blocks represent essential levers for industry to achieve net-zero. They should be pursued in ways that reflect each country's industrial landscape, workforce capacity and policy context, while also leveraging opportunities for optimisation through digitalisation and AI.

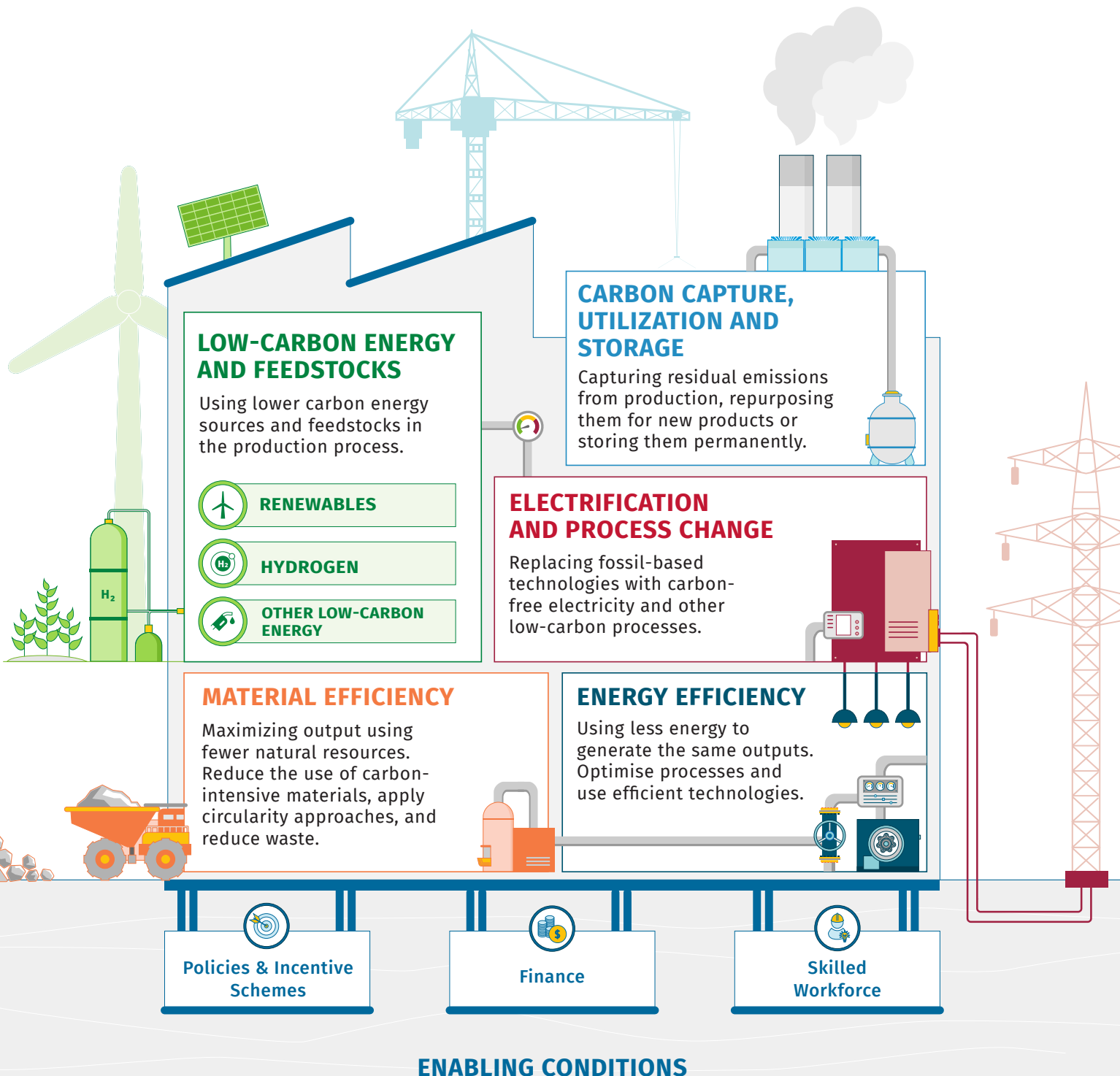


Figure 3 Interdependence of industrial decarbonization building blocks.

The building blocks reflect a logical progression based on feasibility and interdependence, rather than a hierarchy. Practitioners are encouraged to systematically evaluate each block and consider potential synergies between them, as the building blocks are not mutually exclusive. Driving the parallel implementation of different PaMs, in line with national circumstances and priorities, is critical to achieving effective industrial decarbonization. Therefore, while the building blocks are shown as a numbered process, practitioners should flexibly draw from each block according to the specific context of their national industry sectors.

For instance, material efficiency is typically a beneficial starting point, as reducing and optimizing material use influences several other building blocks. Implementing material efficiency measures can lower emissions across industries by reducing the need for raw material extraction and production. Energy efficiency often follows as a critical pathway, as improving process efficiency reduces energy demand before considering a shift to energy sources with a significantly lower carbon footprint. However, the successful deployment of energy efficiency measures may be influenced by factors such as the availability of capital for retrofits, access to financing mechanisms, and the enforcement of energy performance standards at the industrial level. Together, these two building blocks can be considered foundational.

Low-carbon energy and electrification then serve as complementary decarbonization pathways, depending on process-specific requirements. Electrification is particularly well-suited for industrial processes that require lower-temperature heat, while sectors that demand high-temperature heat, such as cement or steel production, may depend more on hydrogen or biofuels. The feasibility of these alternatives depends on factors such as fuel availability, infrastructure readiness, and cost competitiveness (IEA, 2023 [↗](#)). Finally, CCS/CCUS is often seen as a solution for emissions that cannot otherwise be mitigated. While crucial for addressing residual emissions in hard-to-abate sectors, its implementation is heavily dependent on site-specific conditions and economic feasibility.

To assist policymakers, industry leaders, and practitioners in identifying the most relevant building blocks based on their national and sectoral conditions, [Figure 4](#) presents a decision tree. This tool offers a systematic approach for selecting appropriate building blocks of industrial decarbonization, highlighting conducive or non-conducive conditions for each. Once a relevant block is identified, the corresponding section of the guide helps practitioners prioritize measures by selecting an appropriate policy framework, reviewing case studies, and identifying effective decarbonization PAMs.



Photo: Sim Kimhort/ Unsplash

Guide to the Building Blocks of Industrial Decarbonization

The decision tree provides a structures but flexible guide for industrial decarbonization. It suggests a logical sequence of options, and remains flexible: choosing one path does not exclude others.

Instead of a one-time decision, it represents an ongoing, adaptive process of making parallel investments and strategic choices based on national priorities and available technologies.

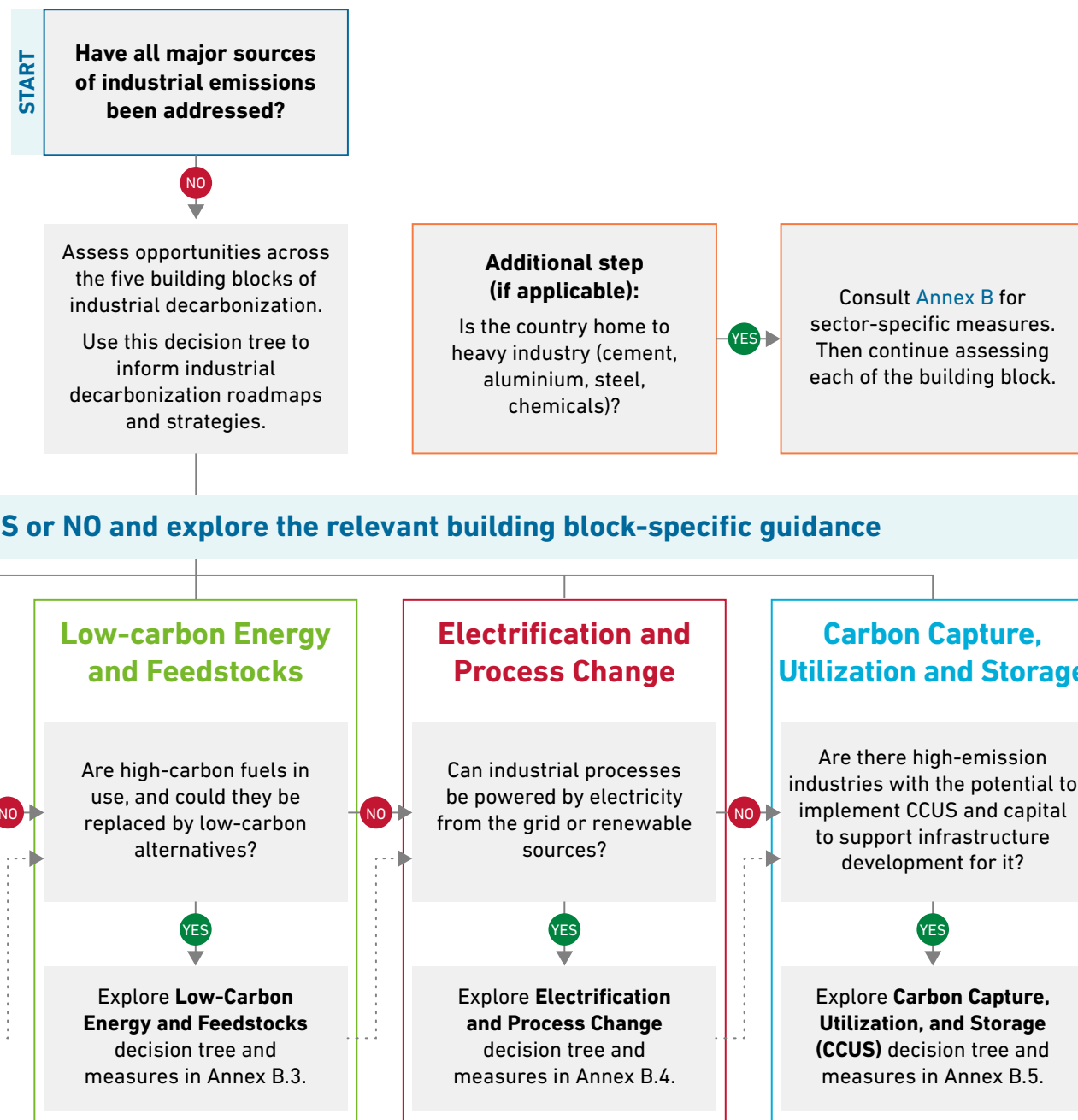


Figure 4 Decision tree guiding the selection of the building blocks of industrial decarbonization.

Building Block 1: Material Efficiency

Material efficiency refers to maximizing output while minimizing input use, often measured through indicators like resource productivity.

It involves strategies that focus on minimizing the use of resources required to produce goods and services. Opportunities to improve material efficiency exist throughout the entire lifecycle of materials and products. In industrial contexts, this includes designing products for longevity, reparability and recyclability, optimizing manufacturing processes, integrating alternative materials, and reducing the need for raw materials through smarter design approaches such as lightweighting of vehicles or buildings. Enhancing material efficiency is a fundamental step in the clean energy transition, as it directly influences energy consumption and emissions in the production of materials such as steel, cement, and aluminum. Moreover, most of the material efficiency measures are widely accessible to all countries, offering cost-effective opportunities.

Material efficiency helps reduce emissions by lowering demand for carbon-intensive materials like steel and cement through better design, reuse, and longer-lasting products.



Industry Trends

Global demand for essential materials has increased significantly over the past decades, driven by population growth, economic development, and industrialization. According to the International Energy Agency (IEA), between 1971 and 2017, global demand has risen threefold for steel, nearly sevenfold for cement, almost sixfold for primary aluminium, and over tenfold for plastics. During this same period, the global population doubled and GDP grew nearly fivefold, contributing to increased consumption and material production. This rising demand has led to substantial increases in material production, energy consumption, and CO₂ emissions (IEA, 2019 [↗](#)).

The conversion of raw materials into materials for use results in substantial energy consumption and CO₂ emissions. The industrial sector accounted for nearly 40% of global final energy consumption and nearly one-quarter of direct CO₂ emissions in 2017. Over the 25 years prior to 2017, emissions from materials production grew by more than 1.5 times, highlighting the urgent need for material efficiency improvements (IEA, 2019 [↗](#)). Most material-related emissions stem from the production of bulk materials, including iron and steel (32%), cement, lime, and plaster (25%), and plastics and rubber (13%) (International Resource Panel, 2020 [↗](#)).

Looking ahead, according to the IEA, global material demand is expected to continue increasing. Without significant changes in material consumption patterns, demand for steel is projected to grow by approximately 30%, cement by 10%, and aluminium by about 75% by 2060 compared to 2017 levels. This trend would contribute to a 15% increase in CO₂ emissions relative to 2017, underscoring the importance of managing material production and consumption to

meet climate targets (IEA, 2019 [↗](#)). Similarly, according to the Organisation for Economic Co-operation and Development (OECD), it is suggested that despite the role of decoupling – which implies an increase in the productivity of materials over time – without further policy interventions, global material use will nearly double from 89 gigatonnes (Gt) in 2017 to 167 Gt in 2060. As a result, total materials extraction is expected to grow by 88%, nearly doubling, over a 43-year period. This trend is primarily driven by rising incomes, urbanization, and industrialization, particularly in emerging economies (OECD, 2019 [↗](#)).

Despite growing material demand, industries have significant opportunities to enhance material efficiency through material-efficient practices.

Strategies can be applied across the entire supply chain, focusing on reducing material demand, increasing the use of lower-emission materials, and optimizing production processes. Over the years material demand management has appeared as a key axis to making the climate goals more achievable. For instance, if its full potential under the IEA's Clean Technology Scenario were achieved, this would reduce steel demand by 24% (equivalent to roughly six times the United States' 2017 production), cement demand by 15% (about 2.5 times India's 2017 output), and aluminium demand by 17% (1.2 times China's 2017 primary production) by 2060 (IEA, 2019 [↗](#)).

By implementing material efficiency strategies, industries can lower production costs through reduced raw material consumption and energy use. These strategies can also improve economic resilience by reducing dependence on raw material imports, exposure to volatile commodity prices, and supply chain vulnerabilities. Additionally, improving material efficiency strengthens industrial competitiveness and frees up capital for further efficiency investments.

The steel sector, for example, has considerable opportunities for material efficiency improvements. Designing products with less steel is a key starting point, as it directly reduces demand. Where steel use is still needed, increasing the recycling rate of scrap steel further reduces the need for energy-intensive primary production. Similarly, in the cement sector, substituting clinker, the most energy-intensive component, with alternative materials like fly ash or slag can reduce energy use and CO₂ emissions (IEA, 2019 [↗](#)).

Case study: LC3 – Reducing Clinker Content through LC3

Substituting clinker with alternative materials is a key material efficiency strategy in cement production. Limestone Calcined Clay Cement (LC3) combines clinker with calcined clay and limestone, both of which are widely available. This blend can reduce CO₂ emissions by up to 40% compared to Ordinary Portland Cement, without compromising performance. LC3 is particularly relevant in regions with limited access to other supplementary cementitious materials such as fly ash or slag. It can be produced with minor adjustments to existing infrastructure and supports reduced energy demand and improved resource use.

Material efficiency is one of the most accessible and cost-effective ways to cut emissions—reducing demand for energy-intensive materials like steel and cement while enhancing industrial resilience and competitiveness by reducing reliance on raw material imports.



Despite the clear benefits of material efficiency, its interventions span entire supply chains and involve multiple stakeholders, making it difficult to quantify their full mitigation potential and costs. As a result, material efficiency has often been underrepresented in climate models and integrated assessment frameworks. However, recent advancements in material flow modelling have improved the integration of material efficiency strategies into climate scenario analysis, reinforcing their role in emissions reduction (IPCC, 2022 [↗](#)).

EXPLORE MORE

- [Standards for building a low-carbon and low-clinker future \[↗\]\(#\)](#)

Enabling Factors and Policy Support

To fully realize the potential of material efficiency in industrial sectors, a range of enabling factors and supportive policies must be in place.

Enabling Factors

- **Regulatory Frameworks:** Clear policies and regulations support material efficiency by setting standards for waste reduction, circular economy practices, and material efficiency. Extended producer responsibility (EPR) schemes and mandatory recycling targets drive industry compliance and innovation.
- **Industry Collaboration & Digital Tools:** Partnerships between industries, governments, and research institutions facilitate knowledge-sharing and best practices. Digital tools such as material tracking, smart manufacturing, and blockchain-based traceability enhance resource optimization and reduce waste.
- **Economic and Cultural Factors:** The structure of a country's economy influences material efficiency opportunities. Urbanized regions may focus on construction material reuse and advanced recycling systems, while consumer behaviour and public awareness play a key role in recycling initiatives and circular economy adoption.

Policy Support

Governments play a critical role in fostering industrial material efficiency through targeted policy interventions. These can be categorized as follows:

- **Informational Policies:** Providing data-driven insights, eco-labeling programs, and best-available technology (BAT) guidance to support industry decision-making and encourage the adoption of resource-efficient practices.
- **Regulatory Policies:** Implementing extended producer responsibility (EPR) schemes, mandatory waste reduction targets, and material efficiency standards to establish clear legal frameworks for resource management.

- **Incentive Schemes:** Offering tax incentives, subsidies for circular economy initiatives, carbon pricing mechanisms, and concessional financing to lower the financial barriers associated with transitioning to resource-efficient production (IEA, 2019 [↗](#)).

Case Study: The EU Eco-design Directive

The EU Eco-design Directive establishes binding minimum requirements not only for energy efficiency but also for a variety of environmental impacts associated with industrial products throughout their life cycle, including resource consumption, emissions, and waste generation. By requiring manufacturers to meet these standards as a condition for product sales within the European market, the Eco-design Directive achieves large-scale reductions in the environmental footprint of products. This framework fosters innovation and ensures that both material and efficiency are integrated into product design from the outset.

EXPLORE MORE

- [European Commission \(2025\). Ecodesign for Sustainable Products Regulation. ↗](#)

Decision Tree for Prioritization

This section presents a decision tree to help users of the guide prioritize material efficiency measures in industry. It guides users through identifying key PaMs, selecting adequate policy frameworks and reviewing case studies while emphasizing the role of industry context and real-world examples.

Step 1. Assess decarbonization options

To support this selection, the Annexes of the guidebook includes: (A) a methodology to estimate GHG impacts using tools like MITICA; (A.1 Marginal Abatement Cost Curve) guidance on evaluating cost-effectiveness through Marginal Abatement Cost Curves (MACC); and (B.1. Material Efficiency) a list of energy efficiency measures with their applications, mitigation potential, and costs. This helps practitioners identify the most impactful and cost-effective actions, aligned with national GHG inventories.

Timeframe	Material Efficiency Measures
Short-Term High readiness in technology, infrastructure or systems. Lower additional cost; ready to scale.	Optimization of Process Water Use in Industry; Optimization of Process Heat Distribution Systems; Efficient Packaging Technologies; Closed-Loop Cooling Systems for Industrial Processes; Use of F-Gases with Small Global Warming Potentials (GWPs) in Industry; Abatement of F-Gases in Industrial Refrigeration; Replacement of Solvent-Based Processes with Water-Based Processes.
Medium-Term Moderate investment or system adaptation needed. Technologies available but requiring further integration.	Industrial Symbiosis and Waste Heat Recovery; Exploitation of Waste Heat (Insulation, Use of High-Temperature Heat Pumps); Anaerobic Digestion for Wastewater Sludge; Sludge Dewatering and Drying for Energy Recovery; Biogas from Industrial Waste for Energy Use; Aerobic Treatment with Energy-Efficient Aeration; Organic Rankine Cycle (ORC) for Waste Heat Recovery; High-Efficiency Combined Heat and Power (CHP) Systems.
Long-Term Higher-cost, emerging, or still maturing technologies requiring substantial investment.	Biogas from Industrial Wastewater Treatment; Advanced Biological Nutrient Removal (BNR) in Industrial Wastewater Treatment; Membrane Bioreactors (MBR) for Industrial Wastewater Treatment; Waste-to-Energy Technologies.

Note: This categorization considers technology maturity, infrastructure needs, and ease of integration. Short-term actions are ready to scale now. Medium-term actions need moderate investment or system adaptation. Long-term actions are typically higher-cost or still emerging.

Technology costs and capital needs vary significantly across regions and countries. Measures that appear cost-effective in one context may not be in another due to differences in energy prices, infrastructure availability, or financing conditions.

Step 2. Choose the appropriate policy framework

1. Is resource efficiency reflected in national strategies or NDCs?



2. Do industries face economic or capacity barriers to resource efficiency?



3. Is there strong infrastructure for recycling, reuse, or industrial symbiosis?



4. Are there standards or regulations on material flows?



5. Are demand-side actors engaged (e.g., consumers, public sector)?



Case studies and examples for consideration

Policymakers should review real-world examples and case studies to guide implementation. Successful case studies offer valuable insights for adapting policies to different contexts, as the opportunities and needs for adopting material efficiency measures can vary widely across industries, regions, and stages of industrial development. In this regard, it is important to assess which policy instruments have worked well in similar sectors or regions and consider adapting successful policies from other areas.



CASE STUDY | Unlocking Material Efficiency in the UK's Cement and Concrete Sector (2023)

Research study by the Department for Energy Security & Net Zero and the Department for Environment, Food & Rural Affairs.

Objective

Study the scope, potential measures and barriers as well as drivers for advancing material efficiency in the cement, construction, steel and vehicle industries.

*Note: the measures do not reflect official government policy but are developed in support of and aligned with the policy vehicles of the UK Industrial Decarbonization Strategy and the UK Concrete and Cement Industry Roadmap to Beyond Net Zero.

Measures related to material efficiency in the cement industry

- Portland cement (CEM I) intensity in concrete
- Portland Cement (CEM I) manufacturing waste recovered as raw material
- Use of recycled concrete fines in cement or concrete production
- Lean design of concrete structures
- Waste reduction in concrete manufacturing
- Use of recycled content in concrete

Implementation vehicles

- Private sector incentives
- Financial relief for energy-intensive industries
- Demand-side measures to induce low-carbon cement purchases
- R&D support for low-carbon cement and efficient use of efficient materials

Application and monitoring

- Ensure regulatory certainty for long-term company investment plans with long payback periods
- Improve the accuracy of UK emissions reporting
- Requirement that CO₂ emissions from buildings and infrastructure are assessed over their whole-life

Further information

- [Unlocking Resource Efficiency, Phase 1 Cement and Concrete Report](#)
- [Unlocking Resource Efficiency, Phase 1 Executive Summary](#)
- [UK Concrete and Cement Industry Roadmap to Beyond Net Zero](#)



CASE STUDY | Putting Industrial Policy to Work for Material Efficiency in Developing Countries – The Case of Kenya (2016)

Case studies developed by UNIDO on material efficiency in the industry.

Objective

Improving material efficiency, pursuing higher resource productivity and reducing energy, water, material costs.

Measures related to material efficiency

- Manufacturing companies to achieve standards such as ISO 9000.2001 and ISO 14001
- Enhance manufacturing by adopting eco-labelling
- Promotion of ICT as a catalyst for technical innovation
- Strategic Impact Assessment (SEA) and Environmental Impact Assessments (EIA)
- Incubation centres including infant green industries
- Trainings, audits and capacity building activities

Implementation vehicles

- Public Private Partnerships (PPP)
- Income tax holiday and exemptions from import duties on machinery, raw materials and inputs and from stamp duty and value added tax (VAT)
- Green loan pilot plans
- Grants for training
- Tax incentives for industrial parks

Application and monitoring

- Improving infrastructure, for example, through the creation of industrial technology
- Parks and incubation centres linked to industry
- Shifting from the 'business as usual approach' ('Red Tape') to an innovative business environment ('Red Carpet')
- Greening Kenya Initiative (GKI)
- Participation in Switch African Green

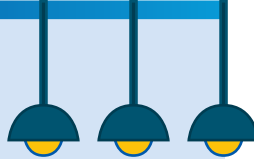
Further information

- [Putting Industrial Policy to Work for Resource Efficiency in Developing Countries](#)

Building Block 2: Energy Efficiency

Energy efficiency refers to the practice of using less energy to provide the same level of service or output. In industrial contexts, this involves optimizing processes and technologies to reduce energy consumption without compromising productivity.

Implementing energy-efficient measures is crucial for industries aiming to lower operational costs, decrease greenhouse gas emissions, enhance competitiveness, and improve the overall industry sector's resilience by reducing its dependence on energy imports. The IEA emphasizes that energy efficiency is the “first fuel” in clean energy transitions, offering some of the most cost-effective options for reducing CO₂ emissions while strengthening energy security.




Energy efficiency offers some of the most cost-effective opportunities for reducing industrial emissions while enhancing competitiveness.

Industry Trends

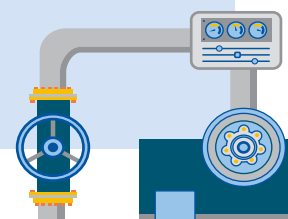
Industries have significant potential to enhance energy efficiency, leading to substantial reductions in emissions and operational costs. The [U.S. Environmental Protection Agency \(EPA\)](#) estimates that increased efficiency can reduce industrial carbon emissions by up to 34% in many sectors, while [United Nations Industrial Development Organization \(UNIDO\)](#) estimates that industries have the technical potential to decrease energy intensity by up to 26%, leading to an 8% reduction in total global energy use. The IEA further highlights that efficiency improvements, alongside electrification and behavioral change, could enhance the global economy's energy intensity by 35% by 2030, reducing energy demand while supporting economic growth. Additionally, approximately 80% of expected energy efficiency gains over the next decade are projected to result in net cost savings for industries, as lower energy consumption offsets initial investments ([IEA, 2021](#)).

For example, industries such as cement and steel require vast amounts of heat and electricity to process primary and secondary mineral and metal products, and production processes in many countries and across facilities hold substantial potential for implementing energy efficiency measures. In particular for steel production, energy costs amount to 20% to 40% of the total production ([Worldsteel Association, 2021](#)) which makes energy efficiency measures highly attractive from an economic perspective as steelmakers can significantly improve their long-term competitiveness by introducing effective energy efficiency technologies.


The cement industry, just like the steel sector, has substantial potential to enhance energy efficiency, particularly in the thermal energy consumption required for clinker production,

the key component of cement. The kilns used for the calcination process of clinker require vast amounts of thermal energy which often are derived from highly CO₂ intensive fuels such as coal or petroleum coke. By improving the efficiency of the combustion processes, thus by reducing the required energy input due to more advanced technologies, both costs and GHG emissions can be reduced. Benchmarking data from the G20 indicates that most countries operate well above the energy efficiency levels achievable with best available technology (BAT). Among G20 nations, only India approached BAT-specific thermal consumption levels across its cement sector in 2018, demonstrating the gap that remains for other countries to improve efficiency ([IEA](#) .

Energy efficiency offers one of the most cost-effective and widely applicable ways for industry to reduce emissions, cutting energy use and costs, strengthening competitiveness, and lowering reliance on energy imports.



Beyond primary energy use, industries are increasingly adopting secondary energy efficiency measures, including efficient lighting and cooling systems, advanced energy management tools, and industrial automation with smart grid integration. While not directly linked to production processes, these measures contribute to overall energy savings and emissions reduction. Energy efficiency strategies can thus be applied at every level of industrial activity, from core manufacturing operations to facility-wide improvements. As such, energy efficiency measures are among the most cost-effective solutions for reducing emissions in energy-intensive industries and play a key role in supporting industrial decarbonization across multiple sectors.

Global trends indicate a growing emphasis on energy efficiency across industrial sectors. The IEA identifies energy efficiency as the single largest measure to curb energy demand in its Net Zero Emissions by 2050 (NZE) Scenario, alongside electrification, digitalization, and material efficiency. In 2022, global energy intensity improvement reached 2%, and doubling this rate to 4% per year could reduce CO₂ emissions by 7 gigatonnes—equivalent to 20% of current global emissions—while significantly cutting industrial energy bills. As a major energy consumer, the industrial sector stands to benefit immensely from efficiency improvements through advanced technologies and optimized processes, ultimately enhancing sustainability and competitiveness ([IEA](#) .

Despite the clear benefits, several challenges hinder the adoption of energy efficiency measures across countries and sectors. Key barriers include (i) a lack of technical capacity, particularly in developing economies where workforce training and technology adoption remain limited; and (ii) regulatory and market barriers, where unclear or inconsistent policies deter industrial investment in efficiency improvements. To ensure effective adoption, countries must assess their specific industrial landscape, energy mix, and regulatory environment to determine the most suitable energy efficiency strategies and policies. A focus should be placed on deploying a combination of the three key mechanisms: regulation, information, and incentives. In this context, various policy support frameworks and regulations can be considered.

Enabling Factors and Policy Support

To fully realize the potential of energy efficiency in industrial sectors, a range of enabling factors and supportive policies must be in place.

Enabling Factors

- **Certification and Standards:**

Strong certification mechanisms, such as ISO 50001, help industries implement structured energy management systems, leading to consistent efficiency improvements. Adherence to internationally recognized energy efficiency standards ensures credibility and allows for benchmarking across sectors.

- **Measurement, Reporting, and Verification (MRV) Systems:**

Robust MRV frameworks are essential for tracking progress, assessing the effectiveness of energy efficiency measures, and ensuring compliance with national and international regulations. Reliable MRV systems enable data-driven decision-making, ensuring that policies and investments deliver measurable impacts.

- **Technology Advancement and Knowledge Transfer:**

The adoption of best available technologies (BAT) is crucial for improving industrial energy efficiency. Facilitating access to state-of-the-art solutions, promoting research and development, and fostering international cooperation on knowledge transfer can accelerate the deployment of energy-efficient technologies.

EXPLORE MORE

- [Bourgault, Jeremy & Matuβek, Milan \(2023\). Audit to measure - comparative overview of national energy audit and energy management implementation policies](#) ↗
- [International Energy Agency \(2017\). Superior Energy Performance \(SEP\)](#) ↗

Policy Support

Governments play a critical role in fostering industrial energy efficiency through targeted policy interventions. These can be categorized as follows:

Informational Policies:

- Developing energy efficiency roadmaps and best practice guidelines to assist industries in implementing cost-effective efficiency measures.
- Establishing energy audit programs that provide businesses with assessments and recommendations for reducing energy consumption.
- Promoting voluntary certification schemes, such as ISO 50001, to encourage structured energy management.
- Supporting the development of Energy Service Companies (ESCOs) that offer turnkey energy-efficient solutions, helping to overcome technical and financial barriers.
- Facilitating energy efficiency networks and voluntary agreements where companies commit to energy-saving targets and share implementation experiences (e.g. Germany's LEEN initiative).

Case Study: The Energy Star Program (n.d). Industrial Energy Management

The U.S. Energy Star program, developed by the U.S. Environmental Protection Agency (EPA), serves as a prominent example of a voluntary labelling initiative. This program sets rigorous efficiency criteria for a wide range of industrial equipment, enabling businesses and consumers to identify high-performing products. While participation in Energy Star is voluntary, the label has gained wide recognition and influence, significantly contributing to energy efficiency across the marketplace.

EXPLORE MORE

- [The Energy Star Program \(n.d\). Industrial Energy Management](#) 
- [European Commission \(2016\). Evaluation of efficiency of the Energy Star Agreement between the EU and the US](#) 

Regulatory Policies:

- Setting minimum energy performance standards (MEPS) for industrial equipment and processes to drive energy efficiency improvements.
- Implementing mandatory energy reporting requirements to enhance transparency and benchmarking across industries.
- Establishing energy efficiency obligation schemes (EEOS), where utilities or industries must achieve specific efficiency targets, often through market-based mechanisms.
- Introducing sector-specific energy efficiency mandates, such as requiring waste heat recovery systems in energy-intensive industries.
- Requiring mandatory energy audits or equivalent measures for large energy-consuming industries, as exemplified by Article 8 of the EU Energy Efficiency Directive (EED), which obliges large enterprises to carry out regular energy audits or implement energy management systems.

Incentive Schemes:

- Providing financial incentives, such as tax credits, grants, and low-interest loans, to offset the capital costs of energy efficiency investments.
- Implementing carbon pricing mechanisms, such as emissions trading systems or carbon taxes, which create financial incentives for energy efficiency improvements.

Decision Tree for Prioritization

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Timeframe	Energy Efficiency Measures
Short-Term High readiness in technology, infrastructure or systems. Lower additional cost; ready to scale.	High-Efficiency Lighting Systems in Industry; Energy-Efficient Compressed Air Systems; Use of Variable Speed Drives (VSD) in Industrial Motor Systems; High-Efficiency Electric Motors in Manufacturing; Energy-Efficient Industrial Motor Systems; Energy-Efficient Refrigeration Systems in Cold Storage.
Medium-Term Moderate investment or system adaptation needed. Technologies available but requiring further integration.	Improved Energy Efficiency in Process Heating; High-Efficiency Heat Pumps for Industrial Space Heating; Energy-Efficient Chillers and Refrigeration; Technologies Steam System Optimization in Industry.
Long-Term Higher-cost, emerging, or still maturing technologies requiring substantial investment.	Heat Pumps for Industrial Drying and Heating; Energy-Efficient Data Centers in Industry.

Note: This categorization considers technology maturity, infrastructure needs, and ease of integration. Short-term actions are ready to scale now. Medium-term actions need moderate investment or system adaptation. Long-term actions are typically higher-cost or still emerging.

Technology costs and capital needs vary significantly across regions and countries. Measures that appear cost-effective in one context may not be in another due to differences in energy prices, infrastructure availability, or financing conditions.

Step 2. Choose the appropriate policy framework

1. Is energy efficiency already reflected in the country's energy strategy or NDC?



2. Are the conditions in place for industries to address cost and capacity barriers to adopting energy efficiency?



3. Is monitoring and enforcement capacity in place?



4. Are downstream actors and the public sector engaged in driving efficiency demand?



5. Does the policy framework support diverse industrial actors (SMEs and large firms)?



Case studies and examples for consideration

Policymakers should review real-world examples and case studies to guide implementation. Successful case studies offer valuable insights for adapting policies to different contexts, as opportunities and needs for energy efficiency can vary widely across industries, regions, and stages of industrial development. In this regard, it is important to assess which policy instruments have worked well in similar sectors or regions and consider adapting successful policies from other areas.



CASE STUDY | Action Plan for Energy Saving and Carbon Reduction in the Cement Industry (2024)

Sino German Cooperation on Climate Change – NDC Implementation in China’s cement industry.

Objective

Decrease energy intensity cement clinker production by 3.7% in 2025 compared to 2020 maintaining the production level at 18 billion tons annually.

Measures related to energy efficiency

- Phasing out old and inefficient cement production capacities
- Upgrading of energy efficiency standards.
- Increase the use of renewable energy and alternative fuels to 30% (synergy with low-carbon fuel block)
- Staggered peak production to optimize supply and demand patterns
- Promote resource recycling using industrial waste to reduce the limestone demand (synergy with material efficiency building block)
- Enhance digital management of the industry to monitor energy use

Implementation vehicles

- Preferential tax policies
- Financial support schemes focused on fixed-asset investments
- Ladder electricity price system to regulate over-consumption

Application and monitoring

- Enhanced supervision
- Strengthened accounting and monitoring of energy consumption patterns
- Reinforced energy-saving review and environmental impact assessments

Further information

- [Action Plan for Energy Saving and Carbon Reduction in the Cement Industry](#)
- [China Issues Action Plan for Energy Saving and Carbon Reduction \(2024-2025\)](#)
- [Expert Interpretation: Accelerating the Green and Low Carbon Transformation of Cement Industry by Energy-saving and Carbon Reduction Transformation and Energy-using Equipment Renewal](#)



CASE STUDY | The Japan Iron & Steel Federation (JISF) Carbon Neutrality Action Plan (2021)

Technology Roadmap Formulated for Transition Finance under the Carbon Neutrality Plan.

Objective

Cut energy-related CO₂ emissions (total volume) in FY2030 by 30% compared to the FY 2013 level by adopting BATs to promote energy conservation, using waste plastics, adopting innovative technologies that are currently under development and scheduled to be in use around 2030, and using raw fuel with less CO₂ emissions. Alignment with NDC.

Measures related to energy efficiency

- Utilization of next-generation coke
- Recovery of waste heat and by-product gas
- Introduction of high productivity power generation system
- Plastic recycling, etc. in coke ovens
- Enhancement of production efficiency through the introduction of artificial intelligence (AI) and IT solutions
- Improvement in thermal conductivity
- Renovation of coke oven to improve efficiency
- Waste heat recovery
- Improvement of burners and introduction of high productivity equipment

Implementation vehicles

- Green bonds (Green Bond Principles 2021)
- Transition finance (Climate Transition Finance Handbook 2023)
- Green loans (Green Loan Guidelines 2022, Green Loan Principles 2023)
- Green/Transition Finance Framework issued transition bonds through a public offering in 2022 by JFE Holdings

Application and monitoring

- Clear implementation roadmap and progress monitoring
- Fostering public understanding on requirements and costs of carbon neutral steel
- Leveraging the New Energy and Industrial Technology Development Organization (NEDO)’s Green Innovation Fund
- Collaborative and multitrack R&D across steelmakers to enhance burden sharing

Further information

- [Policy Engagement](#)

Building Block 3: Low-Carbon Energy and Feedstocks

Low-carbon energy and feedstocks include energy sources that generate significantly lower greenhouse gas emissions than fossil fuels, such as renewables, bioenergy, hydrogen, and synthetic fuels.

Transitioning from fossil fuels to these alternatives is essential for industrial decarbonization, especially in hard-to-abate sectors like cement, steel, chemicals, and heavy transport. Many industrial processes depend on high-temperature combustion, which is challenging to electrify. In these cases, low-carbon energy sources, such as hydrogen, biofuels, ammonia and other sources of low-carbon energy, play a crucial role in achieving deep emissions reductions.

Low-carbon fuels and alternative feedstocks are becoming essential solutions for deep decarbonization.



Industry Trends

Industries that rely on high-temperature processes, such as cement production, steelmaking, and chemical production, face significant decarbonization challenges. While energy efficiency improvements and electrification can mitigate emissions to some extent, many industrial processes still depend on carbon-based fuels for combustion or chemical reactants. In these sectors, low-carbon fuels and alternative feedstocks are becoming essential solutions for deep decarbonization.

Low-carbon energy refers to a spectrum of alternatives that reduce or eliminate emissions compared to traditional fossil fuels. These include near-zero-carbon options like green hydrogen, ammonia, advanced biofuels, and synthetic fuels, as well as lower-carbon transitional fuels such as natural gas, which emits less CO₂ than coal but is still a fossil fuel. For example, transitioning from coal to natural gas in industrial boilers represents a step toward lower-carbon fuel use, while emerging technologies in steel, cement, and other industries are now advancing near-zero-carbon alternatives.

Low-emission fuels, including liquid and gaseous biofuels, hydrogen, and hydrogen-derived fuels such as ammonia and synthetic hydrocarbons produced from hydrogen and CO₂, accounted for only about 1% of global final energy consumption in 2022, with the majority coming from liquid biofuels. However, their potential for emissions reduction is significant. According to the IEA's Net Zero Emissions by 2050 (NZE) Scenario, the share of low-emission fuels, including biogases, hydrogen, and hydrogen-based fuels, is projected to rise to nearly 20% of global final energy consumption by 2050, compared to the just 1% in 2020 (IEA, 2021 [↗](#)).

One of the most promising solutions is hydrogen-based steelmaking. The direct reduction of iron ore using hydrogen (H₂-DRI) eliminates the need for coke, significantly reducing

CO₂ emissions. According to the IEA, hydrogen-based steel could account for up to 30 percent of primary steel production by 2050, provided that sufficient renewable electricity and infrastructure support large-scale hydrogen production; this route can emit up to eight times less CO₂ than the conventional basic oxygen furnace (BOF) route (IEA, 2022 [↗](#)). However, achieving this requires substantial investments in electrolyzer capacity, renewable energy, and modifications to existing steelmaking facilities.

In the cement industry, biomass-derived fuels such as biogas and biochar offer a potential replacement for coal and petroleum coke.

However, careful evaluation is needed, as some waste-derived fuels remain CO₂-intensive. Additionally, synthetic e-fuels, produced from captured CO₂ and green hydrogen, offer a carbon-neutral alternative for industrial heat generation, though high costs and technological barriers currently limit widespread deployment (IEA, 2022 [↗](#)).

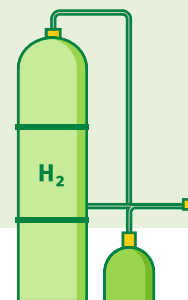
Other low-carbon alternatives, such as green ammonia, are gaining interest for high-temperature industrial applications. When produced using green hydrogen, ammonia serves as a zero-carbon fuel option for industrial heat and heavy transport (IEA, 2022 [↗](#); WEF, 2023 [↗](#)). However, large-scale adoption is constrained by several infrastructure and safety challenges, including the need for specialized transport and bunkering systems, toxicity risks, high flammability, and the potential formation of harmful nitrogen oxide (NO_x) and nitrous oxide (N₂O) emissions during combustion. (UNECE, 2025 [↗](#); Global Maritime Forum, 2022 [↗](#))

Retrofitting existing industrial equipment to accommodate low-carbon fuels is a key strategy to accelerate adoption, allowing industries to transition without requiring complete system overhauls. Additionally, fuel-switching strategies, combined with circular economy approaches, such as using biogenic waste for energy production, can further minimize emissions in the steel and cement industries.

Despite their potential, scaling up low-carbon fuels faces several challenges, including high production costs, infrastructure limitations, feedstock availability, and regulatory uncertainty. Policies such as carbon pricing, production subsidies, and blending mandates are increasingly being implemented to accelerate adoption.

Trade dynamics are increasingly influencing decisions around low-carbon fuels and feedstocks. For example, export-oriented industries such as steel and ammonia production must decarbonize not only to meet climate goals but also to maintain market access amid emerging international regulations. The EU's Carbon Border Adjustment Mechanism (CBAM), for instance, will require exporters of emissions-intensive goods—including iron, steel, and fertilizers—to disclose and reduce the carbon intensity of their products. This is likely to incentivize investments in low-carbon fuels such as green hydrogen and ammonia, as well as the integration of CCS/CCUS and energy efficiency improvements to demonstrate credible emissions reductions.

Low-carbon energy and feedstocks—such as green hydrogen, bioenergy, and synthetic fuels—are essential for deep decarbonization of heavy industry, particularly where high-temperature combustion is difficult to electrify.



In contrast, industries producing primarily for domestic markets may prioritize energy security and cost-effective fuel-switching strategies using locally available biomass, biogas, or hybrid solutions. The availability of renewable electricity is also a critical factor. Countries with abundant solar, wind, or hydropower are better positioned to scale green hydrogen and e-fuels, whereas those with limited renewable potential may face higher production costs and trade-offs.

Enabling Factors and Policy Support

To fully realize the potential of low-carbon energy sources in industrial sectors, a range of enabling factors and supportive policies must be in place.

Enabling Factors

- **Technological Innovation:** Advancements in hydrogen production, biofuel processing, and synthetic fuel development are essential for scaling low-carbon fuels. Improving electrolyzer efficiency and enhancing carbon capture for e-fuel production, can help lower costs and improve feasibility.
- **Infrastructure Development:** The expansion of hydrogen transport networks, ammonia storage facilities, and biofuel distribution systems is crucial for widespread adoption. Industrial hubs, ports, and integrated energy hubs can act as key deployment sites, ensuring efficient supply chains and reducing logistical barriers.
- **Feedstock Availability & Sustainability:** Countries with large agricultural sectors can use biomass and agricultural by-products for industrial applications. However, sustainable feedstock sourcing, land-use safeguards, and local air pollution controls must be in place to avoid unintended environmental impacts. Renewable electricity is especially important for producing green hydrogen and related fuels, which can be a challenge where renewable potential is limited. Ensuring access to clean electricity, coupled with CO₂ capture systems, will be critical to the climate credibility of synthetic fuels. Certification and traceability systems help verify emissions cuts and avoid harmful land-use change.

A distinction can also be made between emerging markets and developing economies (EMDEs) and developed countries. EMDEs, where new infrastructure is still being built, should focus on design-phase interventions maximizing durability, reuse and recyclability. Developed countries, with more scrap available, may benefit more from improving recycling systems and scaling up secondary production.

Policy Support

Governments play a critical role in fostering industrial low-carbon energy deployment through targeted policy interventions. These can be categorized as follows:

- **Informational Policies:** Developing industry roadmaps, facilitating knowledge-sharing on best practices, and implementing certification programs to enhance transparency and promote adoption.

- **Regulatory Policies:** Establishing blending mandates, setting emissions performance standards, and introducing infrastructure requirements to create a stable market for low-carbon fuels. Trade-aligned regulation, such as carbon labelling and CBAM alignment, can further incentivize alignment with international markets.
- **Incentive Schemes:** Implementing carbon pricing mechanisms, providing subsidies for green hydrogen and biofuels, and utilizing contracts for difference (CfDs) to close cost gaps and incentivize private-sector investment (IEA, 2021 [↗](#)).

Case Study: The Central to Germany's Climate Action Program 2030

This program is the [German Renewable Energy Act \(EEG\)](#) [↗](#), which establishes sector-wide emissions goals and mandates a progressive transition toward renewable energy across the economy. The EEG is supported by sector-specific strategies that guide industrial players toward emissions reductions through renewable energy use and the adoption of low-emission technologies.

EXPLORE MORE

- [Germany's Renewables Energy Act, International Energy Agency](#) [↗](#)

Decision Tree for Prioritization

This section presents a decision tree to help users of the guide prioritize low-carbon energy and feedstocks measures in industry. It guides users through identifying key PaMs, selecting adequate policy frameworks and reviewing case studies while emphasizing the role of industry context and real-world examples.

Step 1. Assess decarbonization options

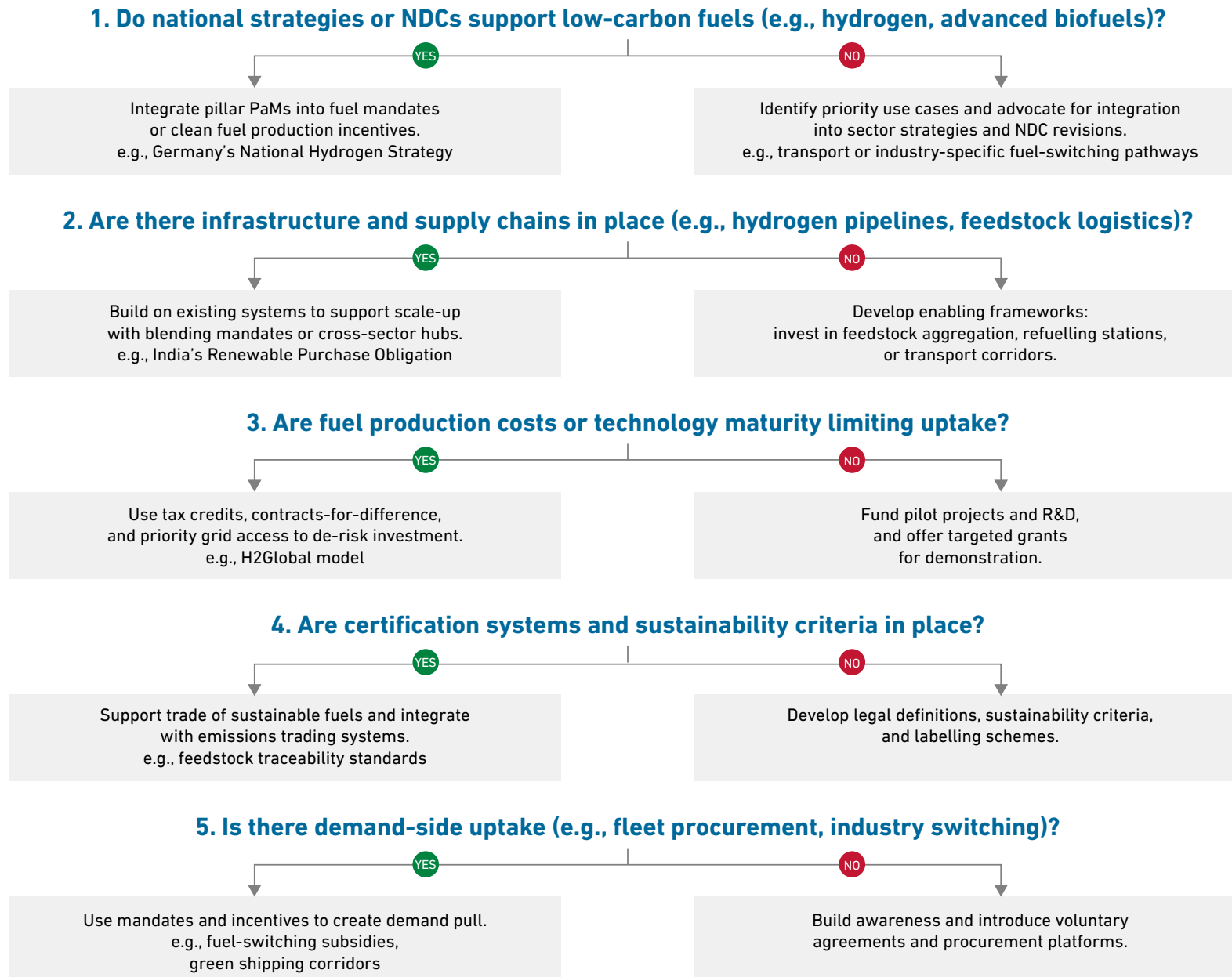
To support this selection, the Annexes of the guidebook includes: (A) a methodology to estimate GHG impacts using tools like MITICA; (A.1 Marginal Abatement Cost Curve) guidance on evaluating cost-effectiveness through Marginal Abatement Cost Curves (MACC); and (B.3. Low-Carbon Energy and Feedstocks) a list of energy efficiency measures with their applications, mitigation potential, and costs. This helps practitioners identify the most impactful and cost-effective actions, aligned with national GHG inventories.

Timeframe	Low Carbon Energy and Feedstocks Measures
Short-Term High readiness in technology, infrastructure or systems. Lower additional cost; ready to scale.	Fuel Switch from Coal to Natural Gas; Fuel Switching from Heavy Fuel Oil (HFO) to Natural Gas; Fuel Switching from Diesel to Natural Gas in Industrial Transport; Fuel Switch from Diesel to Biodiesel in Industrial Transport; Switching from Conventional Diesel to Biofuels in Logistics; Use of Biofuels for Industrial Boilers.
Medium-Term Moderate investment or system adaptation needed. Technologies available but requiring further integration.	Fuel Switch from Coal to Biomass; Replacement of Coal with Biomass in Industrial Boilers; Use of Green Hydrogen for Industrial Heat.
Long-Term Higher-cost, emerging, or still maturing technologies requiring substantial investment.	Production of Synthetic Fuels from H ₂ and CO ₂ ; Carbon-Neutral Synthetic Fuels in Industry; Carbon-Neutral E-Fuels for Industrial Transport.

Note: This categorization considers technology maturity, infrastructure needs, and ease of integration. Short-term actions are ready to scale now. Medium-term actions need moderate investment or system adaptation. Long-term actions are typically higher-cost or still emerging.

Technology costs and capital needs vary significantly across regions and countries. Measures that appear cost-effective in one context may not be in another due to differences in energy prices, infrastructure availability, or financing conditions.

Step 2. Choose the appropriate policy framework



Case studies and examples for consideration

Policymakers should review real-world examples and case studies to guide implementation. Successful case studies offer valuable insights for adapting policies to different contexts, as the adoption of low carbon fuels can vary widely across industries, regions, and stages of industrial development. In this regard, it is important to assess which policy instruments have worked well in similar sectors or regions and consider adapting successful policies from other areas.



CASE STUDY | Hydrogen Breakthrough Ironmaking Technology Pilot Project in Sweden (2018-2024)

HYBRIT is a joint venture between SSAB, LKAB (EU's largest Iron ore producer) and Vattenfall, aiming to replace coal with hydrogen in the steelmaking process. HYBRIT received the World Economic Forum's 'Moving Force in Business' Award in Davos 2025.

Note, HYBRIT is not a policy per se, but rather a technological blueprint for sectoral adoption.

Objective

The key objective of this pilot project was to achieve fossil-free steel production ready for industrialisation by replacing coal-based blast furnaces with direct hydrogen-based reduction technology.

Measures related to use of low carbon fuels

- Fossil-free production of iron ore pellets
- Development of new sponge iron product with unique properties
- Hydrogen-based direct reduction on a semi-industrial scale
- Melting of fossil-free iron raw material in an electric arc furnace
- Green hydrogen (as a carbon-neutral fuel) production and storage

Implementation vehicles

- Support from EU Innovation Fund in development
- Inter-industrial collaboration between iron ore mining company, steelmaker and energy producing company

Application and monitoring

Application at industrial scale in SSAB plants
Requirement: economically viable production of green hydrogen

Further examples of green steel initiatives include:

- [Whyalla Green Steel Project \(Australia\)](#)
- [Hydnum Steel \(Spain\)](#)

Further information

- [Fossil-free steel – a joint opportunity!](#)
- [HYBRIT®. A new revolutionary steelmaking technology.](#)
- [The HYBRIT story: unlocking the secret of green steel production](#)



CASE STUDY | Brazilian National Biofuel Policy (2017)

National Policy to enhance the use of biofuels in the transport and industry sectors.

Objective

Reduce the carbon intensity by expanding the use of biofuels and creating a carbon credit market to offset emissions of greenhouse gases by fossil fuels.

Measures related to use of low carbon fuels

Market mechanism to reduce the carbon share in fuels:

- Target setting for decarbonization and development of decarbonization credits (CBIO) provided to industries based on their fuel production
- For every ton of CO₂ saved, industries obtain one CBIO that can be traded in the market

Increase the fuel quality standard

Development of Energy and Environmental Efficiency using a Life Cycle Assessment tool (RenovaCalc) to obtain accreditation

Implementation vehicles

- Financial incentives to industries in form of a cap-and-trade system
- Financial incentives to develop innovations in biofuel production and combustion
- Legal requirement to purchase a share of CBIOs for fuel production

Application and monitoring

- Regulatory framework to regulate and revitalise the biofuels sector
- CBIOs controlled and certified and the National Petroleum Agency
- CBIOs registered on the Brazilian Stock Exchange adding an additional layer of institutional control
- Burden of proof for biofuel producers to ensure compliance with environmental legislation

Further information

- [Brazilian Biofuels Policy \(RenovaBio\)](#)
- [RenovaBio \(Government of Brazil\)](#)

Building Block 4: Electrification and Process Change

Electrification refers to the transition from fossil fuel-based technologies and processes to electric alternatives and is a fundamental strategy in industrial decarbonization.

This shift is particularly significant for energy-intensive industries, as electric technologies such as electric boilers, heat pumps and induction heating often operate with higher efficiency than their fossil-fuel counterparts, leading to reduced overall energy demand. As electricity generation becomes increasingly reliant on renewable sources, its emissions reduction potential continues to grow, making electrification one of the most effective pathways for cutting CO₂ emissions in the industrial sector. Electrification also complements other decarbonization building blocks: it supports energy and material efficiency by reducing thermal losses and enabling digital energy management, and it enables the use of low-carbon hydrogen produced via electrolysis, which can be further decarbonized through CCUS in hydrogen-based processes.

Replacing fossil fuels with renewable electricity and redesigning core industrial processes, such as switching to electric arc furnaces in steel or electric kilns in ceramics, can deliver major emissions cuts and support long-term net zero transitions.



Industry Trends

Electrification and process change present a significant opportunity to reduce total energy demand in industry, as electric technologies are generally far more efficient than their fossil fuel-based counterparts. The decarbonization benefits of electrification are closely tied to the expansion of renewable energy generation, creating a mutually reinforcing cycle. As industries increasingly transition to electricity, additional capacity is integrated into the power system, helping to manage the variability of renewable energy sources. Likewise, as renewables make up a larger share of electricity generation, the carbon intensity of industrial energy use declines accordingly (IEA [2023](#)), with additional cost savings expected for industries as renewable energy becomes cheaper and more abundant across countries.

Despite these benefits, fossil fuels, particularly coal, remain the dominant energy source for industry, accounting for roughly a quarter of global energy-related CO₂ emissions. In 2022, the industrial sector accounted for 37% of global energy consumption, with its energy mix evolving gradually. The share of fossil fuels in industrial energy use declined from 74% in 2010 to approximately 65% in 2022, largely due to the increased use of electricity, which rose from 19% to 23%, driven by growth in light industries (IEA [2023](#)). However, electrification in industry has progressed more slowly than it needed to align with net-zero pathways.

A substantial portion of fossil fuel use is dedicated to low- and medium-temperature heat and steam production across various sectors, including textiles, paper, and food and beverage processing. Many of these processes could be electrified using commercially available and mature technologies, such as industrial heat pumps and electric boilers (IEA [↗](#)). In contrast, high-temperature processes, including steelmaking, cement production, and petrochemical refining, pose greater challenges due to their extreme heat requirements (often exceeding 1000°C), complex production processes, and high energy demands (IPCC, 2022 [↗](#)).

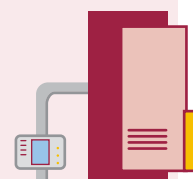
The iron and steel sector illustrates these challenges. Coal currently supplies around 75% of total energy and feedstock demand in the sector, a figure that has remained relatively stable over the past decade. While full electrification remains difficult, significant progress has been made in ancillary services and secondary steel production. For instance, through the use of electric arc furnaces (EAFs) for scrap-based steel production. Similarly, the cement industry, while traditionally reliant on fossil fuels, is exploring electrification potential, such as the use of electrically generated plasma as an alternative heat source in clinker production. Additionally, there are opportunities to integrate cement production with electric steel recycling to enhance overall efficiency and sustainability.

Geothermal energy can provide stable, low-carbon heat for industrial processes, particularly in sectors like food, pulp and paper, and chemicals. It offers potential for medium to high-temperature applications in some regions, helping reduce reliance on fossil fuels where suitable resources and infrastructure exist (IEA, 2024 [↗](#)).

The shift toward electrification is gaining momentum as countries work toward climate targets and seek to reduce fossil fuel dependency. According to the IEA's *World Energy Outlook 2024*, renewable energy sources are projected to supply over 70% of global electricity generation by 2050, underscoring the essential role of clean electricity in industrial decarbonization (IEA, 2024 [↗](#)). The IEA's *Net Zero Emissions by 2050 (NZE) Scenario* highlights that the direct substitution of fossil fuels with low-emissions electricity will be one of the most significant contributors to emissions reductions, accounting for approximately 20% of total reductions by 2050. Industrial electricity demand is projected to more than double between 2020 and 2050, rising by over 11,000 TWh, with most of this increase coming from low- and medium-temperature heat electrification and electric arc furnaces for steel (IEA, 2021 [↗](#)).

However, achieving widespread industrial electrification requires substantial investments in grid infrastructure, energy storage, and policy support. Expanding transmission capacity, ensuring stable electricity supply, and deploying energy management solutions will be critical to meeting the growing demand from industrial electrification while maintaining grid reliability and cost-effectiveness.

Electrification holds major potential to decarbonize low- and medium-temperature industrial processes using mature technologies—yet scaling it for high-temperature sectors like steel and cement will require significant innovation, investment, and grid upgrades.



Enabling Factors and Policy Support

To fully realize the potential of electrification and process change in industrial sectors, a range of enabling factors and supportive policies must be in place.

Enabling Factors


- **Technological Innovation:** Continued advancements in electric process heating technologies are crucial for industrial decarbonization. For example, the development of industrial heat pumps that can operate at higher temperatures is key. Research and development efforts must prioritize improving the efficiency and cost-effectiveness of these technologies to make them viable for a broader range of industrial applications.
- **Grid Capacity and Reliability:** As industries electrify, the demand for electricity will increase substantially. Ensuring that electrical grids can handle these higher loads without compromising reliability is vital. This may require significant upgrades to grid infrastructure, as well as the integration of smart grid technologies to manage and optimize electricity distribution.
- **Industrial Integration and Flexibility:** Electrified processes can also contribute to grid flexibility, especially when supported by thermal storage or demand-side management. Strategically locating electrified industries near renewable generation sites can reduce transmission needs and enhance grid balancing.

Policy Support

Governments play a critical role in fostering industrial electrification through targeted policy interventions. These can be categorized as follows:

- **Informational Policies:** Governments can provide valuable data, case studies, and technical assistance to industries, helping raise awareness of the benefits and feasibility of electrification. These initiatives can guide industries in making informed decisions and adopting new technologies.
- **Regulatory Policies:** Establishing clear standards and regulations that either encourage or mandate the adoption of electric technologies in industrial processes is essential. Such policies can drive systemic change by setting minimum energy performance standards and creating a regulatory environment conducive to the widespread deployment of electrification technologies.
- **Incentive Schemes:** Financial incentives, such as tax credits, grants, and low-interest loans, can significantly reduce the upfront costs of electrification projects. These market-based policies help offset the initial capital investment required for industries to transition to electric technologies, making the shift to electrification more financially feasible (IEA).

EXPLORE MORE

- [Tracking Electrification, The International Energy Agency \(IEA\)](#) 

Decision Tree for Prioritization

This section presents a decision tree to help users of the guide prioritize electrification, technology and innovation measures in industry. It guides users through identifying key PaMs, selecting adequate policy frameworks and reviewing case studies while emphasizing the role of industry context and real-world examples.



Step 1. Assess decarbonization options

To support this selection, the Annexes of the guidebook includes: (A) a methodology to estimate GHG impacts using tools like MITICA; (A.1 Marginal Abatement Cost Curve) guidance on evaluating cost-effectiveness through Marginal Abatement Cost Curves (MACC); and (B.4. Electrification and Process Change) a list of energy efficiency measures with their applications, mitigation potential, and costs. This helps practitioners identify the most impactful and cost-effective actions, aligned with national GHG inventories.

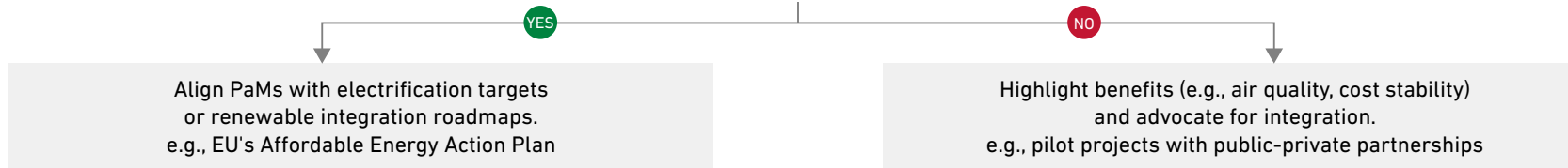
Timeframe	Electrification and Process Change Measures
Short-Term High readiness in technology, infrastructure or systems. Lower additional cost; ready to scale.	Electrification of Forklifts and Material Handling Equipment; Solar Photovoltaic (PV) Systems for Self-Consumption in Industry; Electric Boilers for Steam Generation; Electrification of Heat in Food Processing; Electrification in Industry.
Medium-Term Moderate investment or system adaptation needed. Technologies available but requiring further integration.	On-Site Renewable Energy Generation for Industrial Facilities; On-Site Solar Thermal for Process Heating; Installation of Energy Storage Systems for Industrial Facilities; Electrification of Mechanical Drives in Heavy Industry; Electrification of Drying Processes in the Paper Industry; Electrification of Kilns in the Ceramics Industry; Production of Electricity from Biomass Residues; Use of Renewable Heat in Industry.
Long-Term Higher-cost, emerging, or still maturing technologies requiring substantial investment.	Electrification of High-Temperature Industrial Processes; Hydrogen Fuel Cells for Industrial Backup Power; Electrification of Heavy-Duty Vehicles in Industry.

Note: This categorization considers technology maturity, infrastructure needs, and ease of integration. Short-term actions are ready to scale now. Medium-term actions need moderate investment or system adaptation. Long-term actions are typically higher-cost or still emerging.

Technology costs and capital needs vary significantly across regions and countries. Measures that appear cost-effective in one context may not be in another due to differences in energy prices, infrastructure availability, or financing conditions.

Step 2. Choose the appropriate policy framework

1. Is electrification featured in the national energy or industrial strategy?



2. Is grid infrastructure and energy mix favourable to electrification?



3. Are capital costs a barrier for switching to electric technologies?



4. Are key sectors technologically ready to electrify processes?



5. Are users and energy suppliers engaged?



Case studies and examples for consideration

Policymakers should review real-world examples and case studies to guide implementation. Successful case studies offer valuable insights for adapting policies to different contexts, as industrial electrification opportunities and needs can vary widely across industries, regions, and stages of industrial development. In this regard, it is important to assess which policy instruments have worked well in similar sectors or regions and consider adapting successful policies from other areas.



CASE STUDY | Net Zero Basque Super Cluster (2024)

Industrial hub roadmap part of the World Economic Forum Industrial Clusters Initiative, spearheaded by the Basque Business Development Agency.

Objective

Development of roadmaps for the 23 industries in the oil refining, steel, cement and pulp and paper sector that form the hub.

Measures related to industrial electrification focused on cement and steel

- Electrification of the calcination process and heating through electric energy
- Use of electrolysis for decarbonation of calcium carbonate prior to clinker production in the kiln
- Electrification of heating processes in the steel industry such as use of electric arc furnaces (EAC)
- Use of inductive furnaces
- Use of biogas in the steel industry
- On-site renewable energy production and consumption
- Co-processing of refuse derived fuels (RDF)

- Implementation vehicles
- Advance the development of regional certified financial models for electrification investment
- Incentive schemes for ramp-up of renewable energy use for industrial heating
- Fiscal incentives for R&D and innovation
- 30% fiscal deduction on the CAPEX for clean technologies provided in the Basque country

Application and monitoring

- Close collaboration between government and enterprises forming public-private partnerships
- Prioritisation of shared objectives across industries to leverage scale and synergies
- Fostering scaling and demand aggregation through the hub
- Resource-sharing across industries

Further information

- [Industrial Electrification: Strategies and Policies for Europe - Briefing Paper](#)
- [Net-Zero Basque Industrial Super Cluster](#)



CASE STUDY | The Technology Collaboration Programme on Heat Pumping Technologies (2020)

The TCP-HCP by the IEA, developed the report on industrial heat pumps providing an extensive overview of key applications counting 342 installations around the globe.

Objective

Development of a framework which structures information on IHP applications using existing and new case studies, selecting excellent application opportunities.

Measures related to industrial electrification focused on cement and steel

- Electric boilers both for heating and cooling in the industry (proposed range from -60°C to 150°C)
- Waste heat as source for heat pumps
- Electric drying especially in ceramic industry
- Heat pumps in cutting and washing processes in the mechanical manufacturing industry
- Heat pumps for drying, sterilization, evaporation, and steam generation processes
- Consideration of OSMOSE integration tool for the integration of heat pumps into industrial processes

**Note, recommendations are compiled from additional sources providing insights into policy schemes driving the ramp-up of heat pumps in the industry.*

Implementation vehicles

- Tax levy on manufacturers failing to meet heat pump sales quotas as share of overall sales (UK Clean Heat Market Mechanism)
- European Heat Pump Association (EHPA (subsidy overview)): Grants for heat recovery, grants and contracts for difference for electric boilers and heat pumps, energy saving certificate for different heat pump systems, concessional loans, tax exemptions

Application and monitoring

- Prioritization of industries with large application potential
- Strategic alignment between sectors and stakeholders such as proposed by the Heat Pump Accelerator Platform in the EU

Further information

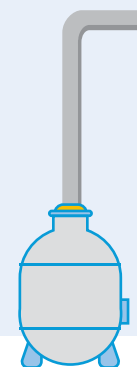
- [Final Report Annex 48: Industrial Heat Pumps, Second Phase](#)
- [Subsidies for industrial heat pumps in Europe](#)
- [The Heat Pump Accelerator Platform](#)
- [House of Commons Official Report - Energy Security and Net Zero](#)

Building Block 5: Carbon Capture, Utilization, and/or Storage

Decarbonizing the industrial sector is particularly challenging, as emissions come from both fossil fuel use and chemical reactions within production processes.

About one-third of industrial energy demand is for high-temperature heat, where alternatives to fossil fuels are still limited. Process emissions, caused by unavoidable chemical reactions, make up around one-quarter of total industrial emissions. Carbon Capture, Utilization, and/or Storage (CCS/CCUS) plays a crucial role in addressing these challenges. It captures CO₂ from large-scale energy and industrial sources, especially in hard-to-abate sectors like cement and steel, and either stores it underground or repurposes it. Where material and energy efficiency, electrification, or low-carbon fuels fall short, CCS/CCUS offers a key solution to achieving deep emissions reductions while supporting industrial competitiveness ([IEA, 2019](#)).

CCUS can play an important role in addressing process emissions that are difficult to eliminate through efficiency measures or fuel switching.



Industry Trends

CCS/CCUS technologies fall into three broad categories ([UNECE, 2021](#); [IEA](#)):

- **Post-combustion capture uses solvents** (typically amine-based) to remove CO₂ from flue gases. This is compatible with cement production and captures both combustion and process emissions without disrupting the production process.
- **Oxyfuel combustion burns fuel** in pure oxygen rather than air, increasing the CO₂ concentration in flue gases and reducing NO₂ emissions. It improves the efficiency of combustion but requires an air separation unit, which adds cost and complexity.
- **Pre-combustion capture separates CO₂ from the fuel gas** before combustion, typically in gasification or reforming systems. While this approach has limited relevance in existing industrial plants, it can be effectively integrated into new hydrogen-based facilities, such as DRI steelmaking using natural gas reforming. UNECE highlights that pre-combustion capture is particularly suitable for hydrogen production and other processes where CO₂ can be removed from syngas before combustion ([IEA](#)).

IN THE STEEL SECTOR: Production relies on two main routes: blast furnace–basic oxygen furnace (BF–BOF) and electric arc furnace (EAF). The BF–BOF route uses coke as a reducing agent and energy source, resulting in high CO₂ emissions. The EAF route, which typically uses recycled scrap, is less emissions-intensive, though still reliant on the carbon intensity of electricity. While the steel sector is increasingly shifting towards green hydrogen–based DRI and EAF wherever feasible, CCS/CCUS remains important for decarbonizing BF–BOF assets, particularly where asset turnover is constrained and infrastructure already exists.

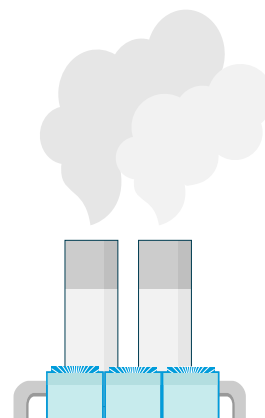
IN THE CEMENT SECTOR: Process emissions from the calcination of limestone represent roughly 60% of total emissions and cannot be avoided through fuel switching or electrification. As such, CCS/CCUS remains the most viable solution for addressing residual emissions in most conventional cement production processes.

Although upstream measures such as material and energy efficiency, electrification, and novel technologies are essential for industrial decarbonization, the current pace of deployment remains insufficient. This makes CCS/CCUS a necessary component for managing residual emissions in hard-to-abate sectors, especially cement and BF–BOF steel. The IPCC AR6 Synthesis Report reinforces this role, highlighting that CCS/CCUS is needed where process emissions cannot be eliminated through other means. (IEA, 2021 [↗](#), IPCC AR6 Synthesis Report [↗](#)),

Despite the emergence of alternative solutions, such as green hydrogen-based DRI in steel and low-clinker or alternative binder cement, many existing industrial assets cannot feasibly transition in the short term. In these contexts, CCS/CCUS is often a scalable solution. However, it is important to note that in many developing countries, CCS/CCUS is considered a last-resort option due to its high capital intensity, long infrastructure timelines, and limited access to shared CO₂ transport and storage infrastructure (UNECE, 2021 [↗](#)).

Around 45 commercial facilities are currently in operation, applying carbon capture, utilisation and storage (CCS/CCUS) to industrial processes, fuel transformation and power generation. While deployment has historically lagged behind expectations, momentum has grown substantially in recent years. More than 700 projects are now in various stages of development across the CCS/CCUS value chain. In 2023, announced capture and storage capacity for 2030 grew significantly — reaching around 435 million tonnes and 615 million tonnes of CO₂ per year, respectively (IEA [↗](#)).

Today, about 65% of global CO₂ capture is from natural gas processing, the most cost-effective application, but the project pipeline is diversifying. By 2030, capture capacity is projected to include 95 Mt from hydrogen production, 90 Mt from power generation, 50 Mt from industrial processes (e.g. cement and steel), and 65 Mt from direct air capture (DAC) plants (IEA [↗](#)).



CCS/CCUS remains a critical solution for reducing residual CO₂ emissions in hard-to-abate sectors, particularly where process emissions from chemical reactions cannot be addressed through energy efficiency, electrification, or low-carbon fuels.

Despite this progress, CCUS deployment continues to face technological, economic, institutional, environmental, and socio-cultural barriers. Current global CCS/CCUS implementation rates remain well below those modeled in pathways limiting global warming to 1.5°C or 2°C. In addition, there is a risk of carbon lock-in, particularly if CCUS is used to prolong the operation of fossil-based assets with long lifetimes, potentially resulting in stranded infrastructure. Strengthening policy frameworks, increasing public support, and advancing technological innovations will be key to overcoming these barriers and accelerating CCUS adoption (IPCC [2024](#)).

Enabling Factors and Policy Support

To fully realize the potential of CCS/CCUS in industrial sectors, a range of enabling factors and supportive policies must be in place.

Enabling Factors

- **Technological Innovation:** Advancements in CO₂ capture technologies are critical for enhancing efficiency and reducing the costs of CCS/CCUS in cement and steel production. Research into CO₂ utilization pathways, including the production of synthetic fuels and chemicals, can provide additional value streams and improve the economic viability of CCS/CCUS projects.
- **Infrastructure Development:** A well-developed CO₂ transport and storage infrastructure is critical to scaling up CCS/CCUS. This includes building dedicated CO₂ pipelines and identifying suitable geological storage sites. Industrial hubs, where multiple facilities share CCS/CCUS infrastructure, can leverage economies of scale to reduce costs and improve overall system efficiency (UNECE, 2021 [2021](#)).

Policy Support

Governments play a critical role in fostering industrial CCUS through targeted policy interventions (AFID, 2024 [2024](#)). These can be categorized as follows:

- **Informational Policies:** Industry-specific roadmaps, best practice guidelines, and technical assistance can help companies navigate the complexities of CCS/CCUS deployment. Clear and transparent communication is also essential to raise public awareness and acceptance, especially regarding safety, environmental risks, and how these are addressed through regulation.
- **Regulatory Policies:** Clear regulatory frameworks for CO₂ storage and emissions standards provide legal certainty and create a favorable environment for CCS/CCUS deployment. This includes rules on CO₂ storage site selection and permitting, pipeline and infrastructure safety, long-term liability, and transparent MRV systems aligned with international standards. Integrating CCS/CCUS into national climate plans and NDCs sends a strong signal of policy commitment.
- **Incentive Schemes:** Financial incentives such as tax credits, grants, and carbon pricing mechanisms can help overcome the high capital and operational costs of CCS/CCUS. Governments can also support investment through public-private partnerships and instruments like carbon contracts for difference (CCfDs), which provide revenue stability and help de-risk early projects.

Case Study: Canada's Investment Tax Credit for CCS/CCUS

Canada's 2022 federal budget introduced a dedicated investment tax credit (CCUS-ITC) to accelerate the deployment of carbon capture technologies. The credit covers between 37.5% and 60% of eligible project costs incurred between 2022 and 2030, depending on the technology and application. To incentivize early action, the value of the credit drops by 50% for expenditures after 2030. Eligibility is contingent on companies implementing a robust validation and verification process to ensure emissions reductions are credible and transparent. (AFID, 2024 [↗](#)).

EXPLORE MORE

- [Canada's Investment Tax Credit for CCS/CCUS \[↗\]\(#\)](#)

Decision Tree for Prioritization

This section presents a decision tree to help users of the guide prioritize CCS/CCUS measures in industry. It guides users through identifying key PaMs, selecting adequate policy frameworks and reviewing case studies while emphasizing the role of industry context and real-world examples.

Step 1. Assess decarbonization options

To support this selection, the Annexes of the guidebook includes: (A) a methodology to estimate GHG impacts using tools like MITICA; (A.1 [Marginal Abatement Cost Curve](#)) guidance on evaluating cost-effectiveness through Marginal Abatement Cost Curves (MACC); and (B.5. [Carbon Capture, Utilization, and/or Storage \(CCS/CCUS\)](#)) a list of energy efficiency measures with their applications, mitigation potential, and costs.

This helps practitioners identify the most impactful and cost-effective actions, aligned with national GHG inventories.

Timeframe	Carbon Capture, Utilization, and/or Storage (CCS/CCUS) Measures
<p>Short-Term High readiness in technology, infrastructure or systems. Lower additional cost; ready to scale.</p>	<p>Some CCS/CCUS applications are already commercially deployed, particularly in natural gas processing, ammonia, and ethanol production, where CO₂ streams are pure and capture is cost-effective.</p> <p>Countries can also advance deployment by investing in RD&D of capture technologies, fostering international collaboration, and prioritizing high-purity or high-intensity CO₂ applications.</p>
<p>Medium-Term Moderate investment or system adaptation needed. Technologies available but requiring further integration.</p>	<p>Carbon Capture and Utilization (CCU) in Chemicals; CO₂ Capture and Utilization (CCU) for Industrial Waste Gases.</p> <p>This period is also well-suited for scaling up demonstration projects, building shared infrastructure, and refining regulatory frameworks.</p>
<p>Long-Term Higher-cost, emerging, or still maturing technologies requiring substantial investment.</p>	<p>CO₂ Capture and Storage (CCS).</p>

Note: Most CCS/CCUS measures are classified as long-term due to their high capital requirements, infrastructure dependence, regulatory needs, and current market maturity.

This categorization considers technology maturity, infrastructure needs, and ease of integration. Short-term actions are ready to scale now. Medium-term actions need moderate investment or system adaptation. Long-term actions are typically higher-cost or still emerging.

Technology costs and capital needs vary significantly across regions and countries. Measures that appear cost-effective in one context may not be in another due to differences in energy prices, infrastructure availability, or financing conditions.

Step 2. Choose the appropriate policy framework

1. Is carbon sequestration represented in national strategies, roadmaps or NDCs?



2. Are storage and transport infrastructure in place or planned?



3. Are CCUS technologies commercially available and cost-competitive?



4. Is there public and stakeholder support for deployment?



5. Are there legal and regulatory frameworks in place?



Case studies and examples for consideration

Policymakers should review real-world examples and case studies to guide implementation. Successful case studies offer valuable insights for adapting policies to different contexts, as carbon capture, utilization, and storage opportunities and needs can vary widely across industries, regions, and stages of industrial development. In this regard, it is important to assess which policy instruments have worked well in similar sectors or regions and consider adapting successful policies from other areas.



CASE STUDY | Industrial Decarbonization Roadmap Framework for the Cement and Steel Industry Morocco (2023)

UNIDO white paper study on decarbonization pathways for the cement and steel industry in Morocco.

Objective

Study the decarbonization measures and develop roadmaps for the cement and steel industry.

**Note: the roadmaps do not reflect official policy, but provide a range of measures to be implemented from 2020 until 2050.*

Measures related to carbon capture, utilization and storage in the cement and steel industry

Cement

- Post-combustion CCS/CCUS
- Oxygen enrichment and oxy-fuel technology
- Carbonation and carbon curing for concrete

Steel

- Use of low-temperature heat to separate CO₂ from BF off-gas
- DRI with CCS/CCUS retrofit for post-combustion capture
- Using carbon-rich steelmaking waste gas to produce basic chemicals

**Note, recommendations provided by the white paper are based on both international best practices and the national context in Morocco.*

Implementation vehicles

- Support piloting and demonstration of CCS/CCUS technologies
- Leverage cooperation with industry stakeholders
- Consider low-interest loans for technological adoption

Application and monitoring

- Regulatory frameworks for carbon utilization and storage
- Green public procurement standards
- Alignment with energy efficiency and material efficiency objectives in the cement and steel industry to leverage synergies

Further information

- [Industrial Decarbonization Roadmap Framework for the Cement and Steel Industry Morocco - White Paper](#)



CASE STUDY | The Technology Collaboration Programme on Heat Pumping Technologies (2020)

- The handbook was published through the US Ministry of Commerce in collaboration of the Department of State's Bureau of Energy Resources (ENR).

Objective

- Deliver a free, accessible, fit-for-purpose and high-level guide for policymakers and regulators on how to catalyze investment into capturing carbon dioxide emissions for use or permanent storage

Measures related to carbon capture

- Direct air capture (DAC) solvent or sorbent based
- Biomass CCS directly processing the biomass into syngas and into hydrogen or CO₂
- Storage in saline reservoirs or depleted oil and gas reservoirs
- Direct utilization in industrial processes requiring CO₂
- Conversion of captured CO₂ into other products to be used in other industrial activities

Implementation vehicles

- Carbon taxes incentivizing the capture of CO₂
- R&D support schemes
- Fostering public-private partnerships to de-risk investments
- Production and investment credits

Application and monitoring

- Enshrine CCS/CCUS in the industry in strong regulatory frameworks (ISO/TC 265 Carbon Dioxide Capture, Transportation, and Geological Storage, can help develop country-specific CCS/CCUS frameworks)
- Effective community engagement
- Training of workforce in the industries relevant for CCS/CCUS (India's National Centre of Excellence in Carbon Capture and Utilization established 2021)
- R&D focused on the CCS/CCUS CO₂ lifecycle including carbon capture, the transport, utilization pathways and storage where it cannot be used

Further information

- [Handbook for Policymakers](#)

3. OVERARCHING MECHANISMS FOR ADVANCING INDUSTRIAL DECARBONIZATION ACROSS BUILDING BLOCKS



This section outlines broader mechanisms to operationalize the design and implementation of industrial mitigation actions, focusing on the practical integration of PAMs within a comprehensive policy framework.

It explores various intervention strategies, including strategic planning, policy development, regulatory measures, and cooperative agreements, to enhance the effectiveness of industrial decarbonization efforts. By examining a few key successful global practices, this guide provides actionable insights and innovative approaches that can be tailored to different national contexts, particularly in developing countries. It covers a wide range of mechanisms highlighting their implementation processes and impact on reducing industrial carbon emissions.

EXPLORE MORE

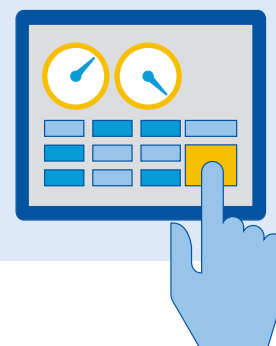
- UNIDO (2023). Policy brief series: insights on industrial development. Policy Packages for Decarbonizing Heavy Industry [↗](#)
- Criscuolo, C., et al. (2022), "Are industrial policy instruments effective? A review of the evidence in OECD countries", OECD Science, Technology and Industry Policy Papers, No. 128, OECD Publishing, Paris [↗](#)



Box 2. Integrating PAMs into Pre-existing Frameworks

Countries with existing industrial policies, strategies, and frameworks should first integrate PAMs into these structures, as this often enables smoother adaptation, broader acceptance, and leverages existing mechanisms and partnerships. Before creating new frameworks, countries should explore how PAMs could be embedded within current national frameworks. Many already have industrial growth plans, energy security strategies, and sectoral strategies that can serve as foundations for implementing PAMs. Where existing frameworks have proven effective, maintaining and adapting them can streamline emissions reductions. Existing climate policies should also be evaluated for alignment with NDC goals, allowing for incremental adjustments rather than entirely new strategies. Japan's Energy Conservation Act, introduced in 1979, shows how a pre-existing framework can evolve to incorporate new PAMs for industrial decarbonization. Initially aimed at promoting energy efficiency after the oil crises, the Act has been updated multiple times to address emerging climate and energy challenges, embedding sector-specific PAMs within an established regulatory structure.

Under the Energy Conservation Act, companies must implement energy-saving measures and meet sector-specific energy efficiency targets. The framework is adaptable, allowing incremental adjustments aligned with Japan's climate goals. Over time, the government has introduced new PAMs within the Act, including stricter performance standards, energy audits, and mandatory energy management plans. By building on this existing structure, Japan has expanded its focus from energy conservation to broader climate mitigation objectives.



Public-Private Partnerships and Voluntary Agreements

Public-Private Partnerships (PPPs) and Voluntary Agreements play a crucial role in driving industrial decarbonization by encouraging industry-led actions and fostering collaboration between government and the private sector.

These mechanisms provide structured yet flexible frameworks for industries to contribute to emissions reductions and the adoption of low-carbon technologies, often beyond minimum regulatory requirements. PPPs are particularly important for piloting innovative and emerging technologies, enabling governments to de-risk early-stage investments and stimulate private sector engagement.

The Netherlands' approach to voluntary agreements demonstrates the effectiveness of a structured, incentive-driven framework. Since 2007, the Netherlands has implemented the third generation of its Long-Term Agreements (LTAs) program, which covers small and medium-sized energy users. This program integrates energy savings across product chains by requiring participants to develop energy efficiency plans and commit to implementing all profitable measures. In return, participants benefit from technical assistance, energy audits, subsidies, and tax relief—backed by sector-specific technology lists that support decision-making.

In China, a similar approach with an even larger scale has been applied through the Top 10,000 Program, which builds upon the earlier Top 1,000 Enterprises Program. Covering approximately 66% of China's overall energy use, this initiative engages over 17,000 enterprises—including industrial establishments, major transportation companies, and large public structures. Designed to encourage energy efficiency improvements, the Top 10,000 Program requires participants to conduct energy audits, set specific energy-saving targets, and develop detailed action plans. These action plans often involve process optimization, technology upgrades, and enhanced energy management practices. Supported by the Chinese government through subsidies, tax breaks, technical assistance, and capacity-building initiatives, the program ensures that participants have the resources and guidance to achieve their targets.

Both examples demonstrate how PPPs and voluntary agreements can create enabling environments for industrial actors to engage in deep decarbonization. They also highlight the value of negotiated targets, co-investment, and long-term technical support to foster trust and measurable emissions reductions.

EXPLORE MORE

- World Economic Forum (2025). United for Net Zero: Public-Private Collaboration to Accelerate Industry Decarbonization [↗](#)
- Fleiter, T., Lotz, M. T., Arens, M., & Schlomann, B. (2021). An overview of implemented and planned policy instruments to decarbonize basic material industries in Germany [↗](#)
- Fleiter, T., Lotz, M. T., Arens, M., & Schlomann, B. (2021). An overview of implemented and planned policy instruments to decarbonize basic material industries in Germany. Working Paper Sustainability and Innovation No. S 01/2021, OECD and Fraunhofer ISI [↗](#)
- International Partnership on Mitigation and MRV (2020). Implementing a national energy efficiency programme [↗](#)



Green Public Procurement and Demand Signals

Public procurement is one of the most powerful tools governments can use to drive industrial decarbonization. As major purchasers of cement, concrete and steel, particularly for infrastructure projects such as roads, bridges, schools and hospitals, governments are uniquely positioned to stimulate demand for low- and near-zero emission materials.


Green public procurement (GPP) is not only about buying differently. It is also about aligning public investment with climate goals and building a more sustainable industrial future.

By embedding emissions criteria into tenders, GPP turns policy into practice. It supports the implementation of Nationally Determined Contributions (NDCs) and industrial decarbonization roadmaps by creating real-world demand for cleaner production. GPP also helps avoid carbon lock-in by ensuring that new infrastructure uses low-emission materials from the outset.

The Industrial Deep Decarbonization Initiative (IDDI), coordinated by UNIDO under the Clean Energy Ministerial, is a key effort supporting GPP adoption. IDDI's Green Public Procurement Pledge encourages governments to progressively commit to buying low-carbon cement, concrete and steel. The pledge allows for different levels of ambition, helping countries align commitments with their national contexts while sending clear market signals.

Public procurement accounts for approximately 14 percent of GDP in developed countries and up to 30 percent in some developing countries. In certain cases, governments are responsible for purchasing around 40 percent of cement and 25 percent of steel used in public construction. This significant buying power makes GPP a critical driver for innovation, investment and emissions reductions across supply chains.

EXPLORE MORE

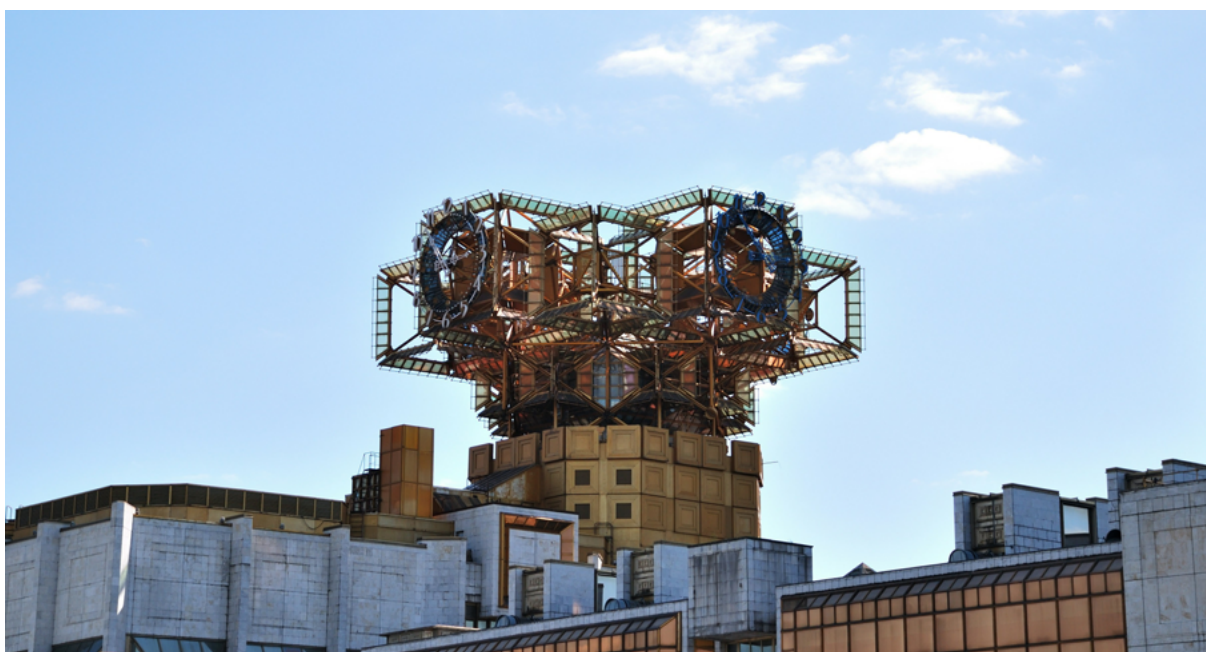
- [Green Public Procurement 101: Building the Future with Low-Carbon Materials](#) 

Industrial Hubs

Industrial clustering, or the development of geographically concentrated industrial parks, is an effective strategy for fostering both economic growth and industrial decarbonization.

By grouping industries in close proximity, countries can streamline the adoption of new technologies, facilitate shared infrastructure, and foster innovation ecosystems that accelerate low-carbon transformation. Clusters allow industries to pool resources for renewable energy, hydrogen pipelines, or CCS/CCUS infrastructure, making these investments more financially viable.

Industrial parks and hubs offer several advantages for decarbonization. First, clustering allows industries to access shared low-carbon infrastructure, such as renewable energy sources, hydrogen pipelines, or carbon capture and storage (CCS) facilities. This shared infrastructure reduces costs and minimizes the financial risks associated with adopting new technologies. For example, the UNIDO-supported Global Hydrogen Industrial Hubs initiative promotes the adoption of green hydrogen in industrial hubs, helping industries transition from fossil fuels to low-carbon hydrogen. This initiative not only reduces emissions but also fosters local job creation and economic development through new supply chains.



In addition to shared infrastructure, industrial hubs enable companies to collaborate on decarbonization goals through coordinated efforts. Countries such as China have embraced the concept of “Eco-Industrial Parks” where hubs are designed with sustainability as a priority. In China’s Suzhou Industrial Park, for instance, industries collectively manage waste, energy, and water resources to optimize efficiency and minimize environmental impacts. This integrated approach to resource management in industrial hubs showcases how sustainability and industrial growth can go hand in hand, with significant reductions in greenhouse gas emissions and resource use.

Countries can also integrate industrial hubs with national decarbonization strategies by focusing on technology and knowledge sharing. In Morocco, with UNIDO support, the country launched a portal on industrial zones to drive green industrial growth. By focusing on knowledge sharing and capacity-building within hubs, Morocco's approach is demonstrating how industrial hubbing can accelerate the adoption of decarbonization technologies across an entire industrial sector.

Case studies: Senegal and Brazil

The Senegalese Government is prioritizing rapid industrialization to drive economic growth—but with it comes rising energy demand. Through a six-year partnership with UNIDO, supported by the Global Environment Facility, Senegal has begun charting a low-carbon industrial pathway. In Dakar and Diamniadio Industrial Parks, efforts have focused on improving energy efficiency, integrating renewable energy, deploying low-carbon technologies, and managing persistent organic pollutants to support cleaner and more resilient industrial development.

- [Promoting Renewable energy and integrated waste management in Senegal Industrial parks](#) 
- [Integrated industrial parks in Senegal](#) 

Industrial clustering not only drives decarbonization but also creates opportunities for local economic growth. In developing countries, hubs can provide small and medium-sized enterprises (SMEs) with access to resources that might otherwise be unattainable, such as advanced technologies, skilled labour, and financial support. UNIDO's cluster development initiatives across Asia and Africa demonstrate how coordinated support can help SMEs reduce their carbon footprint while improving competitiveness. By aligning industrial clustering with green development goals, countries can foster inclusive growth and accelerate the transition to low-carbon economies.

An emerging example of this approach is Brazil's Industry Decarbonization and Hydrogen Hubs, supported by UNIDO and the United Kingdom. These hubs aim to bridge climate innovation and commercial deployment by aligning industrial policy with clean technology investment. Focused on enabling policy frameworks, research and innovation, and project development, the hubs promote a cluster-based model to scale up industrial decarbonization. They are designed to unlock blended finance, mobilize public and private partnerships, and support Brazil in meeting its climate and development targets.

EXPLORE MORE

- [UNIDO. \(2022\). Industrial Clusters and Decarbonization](#) 
- [UNIDO Global Programme Hydrogen in Industry \(2023\). Green Hydrogen Industrial Clusters](#) 
- [Devine-Wright, P \(2022\). Decarbonization of industrial clusters: A place-based research agenda](#) 

ANNEXES





Photo: Pressmaster / Envato

The industrial decarbonization measures described in this annex aim at supporting the prioritization of potential mitigation actions for the industry, in view of its consideration in GHG scenarios and mitigation assessments, and ultimately to support the enhancement of NDCs for the industry sector.

Annexes A, B (1 through 5) and C are focused on specific interventions aimed at reducing GHG emissions in the industrial sector, with Annex D providing an overview of datasets and guides that help exploring additional PAMs options.

For the consideration of measures in GHG scenarios and mitigation assessments, this guidance follows the methodological framework of [MITICA](#) for the evaluation and estimation of impact of the PAMs. In this line, the evaluation of GHG emissions impact uses as a reference 2006 IPCC Guidelines and methodologies employed in national GHG inventories, and reference to MACC for the information on costs of implementation. Practitioners can decide whether to model GHG scenarios, including the estimation of impact of individual or grouped PAMs, using the MITICA tool (available through the [UNFCCC webpage](#)) or any other modelling tools available (TIMES/MARKAL, OssemoSys, GACMO, etc.).

The information provided for each measure includes a description, a methodology for estimating the GHG impact, a cost range, and associated references. The measures are organized in five building blocks of industrial decarbonization as well as additional industry specific measures. National practitioners are encouraged to tailor these PAMs to their country's specific industrial context, considering existing technologies, practices, industrial processes, and support frameworks as discussed in [Section 2](#) of this guidebook.

Annex A. Methodology for Estimating GHG Impact


The methodology to estimate the GHG impact of the measures is based on an overarching rationale for estimating the impact as a function of changing the magnitude and scope of activities related to emissions activity, as depicted in the following expression:

$$ME_{t_i - t_f} = R \cdot M_{t_i - t_f} \cdot [REF_t - MEF_t] \{1\}$$



Where:

- $ME_{t_i - t_f}$ represents the mitigation effect of the PAM for the entire projected period,
- $M_{t_i - t_f}$ is the magnitude of the measure representing the affected activity levels,
- R represents the reduction factor in magnitude from measure implementation,
- REF_t stands for the reference emission factor in the absence of the measure at time t , and
- MEF_t is the mitigation emission factor, post implementation of the measure at time t .

Information on reduction factors and/or mitigation emission factors is provided. Activity levels and reference emission factors are to be determined by practitioners considering the current situation, thus the current estimates made in the national GHG emission inventory. In fact, alignment with the national GHG inventory is paramount to ensure that mitigation measures and scenarios are estimated considering the same rationale for emissions quantification as otherwise the mitigation impact of the selected measures cannot be linked to the national emissions trajectory.

To support the estimation and prioritization of PAMs in the context of mitigation assessments for NDC enhancement processes and considering the overall methodological approach as aligned with the MITICA tool, methodological guidance on using MITICA is provided. Note, however, that practitioners may utilize any tool or methodology available to them to estimate the mitigation impact of PAMs, provided alignment with the [IPCC guidelines](#)  is ensured.

Box 2. Short guide and link to MITICA

- MITICA was presented by the UNFCCC and Gauss at COP28 in Dubai, along with the latest updates of the IPCC software.
- Webinars introducing the foundations, methodologies, and feasibilities of MITICA in English, Spanish, and French.
- MITICA can be obtained by UNFCCC focal points upon request.
- The MITICA manual can be obtained from [UNFCCC resources](#) .
- Further information is found at [MITICA website](#) .

MITICA covers all **GHG inventory sectors** outlined by the IPCC Guidelines, including Energy, Industrial Processes and Product Use (IPPU), Waste, and Agriculture, and Forestry and Land Use Change (AFOLU), providing an integral and comprehensive approach to obtain GHG emission scenarios. In alignment with the Enhanced Transparency Framework of the Paris Agreement and its Modalities, Procedures, and Guidelines, MITICA adheres to the highest standards of transparency and accountability.

MITICA utilizes the national GHG emission inventory in conjunction with economic proxies to establish a baseline emission scenario known as the Without Measures (WoM) Scenario. Building upon this baseline, users have the flexibility to define a set of PAMs and incorporate them into the tool to create mitigation scenarios to assess GHG emission levels considering the impact of these PAMs.

This approach enables the creation of With Existent Measures (WEM) and With Additional Measures (WAM) scenarios, facilitating reporting under the Paris Agreement. **These scenarios play a crucial role in tracking the progress of NDCs and determining the level of ambition within them.** Further guidance on the development of mitigation scenarios in the context of NDC enhancements is provided in [Volume 1 of the NDC 3.0 Guidebook for Industrial Decarbonization](#).

As regards the estimation of specific mitigation PAMs, MITICA provides a range of key pre-defined measures which reflect the different IPCC GHG emissions categories. In the context of the highly specific, mostly technology-based decarbonization options provided in this Volume 2 Guidebook, emissions of the energy sector, the IPPU and waste sector as well as the transport sector, where relevant to the industry, are considered. In order to address the great variety of decarbonization options discussed in this guidebook and beyond, MITICA additionally provides the flexibility to customize generalized sectoral PAMs by adapting a concise set of parameters.

These parameters refer to the type of impact by which the PAMs reduce GHG emissions, which, in line with the generalized methodology for PAM estimation - $ME_{t_i - t_f} = R \cdot M_{t_i - t_f} \cdot [REF_t - MEF_t]$ - either leads to a reduction in the activity level, such as reduced energy or other material consumption due to energy or material efficiency gains, or to the emission factor that is reduced through for instance fuel switching including electrification. Note, some PAMs can unfold impacts on both the activity level and the emission factor, if for instance a new technology is implemented which is both more efficient and less carbon intensive than its fossil-fuel based predecessor.

Therefore, MITICA can be utilized for estimating the GHG mitigation impact for all decarbonization PAMs provided in this guidebook, requiring the practitioner to know the specific impact the different PAMs have on GHG emissions. To guide the practitioner in the correct identification of impact, concise **descriptions of the type of impact** of each PAM is provided by block and for the industry specific PAMs. Moreover, key international research is evaluated to provide further information on the **magnitude of impact of each PAM**.

The illustration below provides a snapshot of a potential decarbonization measure related to the energy emissions in the industry, as specified by the sector, subsector and associated IPCC category 1.A.2. On the right-hand side, in the upper two cells, the reduction factor in activity levels and the reference activity levels are filled in to reflect for instance a reduction in energy consumption of an industry expressed as a percentage reduction (%). The bottom two cells cover the emission factor, and practitioners can fill in the emission factor of the fossil fuel used before implementing the PAMs, for example fuel oil, and the emission factor of the new fuel, which can be either a lower carbon fuel like biofuel or a fossil-free fuel. As such, MITICA provides great flexibility in the adaptation of different decarbonization options to the specific industrial context.

Herein, it is essential to mention that MITICA, in the process of developing mitigation scenarios, is strictly based on the GHG emissions categories the practitioner uploads as per the national GHG inventory of a country. As such, if a country does not account for or does not have GHG emissions in a specific category linked to the IPCC guidelines, the PAM impacting that category will not have affect emissions and thus will not be considered in the mitigation scenarios. In case practitioners wish to use MITICA's methodology separate from the software, the [User Manual v.6 of MITICA](#) can be considered, however in the context of NDC enhancements it is recommended to retain a strict link to the national GHG inventory to ensure consistency.

Furthermore, as mentioned, practitioners can choose to employ different methodologies or complement MITICA with alternative tools such as TIMES/MARKAL, Ossemossys, GACMO, etc. to estimate the impact of the measures and develop mitigation scenarios.

To support the estimation and facilitate the use of modelling tools, for each of the PAMs presented by block in continuation, a description, a methodology to estimate the GHG emission impact, an approximate cost and references are included. Moreover, the costs are presented in terms of the relative cost of reducing GHG emissions, as discussed in more detail in the following.

A.1 Marginal Abatement Cost Curve

Next to the estimated mitigation potential of PAMs, the choice of adequate decarbonization measures is dependent on an assessment of their costs which helps stakeholders, particularly policymakers and industry leaders, prioritise actions based on their cost-effectiveness.

In the context of mitigation measures, Marginal Abatement Cost Curves (MACC) provide an adequate framework for assessing and comparing the cost-effectiveness of different mitigation measures. For each measure, the MACC represents the cost of reducing one tonne of CO₂-equivalent emissions (USD/ton CO₂e). In this guidance document, the MACC are provided for each measure as identified based on desk research.

Note, the MACC values provided reflect a range of costs, indicating the lower and upper bounds of potential costs. The variability in these costs typically depends on:

- **Technological readiness:** Whether the action relies on mature, commercially available technologies or emerging solutions.
- **Regional factors:** Costs may vary depending on local energy prices, labour costs, or supply chain factors.
- **Scale of implementation:** Larger projects may benefit from economies of scale, while smaller implementations might face higher per-unit costs.

The MACC in this guidebook include all implementation costs, such as capital investments, operational costs, and potential savings from reduced energy consumption or improved efficiency. However, it is important to mention that the international sources from which the MACC are compiled utilize a variation of methods, therefore practitioners involved in the cost modelling would have to carefully consider these nuances.

Understanding the MACC is critical for assessing the financial feasibility of each mitigation action. Actions with lower MACC values are typically more attractive, as they offer greater GHG emissions reductions at a lower cost. In some cases, actions might even have negative MACC values, meaning they generate net cost savings while also reducing emissions. Ultimately, the final suitability of a certain measure depends on the technological feasibility, the availability of financial resources and on availability of support frameworks. In this context, the MACC, while crucially supporting the prioritization of PAMs and the effective cost management, do not automatically determine the success of implementation of the PAMs.

Annex B. Measures within the Five Building Blocks of Industrial Decarbonization




In the following, the decarbonization measures as linked to the five building blocks are presented.

B.1. Material Efficiency




Table 1 Material efficiency measures.

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
<p>Industrial Symbiosis and Waste Heat Recovery</p>	<p>Industrial symbiosis involves the collaboration between industries to exchange waste materials and energy, reducing overall emissions. For example, one industry's waste heat can be used by another industry for heating or electricity generation.</p> <p>This can include:</p> <ul style="list-style-type: none"> Waste heat recovery systems: To capture waste heat from one facility and transfer it to another. Materials exchange: Sharing by-products or waste materials between industries for reuse. This action is applicable in industrial parks or regions with multiple industries in close proximity. <p>For further information visit:</p> <ul style="list-style-type: none"> Ellen MacArthur Foundation Industrial Symbiosis Report ↗ IEA Industrial Energy Efficiency Report ↗ 	<p>The mitigation effect of this measure is based on an increase in the efficiency of the industrial process, as they contribute to the better utilization of resources and lower consumption, while maintaining overall activity levels in the industry. Industrial Symbiosis and Waste Heat Recovery involve the reuse of waste heat generated by industrial processes, leading to an improvement in process efficiency.</p> <p>This recovery can contribute to an increase in the efficiency of the system, with a potential recovery of primary energy between 13% and 16% (Larrinaga et al., 2021 ↗). Specifically, different industrial sectors have varying recovery potentials (EXERGY, 2024 ↗): the chemical industry accounts for 11.7% of waste heat potential, iron and steel 16.4%, refineries 34.4%, paper and printing 9.9%, and non-metallic minerals (including cement) 27.3%.</p>	<ul style="list-style-type: none"> (-1200) – (-351) USD/tCO₂-eq 2023 20 -160 USD/tCO₂-eq 2023 (-800) – (-60) CHF/tCO₂-eq 2018

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
<p>Closed-Loop Cooling Systems for Industrial Processes</p>	<p>Many industries rely on open-loop cooling systems that consume large amounts of water and energy. Closed-loop cooling systems recirculate cooling water within the system, significantly reducing water use and energy consumption.</p> <p>Technologies include:</p> <ul style="list-style-type: none"> • Dry cooling systems: Use air-cooled heat exchangers to eliminate water use in cooling. • Hybrid cooling systems: Combine wet and dry cooling for efficiency and flexibility. This action is applicable in industries that require process cooling, such as power generation, petrochemicals, and food processing. <p>For further information visit:</p> <ul style="list-style-type: none"> • IPCC 6th Assessment Report (2023) 	<p>The mitigation effect of this measure is based on an increase in the efficiency of the industrial process, as they contribute to better utilization of resources and lower consumption, while maintaining overall activity levels in the industry. Closed-loop cooling systems utilize natural cooling sources, such as diurnal temperature variations, to recycle cooled air within the system.</p> <p>This reduces the need for external energy inputs, resulting in significant energy savings. Energy savings of up to 76.34% have been observed in cold storage facilities (Chen, Zhang, 2024).</p>	<p>No relevant studies found</p>
<p>Optimization of Process Water Use in Industry</p>	<p>Many industrial processes consume large amounts of water, requiring energy for pumping, heating, and water treatment. Optimizing water use reduces both consumption and the energy needed to process it.</p> <p>Key measures include:</p> <ul style="list-style-type: none"> • Water recycling and reuse: Recirculating process water for repeated use. • Advanced filtration systems: Reducing the need for fresh water by treating and reusing wastewater. • Leak detection and repair: To minimize water losses and the associated energy use. This action is relevant in water-intensive industries such as food processing, textiles, and chemicals. <p>For further information visit:</p> <ul style="list-style-type: none"> • IPCC 5th Assessment Report (2014) 	<p>The mitigation effect of this measure is based on an increase in the efficiency of the industrial process, as they contribute to the better utilization of resources and lower consumption, while maintaining overall activity levels in the industry.</p> <p>The mitigation effect of these measures depends on the scale of implementation, the specific processes in use, and the level of optimization achieved. In terms of energy consumption and emissions reductions, the reduction of water withdrawals can lead to significant energy savings. For instance, studies of the US manufacturing sector, estimate that reducing leaks in industrial water systems alone can save between 604 and 1,100 GWh per year in energy consumption, with a corresponding decrease in CO₂ emissions by 0.23 to 0.41 million metric tons (MMTCO₂e) per year.</p> <p>Further optimizations, such as increasing boiler condensate return and improving blowdown operations, could result in energy savings of up to 157–177 PJ/year, with a corresponding CO₂ emissions reduction of up to 9.85 MMTCO₂e/year (Karki, Rao, 2023).</p>	<ul style="list-style-type: none"> • 50-60 USD/tCO₂-eq 1998




Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
<p>Optimization of Process Heat Distribution Systems</p>	<p>In industries that rely on process heat, a significant portion of energy is lost in distribution systems due to poor insulation, leaks, and inefficiencies. Optimizing these systems through better design, insulation, and monitoring can reduce energy losses and associated CO₂ emissions.</p> <p>Technologies include:</p> <ul style="list-style-type: none"> • Improved insulation: Reducing heat loss in steam, hot water, or thermal oil distribution systems. • Leak detection and repair (LDAR): Identifying and fixing leaks in steam lines and heat distribution systems. • Automated control systems: To monitor and adjust heat flows in real-time to improve efficiency. This action applies to industries such as petrochemicals, food processing, and pulp and paper. 	<p>The mitigation effect of this measure is based on an increase in the efficiency of the process heat distribution, reducing heat losses and thus the required energy consumption for obtaining the desired heat inputs. The impact of optimizing process heat distribution systems depends significantly on the current state of the industry where it is applied, including the existing inefficiencies in heat distribution, the type of energy source in use, and the effectiveness of the optimization technologies. These factors can vary greatly across different industries, processes, and plants. However, selecting the optimal energy efficiency measures for specific industries, plants, and processes remains a challenge. The diversity of industrial operations, products, and equipment requires tailored approaches to identify and implement the most effective measures. Additionally, integrating operational energy management programs can help minimize deviations from targeted energy efficiency performance, ensuring that energy savings and emissions reductions are continuously achieved (Maghrabi et al., 2023 </p>	<ul style="list-style-type: none"> • 40-110 USD/ tCO₂-eq 2020 • 35-1010 USD tCO₂-eq 2020 • 170-222.5 GBP/tCO₂-eq 2024
<p>Efficient Packaging Technologies</p>	<p>The packaging industry is energy-intensive, particularly in the production of materials like plastic, glass, and metal. Energy-efficient packaging technologies can reduce energy consumption and CO₂ emissions.</p> <p>Measures include:</p> <ul style="list-style-type: none"> • Lightweighting: Reducing the amount of material used in packaging, thus lowering the energy required for production. • Use of recycled materials: Incorporating recycled plastic, glass, or metal into packaging to reduce energy demand. • Sustainable packaging alternatives: Such as biodegradable or compostable materials that require less energy to produce and break down more easily at the end of life. This action is relevant in industries such as food and beverages, consumer goods, and pharmaceuticals. <p>For further information visit:</p> <ul style="list-style-type: none"> • Ellen MacArthur Foundation Circular Economy Report  	<p>However, the impact of this measure varies significantly depending on the specific industry and the processes involved. For example, in the food packaging sector, switching from glass to plastic for infant food packaging can decrease GHG emissions by around 30%. Replacing metal cans with retort cups for tuna packaging results in a 10–22% decrease in GHG emissions.</p> <p>Similarly, using recycled glass or stainless-steel barrels instead of non-recyclable bottles for beer packaging can reduce emissions by up to 96%. Moreover, reducing the weight of packaging can also have a significant impact: reducing the weight of a wine bottle by 30% can lower GHG emissions by 4 to 23%. The emissions associated with different packaging materials also vary. Plastic-based packaging typically generates over 3 kg CO₂-eq/kg, while fiber-based alternatives have emissions under 1.5 kg CO₂-eq/kg. However, fiber-based packaging may require more material to provide similar protection, potentially offsetting its environmental benefits.</p> <p>Optimizing design, thickness, and using recycled materials can reduce these emissions further. The overall impact of these efficient packaging technologies depends heavily on the industry sector, the materials used, and the extent of technological adoption (Liu et. Al., 2023 </p>	<ul style="list-style-type: none"> • (-77) – 33 USD/tCO₂-eq 2022 • (-5355) - 2000 NTD/tCO₂-eq 2022

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
<p>Organic Rankine Cycle (ORC) for Waste Heat Recovery</p>	<p>The Organic Rankine Cycle (ORC) is a technology that uses organic fluids with a lower boiling point than water to convert low-temperature waste heat into electricity. This technology is ideal for industries that produce large amounts of waste heat but at relatively low temperatures, such as cement, steel, and glass manufacturing.</p> <p>Key components include:</p> <ul style="list-style-type: none"> • ORC turbines: For converting low-grade heat into electricity. • Heat exchangers: To transfer waste heat into the ORC system. This action is relevant in industries with significant waste heat potential. <p>For further information visit:</p> <ul style="list-style-type: none"> • IPCC 6th Assessment Report (2023) • European Commission Guidelines for Industrial Waste Heat Recovery 	<p>The energy savings and corresponding CO₂ emissions reductions are estimated based on the amount of energy recovered from waste heat, which depends on the specific characteristics of the industrial processes and the technologies employed, as well as the operating conditions of the system.</p> <p>For example, ORC systems in steel production can reduce up to 1.1 Mt CO₂ annually, cement up to 0.6 Mt CO₂, and glass up to 0.1 Mt CO₂. In the case of Germany, the total CO₂ reduction across these industries can range from 0.9 to 2.7 Mt CO₂, accounting for approximately 0.4–1.4% of total industrial emissions in the country. In terms of energy recovery, the technical potential for electricity generation from waste heat recovery can reach 2.4 TWh/a for steel, 1.3 TWh/a for cement, and 0.4 TWh/a for glass (Pili et al., 2020).</p> <p>Furthermore, the efficiency of the ORC system is significantly influenced by the operating conditions of industrial processes, similar to how road conditions affect the performance of ORC systems in vehicles within the transport sector. In the case of waste heat recovery in vehicle engines, energy recovery efficiency is higher under stable conditions such as those on motorways, where exhaust energy can range from 5 kW to 44.5 kW, with recovery efficiency reaching up to 5.5%.</p> <p>Conversely, under fluctuating conditions such as those in urban environments, the energy recovery efficiency drops, as seen in the average recovery efficiency of only 1.43% during New York City Cycle (NYCC) conditions (Wang et al., 2020).</p>	<ul style="list-style-type: none"> • (-52.5)-(-148,2) EUR/tCO₂-eq 2022 • 90,4-158,4 AUD/tCO₂-eq 2021
<p>Biogas from Industrial Waste for Energy Use</p>	<p>Many industries produce significant amounts of organic waste that can be converted into biogas through anaerobic digestion. This biogas can be used to generate electricity, heat, or be upgraded to biomethane for use in natural gas grids.</p> <p>Key technologies include:</p> <ul style="list-style-type: none"> • Anaerobic digesters: Convert organic waste into biogas through microbial processes. • Biogas upgrading systems: Refine biogas into biomethane for injection into natural gas grids. This action is applicable in industries such as food processing, agriculture, and wastewater treatment. 	<p>The mitigation effect of this measure is primarily based on a reduction in the emission factor, as the carbon fraction emitted from biogas is not fossil-based. This reduction largely depends on the type of organic waste used as feedstock and the technologies employed for biogas production. Additionally, the effectiveness of this mitigation measure is significantly influenced by the share of renewable energy within the industrial energy mix. Research indicates that biogas production from organic waste can lead to GHG savings of up to 80%, particularly when the feedstocks are sourced from agro-industrial waste, municipal biowaste, or industrial by-products (Kodba et al., 2023).</p> <p>For instance, many countries have developed biogas plants that focus on industrial waste, integrating these facilities into broader biogas promotion projects. These plants produce biogas that is then used to generate Compressed Bio-methane Gas (CBG), which serves as a renewable fuel for vehicles (Natural Gas for Vehicles, NGV) and as a replacement for liquefied petroleum gas (LPG) in industrial processes like ceramic kilns (Tonrangklang et al., 2017).</p>	<ul style="list-style-type: none"> • (-159.7)-9.7 EUR/tCO₂-eq 2020 • (-220)-(-185) GBP/tCO₂-eq 2018 • (-198)-(-72) USD/tCO₂-eq 2012

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
<p>Waste-to-Energy Technologies</p>	<p>Waste-to-energy (WtE) plants convert municipal solid waste (MSW) and industrial waste into energy (electricity or heat) through processes like incineration, gasification, and anaerobic digestion. By diverting waste from landfills and reducing the use of fossil fuels, WtE reduces GHG emissions.</p> <p>Technologies include:</p> <ul style="list-style-type: none"> • Incineration with energy recovery: Burning waste to generate steam for electricity production. • Gasification: Converting organic waste into syngas for use in power generation. • Anaerobic digestion: Breaking down organic waste to produce biogas for energy use. This action is applicable in waste management, energy production, and municipalities. <p>For further information visit:</p> <ul style="list-style-type: none"> • European Commission Waste-to-Energy Directive  	<p>The mitigation effect of this measure is based on efficiency gains by replacing fossil fuel sources with renewable waste-derived energy which reduces the overall fuel requirements. The potential for reducing carbon emissions is further enhanced when waste feedstocks include renewable and biodegradable materials. The emission reduction potential depends on both the waste sources' characteristics and the processes used to convert them into energy products.</p> <p>For instance, pequi fruit seeds, a byproduct of agro-industrial waste, have been shown to have significant bioenergy potential through torrefaction (a form of thermal treatment), which increases the energy content and reduces CO₂ emissions compared to fossil fuels. Studies on the torrefaction of pequi seed biomass have demonstrated substantial improvements in higher heating value (HHV) and energy yield, with reductions in CO₂ emissions by up to 188.65 kg CO₂eq by substituting diesel with biochar from pequi seeds. This process not only enhances the biofuels' energy yield but also contributes to CO₂ retention, further lowering the carbon footprint of waste-to-energy operations (Silveira et al., 2024 )</p> <p>Additionally, for incineration with energy recovery, there is also a reduction in the emission factor as the energy produced from waste has significantly lower GHG emissions compared to fossil fuel sources. By diverting municipal waste from landfills and recovering energy from it, incineration helps avoid the high emissions associated with landfilling, which generates up to 107% more GHGs per tonne of waste than energy recovery. A study in Spain found that energy recovery from waste has a net carbon balance of 224 kg CO₂e per ton of municipal waste (MW), in contrast to landfill disposal, which generates a net balance of 772 kg CO₂e per ton. This demonstrates that energy recovery not only reduces emissions compared to landfill disposal but also aligns with European waste management strategies aimed at achieving significant reductions in GHG emissions (G Advisory, 2021 )</p>	<ul style="list-style-type: none"> • (-100)-200 EUR/tCO₂-eq 2023 • 122.7-170.6 GBP/tCO₂-eq 2024 • 0-150 USD/tCO₂-eq 2011

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
<p>Biogas from Industrial Wastewater Treatment</p>	<p>Industries such as food processing, pulp and paper, and chemicals generate large volumes of wastewater with high organic content. Anaerobic digestion of wastewater sludge produces biogas, which can be used for electricity and heat generation, reducing emissions from fossil fuels.</p> <p>Key technologies include:</p> <ul style="list-style-type: none"> • Anaerobic digesters: Convert organic waste in wastewater into biogas. • Biogas upgrading systems: Refine biogas into biomethane for use in industrial processes or injection into natural gas grids. This action is relevant for industries with significant wastewater treatment needs. <p>For further information visit:</p> <ul style="list-style-type: none"> • European Commission Biogas Strategy 	<p>The mitigation effect of this measure is primarily based on a reduction in the emission factor, as the carbon fraction emitted from biogas is not fossil-based. The biogas production is largely influenced by the type of wastewater sludge being treated and the technologies used for biogas production. Additionally, the effectiveness of this mitigation measure is significantly impacted by the share of renewable energy within the industrial energy mix. The biogas produced can then be used for electricity and heat generation, displacing fossil fuel consumption (Periyasamy et al., 2023).</p> <p>By using biogas for electricity and heat, these industries not only reduce their emissions but also improve their energy efficiency by converting waste products into valuable energy.</p>	<p>No relevant studies found</p>
<p>Exploitation of Waste Heat (Insulation, Use of High-Temperature Heat Pumps)</p>	<p>Waste heat is a by-product of industrial processes that can be captured and reused for heating or electricity generation.</p> <p>Technologies include:</p> <ul style="list-style-type: none"> • Heat exchangers: Capture waste heat from exhaust gases or cooling water and transfer it to another process. • High-temperature heat pumps: Upgrade low-grade waste heat to higher temperatures for reuse. • Combined heat and power (CHP) systems: Generate electricity from captured waste heat. This action applies in industries with high heat demands, such as steel, cement, glass, and chemicals. <p>For further information visit:</p> <ul style="list-style-type: none"> • IPCC 5th Assessment Report (2014) 	<p>The mitigation effect of this measure is based on increasing the energy efficiency by capturing and reusing waste heat, effectively lowering the energy input requirements for maintaining the needed output level in industrial processes.</p> <p>This effect can vary significantly depending on the amount of recoverable energy waste within the sector, the technologies used to capture and upgrade the waste heat, and the subsequent utilization of this energy.</p> <p>In industrial facilities, approximately 20% to 50% of energy input is wasted as heat, often in the form of exhaust gases, hot equipment surfaces, and heated liquids. This waste heat can be recovered and used for heating or electricity generation, reducing the need for additional fossil fuel consumption. Research shows that up to 1.4 quadrillion BTUs of waste heat could be economically recovered, representing around 9% to 10% of total industrial energy use in the U.S. (Energetics, Inc. and E3M) (Cadmus, 2021).</p>	<ul style="list-style-type: none"> • (-118.7)-85.1 GBP/tCO₂-eq 2024 • (-190)-100 EUR/tCO₂-eq 2015
<p>Membrane Bioreactors (MBR) for Industrial Wastewater Treatment</p>	<p>Membrane bioreactors (MBRs) are advanced wastewater treatment systems that combine biological treatment and membrane filtration, resulting in high-quality effluent and reduced energy consumption compared to conventional systems.</p> <p>Key benefits include:</p> <ul style="list-style-type: none"> • Improved filtration: To remove fine solids and reduce the need for secondary clarification. • Energy savings: Due to reduced aeration requirements and compact design. This action is relevant in industries with high volumes of wastewater and stringent discharge standards, such as pharmaceuticals, food processing, and petrochemicals. 	<p>The mitigation effect of this measure is based on an improvement in process efficiency, particularly through reduced energy consumption in industrial wastewater treatment. The extent of energy savings depends on the energy consumption associated with fouling control and membrane filtration, as well as the specific characteristics of the wastewater being treated.</p> <p>For example, the use of membrane reciprocation as a fouling control strategy in an anaerobic membrane bioreactor (AnMBR) resulted in a 62% reduction in energy consumption compared to conventional biogas sparging (Lim et al., 2023). This highlights the potential for significant energy savings through advanced MBR systems, such as AnMBRs with membrane reciprocation, which can also generate biogas for energy recovery.</p>	<p>No relevant studies found</p>

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
<p>Use of F-Gases with Small Global Warming Potentials (GWPs) in Industry</p>	<p>F-gases, such as hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF₆), have extremely high global warming potentials (GWPs).</p> <p>This action involves replacing high-GWP F-gases used in refrigeration, air conditioning, and electrical insulation with alternatives that have significantly lower GWPs, such as:</p> <ul style="list-style-type: none"> • Hydrofluoroolefins (HFOs) • Natural refrigerants like ammonia, CO₂, or hydrocarbons. <p>For further information visit:</p> <ul style="list-style-type: none"> • IPCC 5th Assessment Report (2014) • European F-gas Regulation 	<p>The mitigation effect of this measure primarily focuses on a reduction in the emission factor by replacing high-GWP (Global Warming Potential) F-gases with alternatives that have significantly lower GWP values.</p> <p>A general classification of these refrigerants could be as follows:</p> <p>Ultra-Low GWP Natural Refrigerants (1 to 100 GWP):</p> <ul style="list-style-type: none"> • Ammonia (R-717): Very low GWP but has limitations due to its toxicity. • CO₂ (R-744): GWP of 1, a natural refrigerant with minimal environmental impact. • Propane (R-290): Low GWP, flammable, but used in applications where safety is properly managed. <p>Medium GWP HFC/HFO Blends (100 to 2500 GWP):</p> <ul style="list-style-type: none"> • R-449A, R-448A, R-407A: Blends designed to reduce GWP compared to traditional HFCs. <p>High GWP HFCs (over 2500 GWP):</p> <ul style="list-style-type: none"> • R-404A, R-507A: These refrigerants have a GWP greater than 2500 and are being phased out due to their high environmental impact. <p>The impact of this measure depends largely on the current usage of F-gases in the industry and the specific F-gas being replaced. By shifting to alternatives with lower GWP, such as Hydrofluoroolefins (HFOs) or natural refrigerants like ammonia, CO₂, or hydrocarbons, the overall emissions from the industrial process can be substantially reduced (European Commission .</p> <p>Since F-gases such as hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF₆) have a global warming potential many times greater than that of CO₂—some up to 24,000 times more potent—this transition has significant potential to mitigate climate change. The effectiveness of this mitigation measure will vary depending on the current GHG emissions from the industrial use of F-gases and the specific alternative adopted (Sovacool, et al., 2021 .</p>	<ul style="list-style-type: none"> • 10 EUR/tCO₂-eq 2016 • 0-50 EUR/tCO₂-eq 2022 • 0-70 EUR/tCO₂-eq 2010

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
<p>Replacement of Solvent-Based Processes with Water-Based Processes</p>	<p>Many industrial processes, especially in the chemical and pharmaceutical industries, rely on volatile organic compound (VOC) solvents, which contribute to greenhouse gas emissions. Replacing these solvent-based processes with water-based alternatives significantly reduces emissions and improves workplace safety.</p> <p>Applications include:</p> <ul style="list-style-type: none"> • Water-based coatings: Used in automotive and furniture industries instead of solvent-based paints. • Water-based adhesives: Replacing solvent-based adhesives in construction and packaging industries. This action is relevant in industries where solvent use is prevalent, particularly manufacturing, construction, and chemical processing. <p>For further information visit:</p> <ul style="list-style-type: none"> • EPA VOC Reduction Guidelines  • European Chemicals Agency on VOC Regulations  	<p>The mitigation effect of this measure is primarily based on a reduction in the emission factor by replacing solvent-based processes with water-based alternatives, which have a lower emission factor and thus lead to decreased emissions.</p> <p>The overall impact of this measure depends on the specific emission factors associated with the solvents currently used in the industrial processes (solvent-based) and the emission factors of the water-based alternatives being adopted.</p> <p>For example, in industries like automotive manufacturing, where painting processes are essential, the use of solvent-based paints results in the emission of volatile organic compounds (VOCs) and significant CO₂ emissions due to energy consumption. Research has shown that by switching from solvent-based painting processes to powder coating or water-based paints, a substantial reduction in both VOCs and CO₂ emissions can be achieved. In the case of vehicle painting processes in China, switching from a traditional solvent-based process (3C2B) to a powder coating method resulted in a reduction of 23.40 kg CO₂ and 1.47 kg VOCs per vehicle (Liang et al., 2025 .</p> <p>The effectiveness of this mitigation measure varies depending on the specific industrial context and the types of solvents currently in use. However, it is clear that the shift to water-based processes can lead to a synergistic reduction in both VOC and CO₂ emissions, offering a cleaner and more sustainable alternative in industries such as automotive manufacturing, construction, and chemical processing.</p>	<p>No relevant studies found</p>

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
<p>Abatement of F-Gases in Industrial Refrigeration</p>	<p>Fluorinated gases (F-gases), such as hydrofluorocarbons (HFCs), are potent greenhouse gases commonly used in refrigeration systems. This action involves replacing high-GWP (Global Warming Potential) F-gases with alternatives that have a lower GWP or eliminating them through alternative refrigeration technologies.</p> <p>Technologies include:</p> <ul style="list-style-type: none"> • Natural refrigerants: Such as ammonia (NH₃), carbon dioxide (CO₂), and hydrocarbons (e.g., propane) in refrigeration systems. • Low-GWP synthetic refrigerants: Such as hydrofluoroolefins (HFOs) as replacements for traditional HFCs. This action is relevant in industries with large-scale refrigeration needs, such as food processing, cold storage, and pharmaceuticals. <p>For further information visit:</p> <ul style="list-style-type: none"> • European F-gas Regulation 	<p>The mitigation effect of this measure is primarily based on a reduction in the emission factor, as the shift from high-GWP (Global Warming Potential) F-gases, such as hydrofluorocarbons (HFCs), to alternatives with significantly lower GWP values results in a substantial decrease in greenhouse gas emissions. The specific impact of this mitigation measure depends on the proportion of the F-gas being replaced in the refrigeration system and the type of refrigerant adopted.</p> <p>Studies indicate that replacing high-GWP refrigerants with alternatives in industrial refrigeration can lead to a considerable reduction in greenhouse gas emissions. For example, transitioning from traditional refrigerants to low-GWP options has been shown to decrease the greenhouse effect intensity by up to 78.2%, alongside other benefits like reductions in energy consumption and ozone depletion potential (Wang et al., 2021).</p>	<p>No relevant studies found</p>
<p>High-Efficiency Combined Heat and Power (CHP) Systems</p>	<p>Combined Heat and Power (CHP) systems simultaneously generate electricity and useful heat from a single fuel source, improving overall energy efficiency. High-efficiency CHP systems use advanced technologies to capture more waste heat and reduce fuel consumption.</p> <p>Technologies include:</p> <ul style="list-style-type: none"> • Gas turbines and steam turbines: For large industrial CHP applications. • Reciprocating engines: For smaller industrial or commercial CHP applications. • Fuel cells: High-efficiency systems for electricity and heat generation. This action is relevant for industries with high electricity and heat demand, such as food processing, pulp and paper, and chemicals. <p>For further information visit:</p> <ul style="list-style-type: none"> • U.S. Department of Energy CHP Basics 	<p>The mitigation effect of this measure is primarily based on an increase in the energy efficiency of the industrial process as heat and electricity are generated simultaneously which reduces the energetic requirements of the industrial process. The effectiveness of this mitigation measure depends on the specific technology used and the characteristics of the industrial application. For example, the integration of gas turbines, steam turbines, reciprocating engines, and fuel cells can improve energy efficiency by capturing more waste heat and reducing the need for additional fuel.</p> <p>In experimental studies, high efficiency reciprocating engines have demonstrated significant improvements in combustion performance, with up to 84% reduction in methane emissions and a 63% to 69% reduction in VOCs emissions. Additionally, the systems can achieve improved thermal efficiency, leading to less fuel consumption and lower overall emissions (Hassan et al., 2023).</p>	<p>No relevant studies found</p>

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
Anaerobic Digestion for Wastewater Sludge	<p>Anaerobic digestion is a biological process where microorganisms break down organic materials in the absence of oxygen, producing biogas (mainly methane) and digestate. Anaerobic digestion can be used to treat industrial wastewater sludge, turning it into biogas for energy use. This reduces the need for fossil fuels in wastewater treatment and reduces methane emissions from untreated sludge.</p> <p>Key technologies include:</p> <ul style="list-style-type: none"> • Anaerobic digesters: For breaking down organic sludge. • Biogas upgrading systems: For refining biogas into biomethane or using it for electricity and heat generation on-site. This action is relevant for industries that produce large volumes of organic wastewater, such as food processing, pulp and paper, and dairy industries. 	<p>The mitigation effect of this measure is primarily based on the reduction of the emission factor, as the biogas produced through anaerobic digestion of wastewater sludge can replace fossil fuel-based energy sources. The effectiveness of anaerobic digestion for wastewater sludge treatment depends on the scale and efficiency of the system, as well as the type of biogas upgrading technology used. Studies show that energy recovery systems, which refine biogas into biomethane or use it for on-site electricity and heat generation, offer the best GHG mitigation effects. For example, the use of energy recovery systems in wastewater treatment can result in significant reductions in GHG emissions, with some studies indicating that up to 93% of emissions in the wastewater sector can be offset through effective sludge management strategies (Chen et al., 2022 ↗).</p>	<ul style="list-style-type: none"> • (-77)-18 EUR/tCO₂-eq 2023
Aerobic Treatment with Energy-Efficient Aeration	<p>Aerobic treatment systems rely on oxygen to break down organic materials in wastewater. Energy-efficient aeration systems reduce energy consumption in these processes by optimizing oxygen transfer efficiency.</p> <p>Technologies include:</p> <ul style="list-style-type: none"> • Fine-bubble diffusers: For increased oxygen transfer efficiency with lower energy input. • Variable-speed blowers: To adjust airflow based on real-time oxygen demand. This action is applicable in industries with high organic wastewater loads, such as chemical, food processing, and beverage manufacturing. <p>For further information visit:</p> <ul style="list-style-type: none"> • European Commission Guidelines for Energy Efficiency in Wastewater Treatment ↗ 	<p>The mitigation effect of this measure is primarily based on the improvement of energy efficiency in the wastewater treatment process, specifically through optimizing the aeration system which reduces the energy input requirements. Research shows that applying optimal control strategies to the aeration process can significantly conserve energy while ensuring effluent water quality. For instance, using a multi-variable energy-saving model that adjusts control parameters, such as dissolved oxygen (DO) levels and sludge discharge quantity, can achieve energy savings of up to 20%. The effectiveness of this mitigation measure is determined by the ability to maintain the proper balance of oxygen in the system to meet the treatment requirements without over-consuming energy. The reduction in energy consumption directly leads to a decrease in greenhouse gas (GHG) emissions associated with energy use, improving the overall sustainability of wastewater treatment processes (Chen et al., 2022 ↗).</p>	<ul style="list-style-type: none"> • -59 EUR/tCO₂-eq 2021

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
<p>Sludge Dewatering and Drying for Energy Recovery</p>	<p>Sludge generated from industrial wastewater treatment is typically high in moisture content, which makes it inefficient for disposal or energy recovery. Sludge dewatering and drying technologies reduce the moisture content, making the sludge suitable for incineration or other energy recovery processes.</p> <p>Technologies include:</p> <ul style="list-style-type: none"> • Centrifugal dewatering: Using centrifugal force to remove water from sludge. • Thermal drying: Using heat to further reduce moisture content. This action is relevant in industries with high sludge production, such as petrochemicals, textiles, and pharmaceuticals. <p>For further information visit:</p> <ul style="list-style-type: none"> • European Commission Sludge Treatment and Disposal Guidelines 	<p>Technologies like centrifugal dewatering and thermal drying are critical in lowering the volume and mass of sludge, allowing it to be transformed into a renewable energy source. Studies show that methods such as ultrasonication combined with torrefaction (a thermal treatment) can achieve over 50% reduction in sludge mass and volume, significantly improving its energy recovery potential.</p> <p>For example, when biochar is produced from the dewatered sludge, it exhibits a high heating value (HHV) of 12.8–14.4 MJ/kg, making it a valuable energy source.</p> <p>The combustion of biochar has been shown to reduce GHG emissions by up to 75% compared to the use of bituminous coal, offering a much more environmentally friendly alternative. In addition, the process results in a cost reduction of up to 85% compared to traditional sludge disposal methods (Lin et al., 2023).</p>	<ul style="list-style-type: none"> • -59 EUR/tCO₂-eq 2021
<p>Advanced Biological Nutrient Removal (BNR) in Industrial Wastewater Treatment</p>	<p>Biological Nutrient Removal (BNR) processes are designed to remove nitrogen and phosphorus from wastewater, preventing nutrient pollution in water bodies. Advanced BNR systems improve process efficiency and reduce the energy required for aeration and mixing.</p> <p>Technologies include:</p> <ul style="list-style-type: none"> • Anammox bacteria: For energy-efficient nitrogen removal. • Simultaneous nitrification-denitrification (SND): To reduce oxygen demand and improve nitrogen removal efficiency. This action is relevant in industries that produce nutrient-rich wastewater, such as agriculture, food processing, and breweries. <p>For further information visit:</p> <ul style="list-style-type: none"> • European Commission Wastewater Nutrient Pollution 	<p>The mitigation effect of this measure is based on an improvement in process efficiency, specifically through the reduction of energy consumption for nutrient removal in industrial wastewater treatment. The extent of energy savings depends on factors such as the current energy consumption for nutrient removal, the specific characteristics of wastewater, and the effectiveness of the technology in removing nutrients. For example, the implementation of Advanced Biological Nutrient Removal and Advanced Process Control (APC) strategies in a full-scale wastewater treatment plant led to a 21.79% reduction in specific energy consumption, while improving nutrient removal rates (+25.48% for nitrogen and +9.25% for phosphorus) (Palatsi et al., 2021). These results highlight the potential of advanced BNR systems to both increase nutrient removal efficiency and reduce energy use.</p>	<ul style="list-style-type: none"> • 8 USD/tCO₂-eq 2021

B.2. Energy Efficiency

Table 2 Energy efficiency measures.

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
<p>Heat Pumps for Industrial Drying and Heating</p>	<p>Heat pumps are highly efficient devices that can transfer heat from one location to another and are particularly useful for low- and medium-temperature heating needs in industrial processes.</p> <p>Heat pumps can be used for:</p> <ul style="list-style-type: none"> Industrial drying: Replacing fuel-based drying processes in food, paper, and textile industries. Space heating: For large industrial buildings or warehouses. Process heating: In chemical and pharmaceutical industries. This action is relevant across industries where heating or drying is essential and can be powered by renewable electricity to further reduce emissions. <p>For further information visit:</p> <ul style="list-style-type: none"> IEA Heat Pump Technologies Report ↗ 	<p>The mitigation effect of this measure is based on an increase in the efficiency of the industrial heat generation process. For instance, transitioning from an electric-based heater to an electric heat pump can result in an efficiency improvement of up to 4 times considering the electric heater having a coefficient of performance of 1 (Schneider, 2023 ↗).</p> <p>Moreover, in case of a transition from a combustion-based heater to an electric heat pump, the emission factor (Gaur et al., 2021 ↗) is reduced as a combustion-based energy source, such as gas or oil, is replaced by electricity, leading to a reduction in greenhouse gas emission factor, which depends on the energy mix of the country or region (Louhisuo et al., 2025 ↗).</p>	<ul style="list-style-type: none"> 50-160 USD/tCO₂-eq, 2022 120 EUR/tCO₂-eq, 2023 100 CHF/tCO₂-eq, 2015
<p>Energy-efficient Industrial Motor Systems</p>	<p>Motors account for a significant portion of industrial electricity consumption, especially in sectors like manufacturing, mining, and chemicals. Implementing more energy-efficient motor systems, such as variable-speed drives (VSDs) and high-efficiency motors, can substantially reduce energy use.</p> <p>Key measures include:</p> <ul style="list-style-type: none"> Replacing outdated motors with high-efficiency motors (e.g., IE3 or IE4 efficiency classes). Installing variable-speed drives (VSDs) to optimize motor performance and energy consumption. Motor management programs to monitor motor health and prevent energy waste. This mitigation action is applicable in all industries that use electric motors, such as manufacturing, utilities, and mining. <p>For further information visit:</p> <ul style="list-style-type: none"> IEA Energy Efficiency Report for Industrial Motors ↗ 	<p>The mitigation effect of this measure is based on an improvement in the efficiency of the industrial process, achieved by a decrease in energy consumption while maintaining the activity levels of the industry (De Almeida, et al., 2024 ↗).</p> <p>This reduction in total fossil fuel consumption can range from 7% to 14% of the energy consumed (De Almeida et al., 2019 ↗), depending on the reference situation and the scope of the intervention. The efficiency improvement is realized through the optimization of processes, leading to a more rational use of resources and a subsequent reduction in emissions associated with energy consumption.</p>	<ul style="list-style-type: none"> (-60)-0 USD/tCO₂-eq, 2023 5-25 USD/tCO₂-eq, 2019

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
Energy-Efficient Chillers and Refrigeration Technologies	<p>Industrial refrigeration systems consume significant amounts of energy, particularly in food processing, pharmaceuticals, and cold storage industries. Upgrading to more energy-efficient chillers and refrigeration technologies can reduce both energy consumption and GHG emissions.</p> <p>These technologies include:</p> <ul style="list-style-type: none"> • Variable-speed chillers: Optimize cooling load based on real-time demand. • Absorption chillers: Use waste heat to provide cooling, reducing energy use. • Natural refrigerants: Such as ammonia or CO₂, to replace high-GWP synthetic refrigerants. This action is highly relevant in industries where temperature control is critical, such as food, pharmaceuticals, and manufacturing. 	<p>The mitigation effect of this measure is based on an increase in the efficiency of the industrial process, which leads to lower consumption of refrigerants and/or reduction in electrical consumption while maintaining activity levels (Kabeel et al., 2017 ↗).</p> <p>Efficiency improvements in refrigeration cycles range from 16.3% to 27.2% when pure refrigerants are replaced with mixed refrigerants, and operating conditions are re-optimised. Additionally, implementing cascade control strategies can lead to an efficiency improvement of up to 5.8%, while individual load consumption management methodologies can reduce electrical consumption by 17% and decrease compressor operation time by 77%, thereby extending equipment lifespan (Acunha, 2024 ↗).</p>	<ul style="list-style-type: none"> • 20-100 USD/tCO₂-eq, 2019 • 21 EUR/tCO₂-eq, 2012 • 10-100 USD/tCO₂-eq, 2024
Improved Energy Efficiency in Process Heating	<ul style="list-style-type: none"> • Process heating is essential for many industries, such as steelmaking, chemical manufacturing, and food processing. <p>Improving energy efficiency in process heating can involve several technologies, such as:</p> <ul style="list-style-type: none"> • High-efficiency burners: Reduce fuel consumption by optimizing combustion. • Recuperative and regenerative burners: Recover waste heat from flue gases. • Improved insulation and refractory materials: Reduce heat loss in furnaces and kilns. • Advanced control systems: Monitor and optimize heat flows in real-time. This action is relevant in industries where high temperatures are required, such as steel, glass, and cement. <p>For further information visit:</p> <ul style="list-style-type: none"> • McKinsey Process Heating Efficiency Report ↗ 	<p>The mitigation effect of this measure is based on an increase in the efficiency of the heating process in industrial applications, effectively lowering the energetic input requirement for maintaining the heat output.</p> <p>Considering the vast array of different approaches to improve process heating, the increase in efficiency may vary. In the case of industrial reheating furnaces, the Oxy-fuel combustion technique can achieve significant improvements in fuel consumption, with energy savings ranging from 16% to 26.2% compared to air/fuel combustion (Zhao et al., 2021 ↗). Additionally, the energy-saving potential of a boiler with a Non-Contact Total Heat Recovery (NCHR) system is 12.97% when compared to a traditional boiler (Liu et al., 2020 ↗). New technologies, such as phase change materials, under experimental study conditions, can achieve a reduction in gas consumption of up to 23.7% (Yan et al., 2021 ↗).</p>	<ul style="list-style-type: none"> • 154 EUR/tCO₂-eq, 2024 • 100-200 USD/tCO₂-eq, 2024 • 150 USD/tCO₂-eq, 2020

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
<p>Use of Variable Speed Drives (VSD) in Industrial Motor Systems</p>	<p>Motors account for a large portion of industrial energy consumption, and most motors operate at a constant speed, even when not needed. Variable Speed Drives (VSDs) allow motor speed to be adjusted to match the actual demand, reducing energy consumption.</p> <p>Key applications include:</p> <ul style="list-style-type: none"> • Pumps and fans: Where flow rates can be controlled with VSDs rather than throttling valves or dampers. • Conveyors and compressors: Where motor speed can be adjusted based on load requirements. This action is relevant in industries using motor-driven systems such as manufacturing, mining, and water utilities. <p>For further information visit:</p> <ul style="list-style-type: none"> • IEA Energy Efficiency Report for Industrial Motors 	<p>The mitigation effect of this measure is based on an increase in the efficiency of the motor systems driving industrial energy supply, by allowing adjustments to energy demands in the industrial process, which optimizes the input of energy and thus lowers consumption.</p> <p>Depending on the specific circumstances, the efficiency gains can vary, but on average, the following improvements can be expected: 15% for pumps, 29% for fans, 4% for compression, and an overall average of 9% (Fraunhofer, 2023). These values reflect the potential efficiency enhancements across different industrial applications, depending on the conditions and technologies involved. Additionally, in other sources, the efficiency improvements can reach as high as 67% (Sadek, 2022) when considering the full scope of all motors, particularly when implementing technical and operational constraints in air blowers, fans, and pumps. However, some sources mentioned more conservative efficiency ranges, typically between 15% and 40% (Energy Institute, 2022).</p>	<ul style="list-style-type: none"> • (-2960) - (-3980) NTD/tCO₂-eq, 2021 • 111 USD/tCO₂-eq, 2022 • (-106) USD/tCO₂-eq, 2021
<p>Energy-Efficient Refrigeration Systems in Cold Storage</p>	<p>Cold storage facilities are energy-intensive due to the continuous operation of refrigeration systems. Energy-efficient refrigeration systems reduce electricity consumption and emissions.</p> <p>Technologies include:</p> <ul style="list-style-type: none"> • Variable-speed compressors: To adjust cooling output based on demand. • Natural refrigerants: Such as CO₂ or ammonia to replace high-GWP synthetic refrigerants. • Advanced control systems: To optimize cooling and reduce energy use during low-demand periods. This action is relevant in industries with large cold storage needs, such as food processing, pharmaceuticals, and logistics 	<p>The mitigation effect of this measure is based on an increase in the efficiency and optimization of cooling processes for industrial cold storages which can both lower the energy requirements for cooling through demand adjustments as well as reduce the use of high GWP refrigerants.</p> <p>Depending on the specific circumstances, the efficiency gains can vary, but on average, improvements of 29% in the coefficient of performance (COP) reflecting the energy input to cooling output ratio, and 37% in cooling efficiency of the air coolers have been observed with the implementation of optimized control strategies. These strategies include dynamic linkage control between compressors and air coolers, resulting in a 21.15% reduction in power consumption (Zhu, 2023).</p>	<ul style="list-style-type: none"> • 1-50 USD/tCO₂-eq, 2010 • 28 USD/tCO₂-eq, 2023 • 23,7 USD/tCO₂-eq, 2011





Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
<p>High-Efficiency Heat Pumps for Industrial Space Heating</p>	<p>Industrial facilities often require space heating in offices, warehouses, and workshops. High-efficiency heat pumps use electricity to move heat rather than generating it directly, leading to significant energy savings.</p> <p>Technologies include:</p> <p>Air-source heat pumps: Extract heat from the outside air to provide indoor heating.</p> <p>Ground-source heat pumps: Use the earth's thermal energy to provide space heating. This action is applicable in industries with significant space heating needs, such as manufacturing, logistics, and warehousing.</p> <p>For further information visit:</p> <ul style="list-style-type: none"> • IEA Heat Pump Technology Report • European Commission Heat Pump Strategy 	<p>The mitigation effect of this measure is based on the improvement of energy efficiency through the use of heat pumps optimizing the flow of heat within a system. However, the effectiveness of the application of heat pumps for industrial space heating, while not an infant technology, is not as evident and while in some cases efficiency gains have been observed, other examples point to negative implementation results.</p> <p>For instance, the study on the hybrid ground source heat pump (HGSHP) system in a cigarette factory highlighted performance issues that suggest limited industrial applicability.</p> <p>The system's Coefficient of Performance (COP) decreased significantly over time, from 5.05 to 4.32 for the heat pumps and from 3.32 to 2.89 for the entire system. Additionally, low cooling loads were linked to high energy consumption and reduced COP, while intermittent operation of the condensation heat recovery system further impacted efficiency. These findings point to the technologies' challenges in meeting the demands of industrial environments, particularly those requiring consistent temperature and humidity control (Du et al., 2023).</p>	<ul style="list-style-type: none"> • (-35) - (-5) USD/tCO₂-eq, 2020 • 50-200 USD/tCO₂-eq, 2020 • 49-160 USD/tCO₂-eq, 2021
<p>High-Efficiency Lighting Systems in Industry</p>	<p>Lighting is a significant source of energy consumption in industrial facilities. Upgrading to high-efficiency lighting systems, such as LEDs, can reduce electricity use and emissions.</p> <p>Technologies include:</p> <ul style="list-style-type: none"> • LED lighting systems: Provide higher efficiency and longer life compared to traditional incandescent or fluorescent lighting. • Lighting control systems: Use sensors and automation to reduce unnecessary lighting when areas are unoccupied. This action is relevant in industries with large indoor spaces, such as warehouses, manufacturing plants, and logistics centers. <p>For further information visit:</p> <ul style="list-style-type: none"> • IPCC 6th Assessment Report 	<p>The mitigation effect of this measure is based on an increase in the efficiency of the lighting applications in the industry, which, by utilizing more energy efficient light bulbs and control systems lower the electricity demand while maintaining the required light intensity and coverage. Energy-efficient lighting systems, such as LED lights, offer significant potential for reducing electricity consumption and emissions in industrial facilities. Depending on the specific circumstances, the efficiency gains can vary, but on average, replacing traditional lighting with LEDs can lead to energy savings of up to 80% (European Cluster Collaboration Platform).</p> <p>Lighting control systems, including sensors and automation, further enhance energy savings by optimizing lighting based on occupancy and daylight availability, contributing to energy savings of up to 70% (Martirano et al., 2021). These improvements reflect the potential for both energy and cost savings across industrial applications, particularly when combining high-efficiency lighting with smart controls (UNFCCC).</p>	<ul style="list-style-type: none"> • 50 USD/tCO₂-eq, 2014 • 160,6 USD/tCO₂-eq, 2014 • 158 USD/tCO₂-eq, 2014

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
Steam System Optimization in Industry	<p>Steam is widely used in industrial processes for heating, drying, and power generation.</p> <p>Steam system optimization reduces energy losses by improving system efficiency through measures such as:</p> <ul style="list-style-type: none"> • Insulation of steam pipes: To reduce heat loss. • Condensate recovery: Reusing steam condensate to reduce the need for additional water and energy. • Steam traps maintenance: Ensuring that faulty steam traps are repaired or replaced to prevent energy waste. This action is applicable across industries using steam systems, such as chemicals, food processing, and textiles. <p>For further information visit:</p> <ul style="list-style-type: none"> • IPCC 5th Assessment Report (2014) • European Commission Steam Efficiency Guidelines 	<p>The mitigation effect of this measure is based on an increase in the efficiency of the steam utilization in industrial processes which through reducing energy losses reduces the total energy consumption in steam systems.</p> <p>Depending on the specific circumstances, the integration of real-time monitoring and flow meters for steam generation and end-use can result in energy savings of up to 9% (Batouta et al., 2024). Additionally, energy-saving actions such as leak repair, pipe insulation, and improvements in boiler combustion efficiency have been shown to reduce thermal energy consumption by approximately 6% (Batouta et al., 2024). These measures are particularly relevant in industries that rely heavily on steam systems, such as chemicals, food processing, and textiles.</p>	<ul style="list-style-type: none"> • 30 EUR/tCO₂-eq, 2020 • (-7)-55 • USD/tCO₂-eq, 2019 • 50-70 EUR/tCO₂-eq, 2022
Energy-Efficient Data Centers in Industry	<p>Data centers are energy-intensive due to the high demands of cooling and operating servers. Improving energy efficiency in data centers can significantly reduce electricity consumption and emissions.</p> <p>Key measures include:</p> <ul style="list-style-type: none"> • Free cooling: Using outside air to cool the data center instead of mechanical cooling. • Advanced power management: Optimizing server energy consumption based on workload. • Server virtualization: Reducing the number of physical servers required to perform the same tasks. This action is relevant in industries that operate large data centers, such as telecommunications, finance, and IT services. <p>For further information visit:</p> <ul style="list-style-type: none"> • IPCC 5th Assessment Report (2014) • European Commission Guidelines for Data Center Efficiency 	<p>The mitigation effect of this measure is based on improving the energy efficiency of data centers.</p> <p>Depending on the specific conditions, integrating free cooling systems—such as using outside air or nearby water sources—can result in energy savings of up to 15% (Koronen et al., 2020). For example, the Aliyun Qiandao Lake Data Center, which uses lake water for cooling, achieves over 80% energy savings (Cai, Gou, 2024), although this is a case of exceptional high efficiency due to its unique location and design. In more typical scenarios, free cooling can still offer substantial savings. Additionally, a cross-system optimization methodology has shown that, under optimal conditions, free cooling can save over 5% of overall energy during the summer and more than 46% of cooling energy during winter weeks (Zhou et al., 2024). These measures are particularly relevant in industries operating large data centers, such as telecommunications, finance, and IT services.</p>	<ul style="list-style-type: none"> • (-133)-234 USD/tCO₂-eq, 2020 • -242 USD/tCO₂-eq, 2020 • (-134)-189 USD/tCO₂-eq, 2020

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
<p>High-Efficiency Electric Motors in Manufacturing</p>	<p>Electric motors are widely used in manufacturing for pumps, fans, compressors, and conveyors. High-efficiency motors use less electricity to perform the same tasks, reducing energy consumption and emissions.</p> <p>Technologies include:</p> <ul style="list-style-type: none"> • IE3 and IE4 efficiency class motors: For improved energy efficiency. • Permanent magnet motors: With higher efficiency compared to traditional induction motors. This action is relevant in manufacturing plants where electric motors are commonly used. <p>For further information visit:</p> <ul style="list-style-type: none"> • EEA Electric Vehicles (2024) 	<p>The mitigation effect of this measure is based on an increase in the efficiency of the electric motors, which lower the requirement of electricity inputs while maintaining the performance demand of the motors. Depending on the specific circumstances, efficiency gains of up to 10% can be achieved with high-efficiency motors. Additionally, in applications below 11 kW, the use of synchronous motors can lead to efficiency gains of up to 30%. Optimizing motor selection, load conditions, and system design further enhances overall energy efficiency in manufacturing plants that rely heavily on electric motors for pumps, fans, compressors, and conveyors (Kaya et al., 2021).</p>	<ul style="list-style-type: none"> • (-60) EUR/tCO₂-eq, 2023 • (-205) - (-70) USD/tCO₂-eq, 2011 • (-180) - (-60) USD/tCO₂-eq, 2020
<p>Energy-Efficient Compressed Air Systems</p>	<p>Compressed air systems are used in a variety of industrial processes but are often inefficient due to leaks, improper sizing, and outdated equipment. Improving the efficiency of compressed air systems can reduce energy consumption and emissions.</p> <p>Key measures include:</p> <ul style="list-style-type: none"> • Leak detection and repair: To reduce air loss and energy waste. • VSD compressors: To optimize energy use by adjusting output to match demand. High-efficiency nozzles: To reduce the amount of compressed air required for certain tasks. This action is relevant in industries such as manufacturing, mining, and chemicals. <p>For further information visit:</p> <ul style="list-style-type: none"> • IPCC 5th Assessment Report (2014) • European Commission Guidelines for Compressed Systems 	<p>The mitigation effect of this measure is based on an increase in energy efficiency, by lowering energy consumption through optimized use of compressed air systems. Depending on the specific circumstances, measures such as leak detection and repair, the use of Variable Speed Drive (VSD) compressors, and the adoption of high-efficiency nozzles can reduce compressed air waste and optimize energy use. It has been shown that implementing these measures allows for a reduction in energy consumption ranging from 20% to 60% (Hernandez-Herrera et al., 2019).</p> <p>This reduction potential is particularly relevant in industries such as manufacturing, mining, and chemicals, where compressed air systems are essential but often inefficient due to leaks, improper sizing, and outdated equipment.</p>	<ul style="list-style-type: none"> • (-35) - 167 USD/tCO₂-eq, 2021 • 7 USD/tCO₂-eq, 2020

B.3. Low-Carbon Energy and Feedstocks

Table 3 Low-Carbon energy measures

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
<p>Production of Synthetic Fuels from H₂ and CO₂</p>	<p>Synthetic fuels, also known as e-fuels, are produced by combining hydrogen (created from electrolysis) with captured CO₂ to create fuels like methane, methanol, or aviation fuels. This action can replace fossil fuels in industries such as aviation and shipping. It requires renewable energy for electrolysis to ensure the hydrogen is “green.”</p> <p>Key technologies include:</p> <ul style="list-style-type: none"> • Electrolyzers: To produce hydrogen. • CO₂ capture technologies: To capture CO₂ from industrial sources. • Fuel synthesis reactors: To combine hydrogen and CO₂ into synthetic fuels. Relevant in the transportation and heavy industry sectors. <p>For further information visit:</p> <ul style="list-style-type: none"> • IEA Report on Hydrogen and Synthetic Fuels  	<p>The mitigation effect of this measure is based on a reduction on the carbon intensity of the fuels used in the industry, represented in lower GHG emission factors in the estimation and lower final emissions. Specifically, this measure seeks an improvement in the emission factor, using renewable electricity for hydrogen production and the capture and conversion of CO₂ into synthetic fuels. The carbon footprint of synthetic fuels produced from hydrogen and CO₂ can vary depending on the energy mix used for electrolysis and the source of captured CO₂. When renewable energy is employed to produce hydrogen through water electrolysis, the overall GHG emissions can be significantly reduced. For instance, the use of CO₂ captured from industrial sources like cement plants in combination with synthetic natural gas (SNG) production can reduce GHG emissions by up to 76% from industrial carbon dioxide (Chauvy et al., 2022 ). Similarly, synthetic fuels produced through the Power-to-X (PtX) process, particularly in regions with low-carbon electricity grids, can achieve GHG intensities as low as 4–37 gCO₂/MJ by 2050 (Watanabe et al., 2023 ). By utilizing green hydrogen and captured CO₂, the carbon footprint of synthetic fuels can be dramatically reduced, with potential emission savings of up to 70% (Sillman et al., 2024 ) when renewable electricity is used. This makes Power-to-X an essential technology in the transition to a low-carbon energy system, offering a sustainable alternative to fossil fuels, particularly for hard-to-abate sectors.</p>	<ul style="list-style-type: none"> • 661 USD/tCO₂-eq, 2007 • 23-70 USD/tCO₂-eq, 2022 • 530-1345 EUR/tCO₂-eq, 2022

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
<p>Use of Biofuels for Industrial Boilers</p>	<p>Industrial boilers typically rely on fossil fuels such as coal, oil, or natural gas for heat production. Switching to biofuels, such as biodiesel or biogas, for boiler operations can significantly reduce emissions. Biofuels can be produced from waste materials, agricultural residues, or dedicated energy crops.</p> <p>Technologies include:</p> <p>Biogas boilers: Convert organic waste or agricultural residues into biogas for heating.</p> <ul style="list-style-type: none"> • Biodiesel boilers: Replace traditional diesel with biodiesel made from vegetable oils or animal fats. • Biomass boilers: Burn biomass directly for heat generation in boilers. This action is relevant in industries that rely on high-temperature process heating, such as cement, food processing, and textiles. <p>For further information visit:</p> <ul style="list-style-type: none"> • IEA Bioenergy Reports 	<p>The carbon content of biofuels varies depending on the feedstock used and the production pathway. For instance, biomethane produced from organic waste, such as cow manure, has lower emissions associated than biofuels produced from fossil-based sources, like natural gas, which can have higher emissions, associated with the fossil origin and the carbon content of natural gas. In contrast, using renewable sources such as biomethane or solid biomass for biofuel production can drastically reduce emissions, achieving levels as low as 10–40 gCO₂-eq/MJ, which results in a substantial improvement in the carbon intensity of fuels (Methanol Institute, 2022).</p>	<ul style="list-style-type: none"> • (-13) - (-4) GBP/tCO₂-eq, 2021 • (-20)–450 EUR/tCO₂-eq, 2020 • 238–605 EUR/tCO₂-eq, 2023
<p>Fuel Switching from Heavy Fuel Oil (HFO) to Natural Gas</p>	<p>Heavy fuel oil (HFO) is commonly used in industrial boilers and power generation, but it produces significant CO₂ emissions. Switching from HFO to natural gas reduces emissions and improves efficiency.</p> <p>Key technologies include:</p> <ul style="list-style-type: none"> • Natural gas-fired boilers: To replace HFO-fired boilers. • Gas turbines: For power generation and process heating. This action is relevant in industries such as power generation, chemicals, and food processing. <p>For further information visit:</p> <ul style="list-style-type: none"> • European Commission Natural Gas Strategy 	<p>The mitigation effect of this measure comes from the reduction of the carbon content of fuels and the associated emission factors, in this case through the switch from Heavy Fuel Oil (HFO) to natural gas, which has a much lower emission factor.</p> <p>This shift can provide a significant reduction in emissions, especially in industrial sectors such as power generation and shipping. In marine engines, for example, the switch from HFO to liquefied natural gas (LNG) has been shown to result in a 21% reduction in GHG emissions, though the exact benefits can vary depending on factors such as methane slip. Methane slip is particularly relevant for low-pressure (LP) LNG engines, where emissions can range from 1.4 g/kWh at high loads to up to 5.6 g/kWh at low loads. However, high-pressure (HP) LNG engines tend to have much lower methane emissions, significantly improving the overall emission factor.</p> <p>Additionally, technologies such as methane oxidation catalysts or blending hydrogen with methane (hythane) can help mitigate methane slip, further improving the potential emissions reductions of the fuel switch.</p>	<ul style="list-style-type: none"> • 4–36 USD/tCO₂-eq, 2018 • 0–40 CAD/tCO₂-eq, 2024 • 193 EUR/tCO₂-eq, 2020

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
<p>Carbon-Neutral Synthetic Fuels in Industry</p>	<p>Carbon-neutral synthetic fuels, also known as e-fuels, are produced using captured CO₂ combined with hydrogen produced from renewable electricity. These fuels can replace traditional fossil fuels in energy-intensive industries such as aviation, shipping, and heavy manufacturing.</p> <p>Key technologies include:</p> <ul style="list-style-type: none"> • Power-to-X (PtX): Converting renewable electricity into synthetic fuels, chemicals, or materials. • Methanation: Combining CO₂ with hydrogen to create methane. • Fischer-Tropsch synthesis: A process that converts syngas (a mixture of CO₂ and H₂) into liquid fuels. This action is relevant in industries where direct electrification is difficult, such as steel, cement, and aviation. <p>For further information visit:</p> <ul style="list-style-type: none"> • IEA Synthetic Fuels Report 	<p>The mitigation effect of this measure is based on a reduction on the carbon intensity of the fuels, by using carbon neutral synthetic fuels in the industry, represented in lower GHG emission factors in the estimation and lower final emissions. For instance, the production of synthetic aviation fuels (SAFs), specifically Fischer-Tropsch synthetic paraffinic kerosene (FT-SPK), from hydrogen (produced via electrolysis using renewable energy) and captured carbon dioxide, directly reduces the emission factor in the aviation sector. That is, blending FT-SPK with conventional Jet A/A1 fuel (up to 50%) can result a 37% reduction in fossil emissions. Additionally, when the life-cycle carbon dynamics of FT-SPK are considered, including both biogenic and fossil carbon sources, a negative carbon flux of -20.0 gCO₂e/MJ is generated, meaning more carbon is sequestered than emitted (Almena et al., 2024).</p>	<ul style="list-style-type: none"> • 0-180 USD/tCO₂-eq, 2020
<p>Fuel Switch from Coal to Natural Gas</p>	<p>Switching from coal to natural gas for electricity generation or industrial heating can significantly reduce CO₂ emissions because natural gas burns more cleanly. This action is applicable in power plants, industrial boilers, and process heating applications.</p> <p>Technologies involved include:</p> <ul style="list-style-type: none"> • Natural gas boilers: Replace coal-fired boilers. • Combined cycle gas turbines (CCGT): For power generation, replacing coal-fired plants. <p>For further information visit:</p> <ul style="list-style-type: none"> • IEA World Energy Outlook • McKinsey Global GHG Abatement Curve 	<p>The mitigation effect of this measure is based on a reduction on the carbon intensity of the fuels, switching from coal to natural gas in the industry, which is represented in lower GHG emission factors in the estimation and lower final emissions. Natural gas emits less CO₂ compared to coal during combustion, and when replacing coal in power plants and industrial boilers, significant reductions in CO₂ emissions can be achieved. For instance, a complete shift from coal to natural gas in the power sector would result in a 30–55% (Ladage et al., 2021) reduction in CO₂-equivalent GHG emissions, depending on methane leakage rates in the natural gas supply chain.</p> <p>Other sources of information suggest that when used for coal-to-gas switching, GHG emissions can be reduced by as much as 40% in some cases (Clean Air Task Force). However, if methane leakage is high, the overall GHG reduction can be diminished or even reversed. To fully realize the mitigation potential, it is crucial to adopt methane abatement measures and, where possible, integrate carbon capture and storage (CCS) technologies in power plants.</p>	<ul style="list-style-type: none"> • 0-58 USD/tCO₂-eq, 2007 • 30-60 USD/tCO₂-eq, 2022 • 20-60 USD/tCO₂-eq, 2022

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
Fuel Switch from Coal to Biomass	<p>Biomass can be used as a renewable energy source to replace coal in various industrial applications.</p> <p>Examples include:</p> <ul style="list-style-type: none"> • Co-firing: Using biomass in existing coal-fired power plants to reduce emissions. • Dedicated biomass plants: Generating electricity and heat entirely from biomass. This is relevant for power generation, cement production, and industries that use coal for process heating. <p>For further information visit:</p> <ul style="list-style-type: none"> • European Commission Biomass Study 	<p>The mitigation effect of this measure is based on a reduction of the carbon content of the fuels, switching from coal to biomass in the industry, represented in lower GHG emission factors in the estimation and lower final emissions. The switch from coal to biomass in combined heat and power (CHP) plants, directly reduces emissions in the energy sector. When coal is replaced with biomass fuels like wheat straw or wood pellets, the emission factor is significantly lowered. For example, when producing 1 MJ of heat, the carbon dioxide equivalent emissions from coal, wheat straw, and wood pellets are 117.01, 22.73, and 78.19 g CO₂e, respectively. This shift reduces emissions by over 80% in the case of wheat straw compared to coal (Zheng et al., 2022).</p>	<ul style="list-style-type: none"> • 149 USD/tCO₂-eq, 2007 • 12-75 USD/tCO₂-eq, 2021 • 18,3-75 USD/tCO₂-eq, 2021
Switching from Conventional Diesel to Biofuels in Logistics	<p>Logistics and transportation sectors are significant emitters of greenhouse gases due to the reliance on diesel fuels. This mitigation measure involves switching from conventional diesel to biofuels, such as:</p> <ul style="list-style-type: none"> • Biodiesel: Produced from vegetable oils or animal fats. • Renewable diesel: A drop-in fuel derived from biomass that can replace conventional diesel in engines without modifications. This is applicable in trucking, shipping, and public transportation sectors that rely heavily on diesel engines. <p>For further information visit:</p> <ul style="list-style-type: none"> • European Commission Biofuels Strategy 	<p>The mitigation effect of this measure is based on an improvement in the emission factor, switching from conventional diesel to biofuels in logistics, which is associated with a lower emissions emission factor and thus lower emissions. Biodiesel, made from vegetable oils or animal fats, and renewable diesel, which can replace conventional diesel without requiring engine modifications, offer substantial benefits for reducing transport-related greenhouse gas emissions. In the specific case of palm biodiesel, increasing its consumption reduces transport CO₂ emissions. Specifically, a 1% increase in palm biodiesel usage leads to a long-run reduction in CO₂ emissions by 0.004%. Furthermore, a 10% increase in the share of palm biodiesel in fuel for transport by 2030 would reduce the rate of increase in road transport carbon emissions. However, the transition to palm biodiesel may cause short-term emissions increases. A 1% rise in palm biodiesel consumption in the short run is linked to a 0.001% increase in CO₂ emissions. Nevertheless, these short-term effects are outweighed by the long-run benefits (Solaymani, 2023).</p> <p>Countries that incorporate in road transport biofuels with low emission intensities into their fuel mix can achieve reductions of up to 26% in emissions, while others with higher biofuel emission intensities see smaller reductions. For example, biofuels with emission intensities as low as 9.5 g CO₂e/MJ can drastically reduce emissions compared to higher emission biofuels, which may have intensities up to 22.8 g CO₂e/MJ (EEA).</p>	<ul style="list-style-type: none"> • 194-488 EUR/tCO₂-eq, 2013 • 49-525 EUR/tCO₂-eq, 2020 • 0-212 CAD/tCO₂-eq, 2023

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
Use of Green Hydrogen for Industrial Heat	<p>Hydrogen is a clean fuel that can replace fossil fuels in high-temperature industrial processes, especially in sectors like chemicals, steel, and cement production. Green hydrogen, produced via electrolysis using renewable electricity, offers a zero-carbon alternative to natural gas or coal.</p> <p>This action involves:</p> <ul style="list-style-type: none"> Hydrogen boilers: To generate high-temperature heat. Hydrogen burners: For direct use in industrial furnaces or kilns. This technology is most applicable in energy-intensive industries with high heat demand. <p>For further information visit:</p> <ul style="list-style-type: none"> IEA Hydrogen Report 	<p>The mitigation effect of this measure is based on an improvement in the emission factor, by deploying green hydrogen instead of conventional fuels, thus effectively reducing the emission factor of the fuel input. The use of green hydrogen for industrial heat generation directly reduces emissions in energy-intensive sectors such as steel, cement, and chemicals as it replaces conventional high-carbon content fuels combusted for heating purposes.</p> <p>Green hydrogen, produced through water electrolysis using renewable electricity, replaces fossil fuels like natural gas or coal in high-temperature industrial processes. Since green hydrogen has zero carbon emissions during production and use, its adoption results in a significant decrease in the carbon intensity of industrial heat generation. By replacing fossil fuels with green hydrogen, which has a zero-emission factor, the emissions are reduced to 0 Kg CO₂e (OECD, 2022).</p>	<ul style="list-style-type: none"> 500-1250 USD/tCO₂-eq, 2024 100-350 USD/tCO₂-eq, 2024 30-900 USD/tCO₂-eq, 2022
Replacement of Coal with Biomass in Industrial Boilers	<p>Industrial boilers are widely used in sectors such as food processing, textiles, and chemicals for steam generation and process heating. Switching from coal to biomass, such as agricultural residues, wood chips, or dedicated energy crops, can reduce CO₂ emissions significantly.</p> <p>Key technologies include:</p> <ul style="list-style-type: none"> Biomass-fired boilers: Replace coal-fired boilers for industrial steam and heat production. Co-firing: Allows biomass to be blended with coal in existing boilers to reduce emissions. This action is relevant across industries that rely heavily on process heat and steam. 	<p>The mitigation effect of this measure is based on a reduction in the emission factor, due to switching from coal to biomass in industrial boilers which has a much lower emission factor than conventional fuels. Biomass absorbs CO₂ during its growth and releases an equivalent amount when burned, unlike fossil fuels, which emit large quantities of CO₂ in a short period. When co-fired with coal, biomass can achieve up to a 93% reduction in CO₂ emissions compared to coal combustion (Sharma et al., 2021).</p>	<ul style="list-style-type: none"> 149 USD/tCO₂-eq, 2007 18,3-73 USD/tCO₂-eq, 2020 59-107,28 USD/tCO₂-eq, 2024
Fuel Switching from Diesel to Natural Gas in Industrial Transport	<p>Many industries rely on diesel-powered trucks, forklifts, and other machinery for internal and external transportation. Switching from diesel to natural gas, particularly compressed natural gas (CNG) or liquefied natural gas (LNG), can reduce CO₂ emissions.</p> <p>Key technologies include:</p> <ul style="list-style-type: none"> CNG trucks and forklifts: For short- to medium-range transport. LNG vehicles: For longer-range transport of goods or raw materials. This action is relevant for industries with significant internal logistics or material transport needs, such as mining, construction, and manufacturing. 	<p>The mitigation effect of this measure is based on a reduction in the emission factor, due to switching from diesel to natural gas in industrial transport, particularly using compressed natural gas (CNG) or liquefied natural gas (LNG), which have lower emissions factor and can significantly reduce greenhouse gas (GHG) emissions (BioCNG). Heavy-duty natural gas vehicles (NGVs) have been shown to emit approximately 6.3% less GHG compared to diesel-powered vehicles of similar weight. On average, each CNG heavy-duty vehicle (HDV) can reduce emissions by around 39.3 tons annually. While the mitigation effect depends on context-specific conditions, such as the different efficiencies of combustion engines, scale of adoption and vehicle use, the overall mitigation effect could range from a 6% reduction in emissions per vehicle to larger reductions when deployed at a wider scale across industries (Seo et al., 2020).</p>	<ul style="list-style-type: none"> 593 CAD/tCO₂-eq, 2015 (-100) - 240 EUR/tCO₂-eq, 2019

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
Carbon-Neutral E-Fuels for Industrial Transport	<p>E-fuels (synthetic fuels) are produced using CO₂ captured from the air or industrial sources combined with hydrogen generated from renewable electricity. E-fuels can replace traditional fossil fuels in industrial transport, particularly in sectors where electrification is challenging, such as shipping and aviation.</p> <p>Technologies include:</p> <ul style="list-style-type: none"> • Methanol synthesis: Using CO₂ and hydrogen to produce methanol for industrial transport. • Fischer-Tropsch synthesis: Producing liquid fuels (e.g., synthetic diesel or kerosene) for trucks, ships, or aircraft. This action is relevant in industries with significant transport needs, including heavy-duty vehicles, shipping, and aviation. <p>For further information visit:</p> <ul style="list-style-type: none"> • European Commission E-Fuels Strategy 	<p>The mitigation effect of this measure is based on an improvement in the emission factor, particularly by replacing conventional fossil fuels with carbon-neutral e-fuels, which drastically reduces GHG emissions in industrial transport. The total emissions of hydrogen used in e-fuel production varies depending on its source. Grey hydrogen, produced from fossil fuels, has a substantial carbon footprint (120–155 gCO₂eq/MJ). In contrast, blue hydrogen, which involves carbon capture and storage (CCS), has a lower carbon footprint (40–90 gCO₂eq/MJ), and green hydrogen, produced using renewable energy, shows significantly reduced levels of greenhouse gas emissions (4.6–43.3 gCO₂e/MJ depending on the energy source).</p> <p>By utilizing green hydrogen to produce e-fuels, the emission factor of fuels used in industrial transport is substantially reduced. For example, green hydrogen, which has the potential to contribute to meeting international maritime emissions reduction targets, could reduce CO₂ emissions in the shipping sector by up to 9%. This makes e-fuels a promising solution for decarbonizing heavy transport sectors (Atilhan et al., 2021).</p>	<ul style="list-style-type: none"> • 793-1598 USD/tCO₂-eq, 2020 • 250 USD/tCO₂-eq, 2017 • 612 USD/tCO₂-eq, 2023
Fuel Switch from Diesel to Biodiesel in Industrial Transport	<p>Biodiesel is a renewable alternative to diesel, produced from organic materials such as vegetable oil, animal fat, or waste cooking oil. Switching from diesel to biodiesel in industrial transport reduces lifecycle emissions.</p> <p>Key applications include:</p> <ul style="list-style-type: none"> • Biodiesel-powered trucks and buses: Used for internal logistics and transport. • Biodiesel-powered equipment: For forklifts, loaders, and other industrial vehicles. This action is relevant in industries that rely heavily on diesel-powered transport, such as manufacturing, mining, and construction. <p>For further information visit:</p> <ul style="list-style-type: none"> • IEA Biofuels Report 	<p>The mitigation effect of this measure is primarily based on a change in the emission factor, as switching from diesel, such as petroleum diesel to biodiesel in industrial transport can result in a reduction of greenhouse gas (GHG) emissions of between 79% and 86% (Xu et al., 2022) depending on the feedstock used for biodiesel production. This transition leads to a significant reduction in the emission factor, as biodiesel, being a renewable biofuel, has a considerably lower lifecycle emission profile than conventional diesel (O'Connell et al., 2023). Furthermore, certain studies indicate that for heavy-duty engines, 100% biodiesel (B100) can achieve emissions reductions of up to 74% (Alternative Fuels Data Center).</p>	<ul style="list-style-type: none"> • 244-400 USD/tCO₂-eq, 2007 • 194-488 EUR/tCO₂-eq, 2013

B.4. Electrification and Process Change

Table 4 Electrification and process change measures.

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
Electrification in Industry	<p>Electrification in industry involves replacing fossil-fuel-based processes with electric technologies. This is particularly effective in sectors where heat generation is necessary, such as:</p> <ul style="list-style-type: none"> • Electric furnaces: Used in metal processing and glass manufacturing. • Electric boilers: For steam generation in food processing or chemical industries. • Industrial heat pumps: Provide both heating and cooling, improving overall energy efficiency. This action is applicable in industries that can transition from direct fossil fuel use to electricity, including manufacturing, food processing, and textiles. <p>For further information visit:</p> <ul style="list-style-type: none"> • IEA Electrification Report • McKinsey Electrification Report 	<p>The mitigation effect of this measure is based on an increase in the energy efficiency of the industrial process with a reduction in the final energy input ranging between 20% and 79% (Silvia Madeddu, et al., 2020) as well as on the change of the emission factor due to a change from a fossil-fuel based energy source to grid or on-site generated electricity.</p> <p>Transitioning from fossil combustion-based systems to electric alternatives in industrial processes can significantly improve efficiency (Jaiswal et al., 2022), depending on the specific conditions of the industry and the technology applied. Furthermore, this transition involves a change in the emission factor, as a hydrocarbon-based energy source (such as gas or oil) is replaced by electricity, leading to a reduction in greenhouse gas emissions, which depends on the energy mix of the country or region (Louhisuo et al., 2025)</p>	<ul style="list-style-type: none"> • 130-450 EUR/tCO₂-eq, 2020 • 130 USD/tCO₂-eq, 2021 • 116-165 USD/tCO₂-eq, 2023
On-Site Renewable Energy Generation for Industrial Facilities	<p>Industrial facilities can reduce emissions by generating renewable energy on-site, either through solar, wind, or biomass systems. This reduces reliance on grid-supplied electricity and provides a direct emissions reduction.</p> <p>Key technologies include:</p> <ul style="list-style-type: none"> • Solar photovoltaic (PV) systems: Installed on rooftops or adjacent land for electricity generation. • Wind turbines: For on-site electricity generation, particularly in regions with good wind resources. • Biomass CHP systems: For combined Heat and power generation from biomass resources (such as agricultural or forestry residues) can meet industrial heat demand while reducing CO₂ emissions. This action is applicable across various industries, particularly those with large facilities or land areas suitable for renewable energy installations. 	<p>The mitigation effect of this measure is based on a reduction in the emission factor, as replacing grid electricity with renewable energy can significantly reduce the emission factor of the facility's energy supply (Zemite et al., 2024), whereas the extent of emissions reduction depends on the level of renewable energy generated on-site and on the energy mix of the grid (Ahmed et al., 2022). In scenarios where renewable energy systems meet 100% of the facility's energy demand, the emissions from energy supply can be virtually eliminated (emission factor zero) (Chuang et al., 2018). However, the mitigation effect will vary based on factors such as the scale of renewable energy capacity installed, local renewable resources (e.g. wind or solar availability), and the proportion of energy demand that is covered by renewables.</p> <p>The overall mitigation effect could range from partial reductions in emissions when renewable energy supply is limited, to near-total reductions when on-site renewable energy fully replaces conventional energy sources.</p>	<ul style="list-style-type: none"> • (-7.1)-59 USD/tCO₂-eq, 2020 • 6,46-82,86 USD/tCO₂-eq, 2020 • (-73)-57 USD/tCO₂-eq, 2021

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
<p>On-Site Solar Thermal for Process Heating</p>	<p>Solar thermal systems can be used to generate heat for industrial processes, particularly in industries with medium-temperature heat requirements (e.g., drying, washing, pasteurization). These systems reduce the reliance on fossil fuel-based heat.</p> <p>Key technologies include:</p> <ul style="list-style-type: none"> • Flat-plate solar collectors: For low- to medium-temperature heat applications. • Concentrated solar power (CSP) systems: For higher-temperature processes, using mirrors to focus sunlight. This action is relevant in industries such as food processing, textiles, and chemicals. <p>For further information visit:</p> <ul style="list-style-type: none"> • IPCC 5th Assessment report (2014) 	<p>The mitigation effect of this measure is based on a reduction in the emission factor, as on-site thermal energy production reduces the reliance on fossil fuels for heating purposes. The extent of emissions reduction depends on the scale of the solar thermal system and the proportion of heat demand met by solar energy. In cases where solar thermal systems meet a significant portion of the facility's heat demand, the emissions from fossil fuel-based heat sources can be reduced proportionally. For instance, when solar thermal systems replace fossil fuel-based heating entirely, the emissions associated with heat generation can be virtually eliminated (emission factor zero) (Chuang et al., 2018).</p> <p>The overall mitigation effect will vary based on factors such as the capacity of the installed solar thermal system, the specific heat demand of the industrial process, and the availability of sunlight. The mitigation effect could range from partial emissions reductions when solar thermal heat supplements conventional heating, to larger reductions when solar thermal systems provide the majority or entirety of the heat demand.</p>	<ul style="list-style-type: none"> • 0-30 EUR/tCO₂-eq, 2021 • 60 USD/tCO₂-eq, 2023 • 104 USD/tCO₂-eq, 2024
<p>Hydrogen Fuel Cells for Industrial Backup Power</p>	<p>Hydrogen fuel cells can replace traditional diesel or natural gas generators for industrial backup power applications. Hydrogen is converted into electricity with water vapor as the only by-product, making this a clean alternative to fossil fuel-based power.</p> <p>Key technologies include:</p> <ul style="list-style-type: none"> • Proton exchange membrane fuel cells (PEMFC): For backup power in industrial facilities. • Solid oxide fuel cells (SOFC): For larger-scale, high-efficiency backup power systems. This action is applicable across industries that require backup power, such as data centers, manufacturing, and critical infrastructure. <p>For further information visit:</p> <ul style="list-style-type: none"> • IEA Hydrogen Report 	<p>The mitigation effect of this measure is based on a reduction in the emission factor due to utilizing hydrogen fuel cells instead of fossil fuels such as diesel or natural gas for powering generators serving as backup power. The extent of emissions reduction depends on the scale of the hydrogen fuel cell system and the proportion of backup power needs met by hydrogen-powered generation. Since PEMFC and SOFC fuel cells produce zero carbon emissions during operation (Al Rikabi et al., 2023), replacing fossil fuel-based generators with these systems results in a significant reduction in greenhouse gas (GHG) emissions, particularly in industries where backup power is critical, such as data centers (Vertiv, 2022), manufacturing, and infrastructure.</p> <p>The overall mitigation effect will vary based on factors such as the capacity of the hydrogen fuel cell systems installed, the frequency and duration of backup power use, and the extent to which hydrogen can replace conventional fossil fuel-based generators. In cases where hydrogen fuel cells provide the entire backup power requirement, the emissions associated with backup power generation can be virtually eliminated.</p>	<ul style="list-style-type: none"> • 500-1250 USD/tCO₂-eq, 2024 • 530-1345 EUR/tCO₂-eq, 2022 • 660 USD/tCO₂-eq, 2022

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
<p>Production of Electricity from Biomass Residues</p>	<p>Biomass residues, such as agricultural waste, forestry by-products, and industrial organic waste, can be used as fuel to generate electricity within several industries.</p> <p>Technologies include:</p> <ul style="list-style-type: none"> • Direct combustion plants: For burning biomass residues to produce steam for power generation. • Gasification technologies: For converting biomass into syngas, which can be burned in gas turbines. • Co-firing: Mixing biomass with coal in coal-fired power plants to reduce emissions. This action applies to industries producing large quantities of biomass waste, such as agriculture and forestry. <p>For further information visit:</p> <ul style="list-style-type: none"> • European Commission Biomass Study • IPCC 5th Assessment report (2014) 	<p>The mitigation effect of this measure is based on an improvement in the emission factor, as biomass residues have a much lower emission factor than fossil fuels thus reducing the emissions occurring in electricity generation. The GHG emissions of biomass power generation depend on the combustion technology used and the type of biomass residue. For example, small-scale biomass gasification has been shown to emit significantly less CO₂, CO, and soot compared to open burning of biomass. On average, small-scale gasifiers emit 2.04 kg of CO₂ per kWh of electricity produced, which is lower than the emissions from open burning or large-scale power generation (Ahmed et al., 2019).</p> <p>Biomass combustion and gasification technologies, such as direct combustion plants and gasification systems, can provide a cleaner alternative to fossil fuel-based power generation, with reductions in greenhouse gas emissions. While small-scale biomass gasification systems are generally more efficient and lower emitting than open burning, their emissions can still be higher than those from large-scale biomass power generation. However, improvements in gasifier technology can help reduce these emissions further, making small-scale systems more competitive with large-scale biomass plants in terms of emissions. The mitigation effect of this measure can range from moderate reductions in emissions when small-scale systems are used, to more substantial reductions when large-scale biomass systems replace fossil fuel power generation.</p>	<ul style="list-style-type: none"> • 23-31 USD/tCO₂-eq, 2013 • 23-33 USD/tCO₂-eq, 2007 • 25 USD/tCO₂-eq, 2015
<p>Installation of Energy Storage Systems for Industrial Facilities</p>	<p>Industrial facilities can install energy storage systems to store excess renewable energy or to balance load during peak demand periods. This reduces the need for grid-supplied electricity and can provide backup power during outages.</p> <p>Key technologies include:</p> <ul style="list-style-type: none"> • Battery energy storage systems (BESS): To store electricity generated on-site or from the grid. • Thermal energy storage (TES): For storing excess heat for later use in industrial processes. • This action is relevant across industries with significant energy demand, particularly those that generate renewable energy on-site. <p>For further information visit:</p> <ul style="list-style-type: none"> • European Commission Energy Storage Strategy • IPCC 5th Assessment report (2014) 	<p>The mitigation effect of this measure is based on a more efficient use of electricity, in particular if produced on-site, due to the utilization of storage systems which allows for reducing the reliance on grid-supplied electricity in the industry. The extent of emissions reduction depends on the scale of the energy storage system and the amount of renewable energy saved, stored, and utilized (National Institute for Ecology and Climate Change Mexico, 2020). Modelling results show that electricity storage systems could allow for a reduction equivalent to 46% of total emissions in the electricity sector, compared to the scenario without electricity storage.</p>	<ul style="list-style-type: none"> • 40 USD/tCO₂-eq, 2013 • 30-35 USD/tCO₂-eq, 2022

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
<p>Electrification of Mechanical Drives in Heavy Industry</p>	<p>Many heavy industries, such as mining and construction, rely on fossil fuel-powered mechanical drives for equipment such as excavators, conveyors, and crushers. Electrifying mechanical drives can reduce emissions, especially if powered by renewable electricity.</p> <p>Key technologies include:</p> <ul style="list-style-type: none"> • Electric excavators and loaders: Replacing diesel-powered equipment with electric alternatives. • Electric conveyors and crushers: For material transport and processing. This action is relevant in heavy industries such as mining, construction, and quarrying. <p>For further information visit:</p> <ul style="list-style-type: none"> • IPCC 5th Assessment report (2014) 	<p>The mitigation effect of this measure is based on an increase in energy efficiency due to the deployment of more energy efficient mechanical drives reducing the overall energy demand of the industrial process as well as on a change in the emission factor, if the mechanical drives are powered by renewable energy instead of fossil fuels with higher emission factors. Electric excavators and loaders typically have a higher energy efficiency compared to their diesel counterparts. In addition, an innovative hydraulic hybrid excavator system, using an electrical hydraulic powertrain and energy regeneration strategies, has demonstrated energy savings ranging from 36.69% to 45.16%, associated with a reduction in fuel consumption (Yu et al, 2021). Furthermore, this transition involves a shift in the emission factor, as the fossil fuel-based energy sources are replaced by electricity. The extent of the reduction in greenhouse gas emissions depends on the energy mix of the country or region (Louhisuo et al., 2025), with greater emissions reductions achievable in regions where electricity is generated predominantly from renewable sources.</p>	<ul style="list-style-type: none"> • (-200) -(-70) USD/tCO₂-eq 2017 • (-43) – (-1) USD/tCO₂-eq 2020 • -60 EUR/tCO₂-eq 2023
<p>Electrification of High-Temperature Industrial Processes</p>	<p>High-temperature processes, such as those in the cement, steel, and chemical industries, traditionally rely on fossil fuels like coal and natural gas.</p> <p>Electrifying these processes using technologies like electric arc furnaces or electric kilns can reduce emissions, particularly if renewable electricity is used.</p> <p>Key technologies include:</p> <p>Electric arc furnaces (EAF): For steel production.</p> <p>Electric kilns: For cement and ceramics production.</p> <p>Induction heating: For metalworking processes such as forging and casting. This action applies across industries that rely on high-temperature heat for production processes.</p> <p>For further information visit:</p> <ul style="list-style-type: none"> • IEA Energy Technology Perspectives Report (2020) 	<p>The mitigation effect of this measure is based on an increase in energy efficiency due to the deployment of electric furnaces which reduce the energy input requirement while maintaining the required output of the industrial process as well as on a change in the emission factor, due to the utilization of grid or on-site generated renewable electricity instead of carbon intensive fossil fuels. Electric arc furnaces (EAF) in steel production, for example, offer a much more energy-efficient alternative compared to traditional methods, such as the blast furnace-basic oxygen furnace (BF-BOF) process. The EAF process typically consumes about one-third of the energy required by the BF-BOF process and can reduce carbon emissions to just 10%–20% of those produced by conventional methods (Louhisuo et al., 2025).</p> <p>Additionally, using clean fuels and green power for EAF steelmaking has been proposed as a pathway to near-zero carbon emissions, contributing further to emissions reductions. Furthermore, this transition involves a shift in the emission factor, as coal and natural gas are replaced with electricity, which can be sourced from renewable energy. The extent of the reduction in greenhouse gas emissions depends on the energy mix of the country or region (Tian et al., 2023), with greater reductions achievable in regions where electricity is predominantly generated from renewable sources.</p>	<ul style="list-style-type: none"> • 130-450 EUR/tCO₂-eq, 2020 • 130 USD/tCO₂-eq, 2021 • 116-165 USD/tCO₂-eq, 2023

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
<p>Electrification of Forklifts and Material Handling Equipment</p>	<p>Forklifts and other material handling equipment, commonly used in warehouses and manufacturing plants, are traditionally powered by diesel or propane. Electrification of this equipment can reduce CO₂ emissions, particularly if powered by renewable electricity.</p> <p>Key technologies include:</p> <ul style="list-style-type: none"> • Battery-electric forklifts: Replacing diesel or propane-powered forklifts with battery-electric versions. • Electric pallet jacks and reach trucks: For moving materials in logistics and warehouses. This action is relevant in sectors like logistics, warehousing, manufacturing, and retail. <p>For further information visit:</p> <ul style="list-style-type: none"> • IEA Electrification in Industry Report 	<p>The mitigation effect of this measure is based on a change in the emission factor as switching from fuel powered to electricity powered equipment is associated with a lower emission factor when utilizing the equipment in industrial processes.</p> <p>Electrically powered forklifts are shown to be more advantageous than those running on liquefied petroleum gas (LPG), with lower carbon emissions across a variety of operations. For instance, forklifts powered by LPG emit approximately 3.391 kg CO₂ per kg of LPG, while battery-electric forklifts emit just 0.54 kg CO₂ per kWh (Boenzi et al., 2017). While this represents a substantial reduction in emissions, it could be further improved if the electricity used is sourced from renewable energy only. The extent of the reduction in greenhouse gas emissions depends on the energy mix of the country or region (Louhisuo et al., 2025) with the greatest reductions occurring in areas where renewable energy makes up a large portion of the country's energy mix.</p>	<ul style="list-style-type: none"> • 0-30 USD/tCO₂-eq, 2009 • (-59)-113 USD/tCO₂-eq, 2020 • 53 EUR/tCO₂-eq, 2017
<p>Use of Renewable Heat in Industry</p>	<p>Renewable heat involves the use of renewable energy sources such as biomass, solar thermal, and geothermal energy to meet industrial heat demand. This can reduce reliance on fossil fuels for heating applications.</p> <p>Technologies include:</p> <ul style="list-style-type: none"> • Biomass boilers: Use agricultural or forestry residues to generate heat. • Solar thermal collectors: Capture sunlight to generate heat for industrial processes. • Geothermal heat pumps: Use the Earth's heat for heating applications in industries. This action is applicable in sectors with high heat demands, such as food processing, textiles, and paper manufacturing. 	<p>The mitigation effect of this measure is based on a change in the emission factor as renewable energy replaces the need for fossil energy sources in industrial heating while maintaining the required output level. The extent of emissions reductions depends on the share of renewable heat used in the industrial process and the specific technology deployed. For example, geothermal energy has a carbon intensity ranging from less than 40 kg CO₂ eq/MWh for closed-loop systems to as high as 122 kg CO₂ eq/MWh for certain flash steam technologies (Ball, 2024). Renewable sources like solar thermal and biomass have lower emissions compared to fossil fuel-based heating systems.</p> <p>In applications where renewable heat replaces fossil fuels, emissions can be drastically reduced, especially in regions with abundant renewable energy sources. The specific reduction in emissions is relative to the percentage of heat derived from renewable sources, with greater reductions achievable when renewable technologies like geothermal or solar thermal are utilized to a higher extent. The overall impact on greenhouse gas emissions will depend on the technology's efficiency and the energy mix used in the region.</p>	<ul style="list-style-type: none"> • 0-35 USD/tCO₂-eq, 2010 • (-25)-20 USD/tCO₂-eq, 2020 • 76 USD/tCO₂-eq, 2024

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
<p>Electrification of Drying Processes in the Paper Industry</p>	<p>Drying processes in the paper and pulp industry are energy-intensive and traditionally rely on fossil fuels. Electrifying these processes can reduce emissions significantly, especially when powered by renewable electricity.</p> <p>Key technologies include:</p> <ul style="list-style-type: none"> • Electric drying: Using electric heaters to dry pulp and paper instead of steam generated from fossil fuels. • Electric infrared drying systems: For specific applications requiring high-speed drying. This action is applicable in the paper and pulp industry, particularly in regions where renewable electricity is abundant. 	<p>Electric drying systems, including electric heaters and infrared drying technologies, improve energy efficiency by reducing the need for steam generated from fossil fuels, which further is associated with a fuel switch from fossil fuels to electricity supplied by the grid. For example, the transition from traditional technologies to electric dryer systems has been shown to reduce energy consumption by up to 54% in specific applications (Ibrahim et al., 2024), such as drying medicinal and aromatic plants. Moreover, the shift to electric dryers, especially when powered by renewable electricity, leads to a substantial reduction in carbon emissions. The extent of emissions reductions depends on the energy mix of the region (Louhisuo et al., 2025), with greater reductions achievable in areas where renewable energy is the primary source of electricity.</p>	<ul style="list-style-type: none"> • 17,8-59,8 EUR/tCO₂-eq, 2022 • (-101,8) – 674,21 USD/tCO₂-eq 2017
<p>Electrification of Heavy-Duty Vehicles in Industry</p>	<p>Heavy-duty vehicles (HDVs), such as trucks, construction machinery, and mining equipment, are significant contributors to GHG emissions in industries like mining, construction, and logistics. Electrification of these vehicles reduces emissions from diesel fuel combustion.</p> <p>Technologies include:</p> <ul style="list-style-type: none"> • Battery-electric trucks and machinery: For short and medium-range operations. • Hybrid electric vehicles (HEVs): Combine an internal combustion engine with an electric motor for improved efficiency. • Fuel cell electric vehicles (FCEVs): Use hydrogen to power electric motors in heavy-duty applications. This action is applicable in industries relying on HDVs for transportation, logistics, and heavy construction. <p>For further information visit:</p> <ul style="list-style-type: none"> • IEA Heavy-Duty Electric Vehicles Report 	<p>The mitigation effect of this measure is based on an increase in efficiency due the utilization more energy efficient motor systems in trucks which reduces the energy consumption, as well as on a change of the emission factor as battery electric trucks run on electric energy instead of on fossil fuels. Battery-electric trucks, for example, offer significant improvements in energy efficiency, achieving a source-to-wheel efficiency of 70-80%, compared to conventional diesel vehicles. This means that only a fraction of the energy produced is lost, significantly enhancing the vehicle's performance (Milence, 2023). In addition, battery-electric trucks have been shown to achieve a 63% reduction in emissions compared to their diesel counterparts, with this figure improving to an 84% reduction when powered by renewable electricity.</p> <p>Fuel cell electric vehicles (FCEVs) also offer a reduction in emissions, but the extent of the reduction depends on the source of the hydrogen used. When hydrogen is produced from renewable electricity, emissions can be reduced by up to 85%. However, when hydrogen is derived from fossil fuels, the reduction is more limited at 15% (ICCT, 2023). The results show that the efficiency improvement of battery-electric vehicles is considerably higher than conventional diesel vehicles across different weight classes, vehicle types, and duty cycles. The vehicle energy efficiency ratio is about 3.5 at highway speeds and 5 to 7 times the efficiency of conventional diesel vehicles when operated at lower speed duty cycles, where idling and coasting losses from conventional engines are highest (California Air resources Board). Furthermore, this transition involves a change in the emission factor, as a hydrocarbon-based energy source (such as gas or oil) is replaced by electricity, leading to a reduction in greenhouse gas emissions, which depends on the energy mix of the country or region. The overall mitigation effect depends on the technology employed and the specific sector conditions.</p>	<ul style="list-style-type: none"> • 30-55 EUR/tCO₂-eq, 2015 • 0-30 USD/tCO₂-eq, 2009 • (-59)-113 USD/tCO₂-eq, 2020

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
Electrification of Kilns in the Ceramics Industry	<p>Kilns in the ceramics industry traditionally rely on natural gas or other fossil fuels for high-temperature processes. Electrifying kilns can reduce CO₂ emissions, particularly if renewable electricity is used.</p> <p>Key technologies include:</p> <ul style="list-style-type: none"> • Electric resistance kilns: For ceramics firing at high temperatures. • Induction heating: For specific applications requiring efficient, localized heating. This action is relevant for ceramics manufacturers, including those producing bricks, tiles, and sanitary ware. 	<p>The mitigation effect of this measure is based on both an increase in efficiency due to a lower total energy consumption of electric kilns as compared to their fossil fuel counterparts and a change in the emission factor due to the use of electricity instead of fossil fuels with higher emission factors.</p> <p>Electrification of kilns in the ceramics industry leads to significant improvements in energy efficiency compared to traditional fossil fuel-based heating. By replacing combustion-based technologies with electric alternatives, the overall energy consumption of the process is reduced. For example, in the case of the Rotary Kiln Electric Furnace (RKEF) process, energy efficiency can reach up to 53% (Rong et al., 2017 [1]), compared to the 13%–15% efficiency typically seen with fossil fuel combustion kilns (Zhou, Qin, 2017 [2]). The reduction in the emission factor depends on the current fuel used and the emission intensity of the electricity supply. As the grid becomes cleaner, with a greater share of renewable energy, the reduction in emissions from electrified processes can be substantial.</p>	<ul style="list-style-type: none"> • 2203-8416 CNY/tCO₂-eq, 2024 • 250-900 CNY/tCO₂-eq, 2023 • 168 EUR/tCO₂-eq, 2024
Electric Boilers for Steam Generation	<p>Industrial boilers are widely used for steam generation, traditionally fueled by coal, oil, or natural gas. Replacing these fossil fuel-based boilers with electric boilers can reduce emissions significantly, especially when powered by renewable electricity.</p> <p>Key applications include:</p> <ul style="list-style-type: none"> • Electric resistance boilers: Directly convert electricity into heat for steam generation. • Electrode boilers: Use electrical currents passed through water to generate steam. This action is applicable across industries that use steam for process heating, such as food processing, textiles, and pharmaceuticals. 	<p>The mitigation effect of this measure is based on an increase in the energy efficiency of electric boilers which reduce the overall fuel consumption of the process as well as a reduction in the emission factor by deploying electricity inputs to power the heating process instead of fossil fuel inputs with higher emission factors. The shift to electric boilers reduces both, with the magnitude of these benefits depending on the existing fuel type and the emission factor of the electricity grid.</p> <p>The efficiency of electric boilers can increase by a considerable margin, typically ranging from 6% to 11% compared to conventional fossil fuel-based systems (Rapter et al., 2020 [1]). This improvement is especially significant when renewable energy sources are used, as the carbon intensity of the electricity generated directly influences the overall emissions from the steam generation process. In terms of emissions reductions, electrifying steam generation systems can lead to an overall reduction in greenhouse gas emissions between 7% and 10% (Wolf et al., 2023 [2]), with the exact impact dependent on factors such as the fuel currently in use and the carbon intensity of the local electricity grid.</p>	<ul style="list-style-type: none"> • 130-450 EUR/tCO₂-eq, 2023 • 494-2346 EUR/tCO₂-eq, 2020 • 82-250 USD/tCO₂-eq, 2022 • 143 USD/tCO₂-eq, 2020

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
<p>Electrification of Heat in Food Processing</p>	<p>Heat is required in many stages of food processing, from pasteurization to drying. Electrifying these processes with technologies like heat pumps, electric ovens, and electric boilers can significantly reduce emissions, particularly when renewable electricity is used.</p> <p>Technologies include:</p> <ul style="list-style-type: none"> • Electric heat pumps: For low to medium-temperature processes. • Electric boilers: For generating steam for cooking, cleaning, or sterilization. • Electric ovens: For baking, roasting, or drying food products. This action is highly relevant in the food and beverage industry, which has significant heat requirements. <p>For further information visit:</p> <ul style="list-style-type: none"> • European Commission Guidelines for Food Industry Efficiency 	<p>The mitigation effect of this measure is based on an increase in the energy efficiency as electrified equipment uses less energy to achieve the required output and as electricity supplied by the grid has a lower emission factor than direct fossil fuel inputs. Electrifying heat in food processing—using technologies like electric heat pumps, electric boilers, and electric ovens—significantly improves energy efficiency and reduces greenhouse gas (GHG) emissions (Attuonwu, Tasso, 2021). For example, energy consumption can be reduced by a factor of up to 2.2, while GHG emissions can be cut by as much as 2.6 times when switching from conventional fossil fuel-based systems to electrified technologies (Im, Kim, 2020).</p> <p>These improvements are particularly noticeable in processes such as drying, baking, and pasteurization, where electrified technologies can offer faster and more efficient heat transfer compared to traditional methods. The reduction in GHG emissions largely depends on the existing fuel sources being replaced. The impact on emissions is influenced by the current fuel mix—whether fossil fuels or other heat sources are in use—and the type of electricity used to power the new electrified systems.</p>	<ul style="list-style-type: none"> • 40-600 CHF/tCO₂-eq, 2024 • (-37,65)-66,33 USD/tCO₂-eq, 2020 • 60-70 USD/tCO₂-eq, 2023
<p>Solar Photovoltaic (PV) Systems for Self-Consumption in Industry</p>	<p>Installing solar PV systems on-site in industrial facilities allows for self-generation of electricity, reducing reliance on grid-supplied fossil-fuel-based electricity and lowering CO₂ emissions. This mitigation action is particularly applicable in sectors with large rooftops or open areas, such as manufacturing, warehouses, and logistics.</p> <p>Technologies include:</p> <ul style="list-style-type: none"> • Rooftop solar PV: Installed on the roofs of industrial buildings. • Ground-mounted solar PV: Installed on the ground around industrial facilities for self-consumption. This action is applicable across industries that consume significant amounts of electricity. <p>For further information visit:</p> <ul style="list-style-type: none"> • IEA Solar PV Report 	<p>The mitigation effect of this measure is based on a reduction in the emission factor driven by a switch from fossil fuels to on-site renewable energy production, thus substituting higher carbon content fuels with a no carbon alternative for providing power to the industrial process. The mitigation effect of this measure depends on the percentage of renewable energy integrated into the total energy consumption of the sector, which can vary considerably.</p> <p>However, as a reference, the installation of a 1.3 MW solar PV system generated 1,876 MWh of electricity annually, leading to a reduction of approximately 966 tonnes of CO₂. This change resulted in displacing 18.4% of the plant's electricity consumption from the national grid with a renewable energy source, significantly lowering greenhouse gas (GHG) emissions (Kamran et al., 2024). The exact impact on emissions reductions will depend on factors such as the energy consumption of the facility, available installation space, solar radiation levels, and the emission factor of the local electricity grid.</p>	<ul style="list-style-type: none"> • 169 USD/tCO₂-eq, 2007 • 0-20 EUR/tCO₂-eq, 2010 • (-7,1)-51,9 USD/tCO₂-eq, 2020

B.5. Carbon Capture, Utilization, and/or Storage (CCS/CCUS)

Table 5 Carbon capture, utilization, and/or storage measures.

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
<p>CO₂ Capture and Storage (CCS)</p>	<p>Carbon capture and storage (CCS) involves capturing CO₂ from industrial sources and power plants, then transporting it to be stored underground in geological formations. It is especially relevant for industries with hard-to-abate emissions, such as:</p> <ul style="list-style-type: none"> • Cement production • Steel production • Coal-fired power generation • Technologies include post-combustion capture, pre-combustion capture, and oxy-fuel combustion. <p>For further information visit:</p> <ul style="list-style-type: none"> • IEA Carbon Capture and Utilization Report 	<p>The GHG mitigation impact of carbon capture measures corresponds to the volume of CO₂ that is successfully captured and prevented from entering the atmosphere. Implementing Carbon Capture, Utilization, and/or Storage (CCS/CCUS) can reduce the emissions of industrial processes by capturing up to 90% of CO₂ emissions (Climate Portal MIT, 2021), depending on the technology and project conditions. Furthermore, CCS/CCUS has a net CO₂ abatement potential ranging between 47% and 91% (Emborg et al., 2024), as the captured CO₂ is either stored permanently or utilized in industrial applications.</p>	<ul style="list-style-type: none"> • 46-137 USD/tCO₂-eq 2015 • 20-120 USD/tCO₂-eq 2021 • 27-150 CAD/tCO₂-eq 2023
<p>Carbon Capture and Utilization (CCU) in Chemicals</p>	<p>Carbon capture and utilization (CCU) involves capturing CO₂ from industrial processes and using it as a raw material to produce valuable chemicals such as:</p> <ul style="list-style-type: none"> • Methanol: Can be synthesized from CO₂ and hydrogen. • Urea: Produced using CO₂ in the process. • Plastics and polymers: Using captured CO₂ as a building block for manufacturing. This action is highly relevant for the chemical industry, which can utilize CO₂ emissions to create products with lower carbon footprints. <p>For further information visit:</p> <p>IEA Carbon Capture and Utilization Report</p>	<p>The GHG mitigation impact of carbon capture measures corresponds to the volume of CO₂ that is successfully captured and prevented from entering the atmosphere. By replacing fossil-fuel-based raw materials and energy sources with captured CO₂, the emissions of the chemical production process can be significantly reduced. The extent of emissions reduction depends on factors such as the level of CO₂ captured, the technology used for CO₂ conversion, and the scale of market adoption of CCU technologies.</p> <p>For instance, the use of CCU in the petrochemical industry has the potential to reduce fossil fuel consumption by up to 32%, which can substantially lower CO₂ emissions associated with chemical production (Kawai et al., 2024). However, the mitigation effect will vary based on factors such as the efficiency of CO₂ conversion technologies, the scale of CCU deployment, and the market demand for chemicals produced using captured CO₂.</p>	<ul style="list-style-type: none"> • 237,81-253,51 CNY/tCO₂-eq 2023 • 429 USD/tCO₂-eq 2023 • 250-600 RMB/tCO₂-eq 2024

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
<p>CO₂ Capture and Utilization (CCU) for Industrial Waste Gases</p>	<p>CO₂ capture and utilization (CCU) involves capturing CO₂ from industrial waste gases and using it as a feedstock for producing fuels, chemicals, or building materials. This reduces emissions and creates valuable products.</p> <p>Key applications include:</p> <ul style="list-style-type: none"> • Carbon-to-fuels: Using captured CO₂ to produce synthetic fuels like methanol. • Carbon-to-chemicals: CO₂ can be converted into valuable chemicals such as urea. • Carbon-to-concrete: CO₂ can be sequestered in concrete to improve its strength. This action is relevant across industries producing significant CO₂ emissions, such as steel, cement, and chemicals. <p>For further information visit:</p> <ul style="list-style-type: none"> • IEA Carbon Capture and Utilization Report 	<p>The impact of this measure on GHG emissions is equivalent to the total amount captured as emissions once released are removed or withheld from the atmosphere. By capturing CO₂ from industrial waste gases and converting it into valuable products such as fuels, chemicals, and building materials, the CO₂ emissions are both reduced and repurposed for beneficial uses. The extent of emissions reduction depends on the scale of CO₂ captured and utilized, as well as the specific applications of the captured CO₂.</p> <p>For example, captured CO₂ can be used in carbon-to-fuels processes to produce synthetic fuels like methanol, in carbon-to-chemicals processes to produce urea, or sequestered in concrete to improve its strength. This action is particularly relevant for industries like steel, cement, and chemicals, which are significant emitters of CO₂. Estimates suggest that CO₂ utilization could capture between 10% and 33% of total captured CO₂ (BCG, 2024 ↗).</p>	<ul style="list-style-type: none"> • 60-80 USD/tCO₂-eq 2016 • 88-205 EUR/tCO₂-eq 2023 • 15-120 USD/tCO₂-eq 2019

Annex C. Industry Specific Measures

The industry specific measures involve different PAMs that are directly linked with a specific industry.

The following industries are identified:

- Energy industry
- Iron and steel industry
- Cement and glass industry
- Chemical industry

Energy Industry

- Use of Renewable Energy Sources (RES) for Power Production
- Replacement of Coal-Based Power with Wind/Solar Energy
- Reduction of Transmission and Distribution Losses
- Improve Efficiency in Power Plants (Conversion of Coal/Liquid Plants and Single-cycle NG Plants to Combined Cycle NG Plants)
- Biomass Co-Firing in Power Plants
- Development of Advanced Metering Infrastructure (AMI) in the Electricity Grid
- Commissioning of New Efficient Plants and/or Fuel Switch to Less Carbon-Intensive Fuels

Iron and Steel Industry

- High-Efficiency Slag Recycling in Steelmaking
- Hydrogen-Based Direct Reduced Iron (DRI) Production
- Electric Arc Furnaces for Steel Production
- Scrap Preheating in Steel Production
- Electrolysis of Iron Ore in Steelmaking
- Electrification of Annealing in Metalworking
- Advanced Metal Recovery from Slag and Dust
- Recycling and Material Efficiency in the Aluminium Industry
- Energy Efficiency Improvements in Steel Rolling Mills
- Use of Recycled Steel in Manufacturing

Cement and Glass Industry

- Reduction of Process-Related CO₂ Emissions in Cement Production
- Carbon Capture and Storage (CCS) in the Cement Industry
- Low Carbon Cement Alternatives
- Use of Waste-Derived Fuels in Cement Production
- Electrification of Cement Production
- Enhanced Glass Recycling in Manufacturing
- Electrification of Process Heating in Glass Manufacturing




Chemical Industry

- Abatement of N₂O Emissions in Nitric and Adipic Acid Production
- Carbon Capture and Utilization in the Chemical Industry
- Nitrogen Use Efficiency in Fertilizer Production
- Use of Biomass Feedstock in Chemical Industry
- Green Ammonia Production in Chemical Industry
- Advanced Catalysts for Petrochemical Processes
- Fuel Switching to Green Hydrogen in the Chemicals Industry
- Abatement of Nitrous Oxide (N₂O) Emissions in Fertilizer Production

Table 6 Industry specific measures.

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
Energy industry			
<p>Use of Renewable Energy Sources (RES) for Power Production</p>	<p>Renewable energy sources (RES) like solar, wind, hydro, and geothermal replace fossil fuels in power generation in the industry, leading to significant emission reductions.</p> <p>Relevant technologies include:</p> <ul style="list-style-type: none"> • Solar photovoltaic (PV) panels • Wind turbines (onshore and offshore) • Hydropower plants • Geothermal power plants Applicable in energy utilities and sectors with high electricity consumption. <p>For further information visit:</p> <ul style="list-style-type: none"> • IEA World Energy Outlook 2022 • IPCC AR5 Working Group III, Chapter 7 on Energy Systems (2014) 	<p>The mitigation effect of this measure is based on the reduction of the emission factor through the replacement of fossil fuels in power generation with renewable energy sources. The mitigation effect of this measure, Use of Renewable Energy Sources (RES) for Power Production, can vary depending on the RES used, meaning that variations exist in the variable usage, for example transmission and distribution losses can vary from 2% to 20%, with 12% being a standard estimate. Although this estimate can vary per country.</p> <p>The use of thermal plants typically accounts for 5% to 10% of energy consumed. The mitigation effect depends on factors like country-specific emission factors for thermal plants, RES generation, and transmission network efficiency. The measure is more effective for plants that still use fossil fuels (User Manual v.6 of MITICA section 4.1.1.).</p>	<ul style="list-style-type: none"> • 0-20 EUR/tCO₂-eq 2010 • 0-15 EUR/tCO₂-eq 2022 • 86-480 USD/tCO₂-eq 2024
<p>Replacement of Coal-Based Power with Wind/Solar Energy</p>	<p>Replacing coal-fired power plants with renewable energy sources such as wind or solar can dramatically reduce CO₂ emissions. This action is especially relevant in countries that rely heavily on coal for electricity generation.</p> <p>Applicable technologies include:</p> <ul style="list-style-type: none"> • Onshore and offshore wind turbines: For large-scale wind power generation. • Solar photovoltaic (PV) panels: For utility-scale and distributed generation. • Solar thermal plants: Use mirrors to concentrate sunlight and generate electricity through steam turbines. The action applies across the power generation sector, particularly in regions with good solar or wind potential. <p>For further information visit:</p> <ul style="list-style-type: none"> • IEA Renewables Report (2020) 	<p>The mitigation effect of this measure is based on the reduction of the emission factor through the replacement of coal-based power plants with wind and solar alternatives. The mitigation effect of this measure can vary depending on the replaced energy used. The mitigation effect can be calculated through the reduction of the volume of coal or other fossil fuels consumed, measured in TJ, and applying the corresponding CO₂ emission factors. The annual mitigation impact is derived by multiplying the fuel reduction by the CO₂ emission factor (User Manual v.6 of MITICA section 4.1.1.).</p>	<ul style="list-style-type: none"> • 0-30 USD/tCO₂-eq 2007 • 60 USD/tCO₂-eq 2023 • 64 USD/tCO₂-eq 2014


Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
Reduction of Transmission and Distribution Losses	<p>Between 2% and over 20% of the primary energy used in electricity generation is lost during the transmission and distribution process. These losses occur due to resistance in transmission lines, conversion inefficiencies in transformers, and inadequate insulation. This mitigation action involves upgrading infrastructure with:</p> <ul style="list-style-type: none"> • High-voltage direct current (HVDC) systems: Reduce line losses over long-distance transmission. • Smart grid technologies: Real-time optimization of electricity flow to minimize losses. • Upgrading transformers and switch gear: Improve the efficiency of energy conversion and reduce losses. Applicable for utilities, industries with their own electricity networks, and regions with outdated grid infrastructure. <p>For further information visit:</p> <ul style="list-style-type: none"> • IEA Renewables Report (2020) • IEA World Energy Outlook 2022 	<p>The mitigation effect of this measure is based on the improvement of energy efficiency through the optimization of the transmission and distribution process of electricity generation. The mitigation effect of this measure can vary depending on the reduction of the transmission and distribution losses of electricity. Transmission losses typically range from 2% to 20% (varies per country), with grid loss after mitigation estimated as 10% in the absence of specific data. Additionally, grid CO₂ emissions factor varies and is completely dependent on the country's energy mix. The actual mitigation effect varies based on country-specific emission factors for thermal plants, RES generation, and transmission network efficiency. Countries with poor electrical infrastructure can benefit relatively more from reduced losses (User Manual v.6 of MITICA section 4.1.1).</p>	<ul style="list-style-type: none"> • 63 USD/tCO₂-eq 2015 • 5-50 EUR/tCO₂-eq 2018 • -40 EUR/tCO₂-eq 2012
Improve Efficiency in Power Plants (Conversion of Coal/Liquid Plants and Single-cycle NG Plants to Combined Cycle NG Plants)	<p>Power plants using coal, oil, or single-cycle natural gas (NG) typically have lower thermal efficiencies compared to combined-cycle NG plants, which use both gas turbines and steam turbines to generate electricity. This action involves retrofitting existing power plants to combined-cycle configurations, which can increase efficiency by up to 60%. Relevant industries include energy utilities and power generation sectors in coal-dependent regions.</p> <p>For further information visit:</p> <ul style="list-style-type: none"> • IEA Energy Technology Perspectives (2020) • McKinsey Global GHG Abatement Curve 	<p>The mitigation effect of this measure is based on the reduction of the emission factors through the replacement and or retrofitting of old inefficient fossil fuel plants with combined cycle natural gas plants. The mitigation effect of this measure, Improve Efficiency in Power Plants (Conversion of Coal/Liquid Plants and Single-cycle NG Plants to Combined Cycle NG Plants), can vary depending on factors such as the installed capacity, capacity factor (typically 70% if specific data is unavailable), plant efficiency (usually 55%), and emission factors of the fossil plants being replaced. Default emission factors are provided for various fuels, with natural gas. This measure serves as an interim step for reducing emissions while transitioning to renewables, may benefit companies that still have not initiated their first step towards renewable energy (User Manual v.6 of MITICA section 4.1.2).</p>	<ul style="list-style-type: none"> • 80 USD/tCO₂-eq 2007 • 12 USD/tCO₂-eq 2007 • 59.2 USD/tCO₂-eq 2021

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
Biomass Co-Firing in Power Plants	<p>Biomass co-firing involves burning biomass, such as wood chips, agricultural residues, or dedicated energy crops, alongside coal in power plants. This reduces the amount of coal used and, consequently, CO₂ emissions</p> <p>Technologies include:</p> <ul style="list-style-type: none"> • Direct co-firing: Biomass is directly added to the coal in the furnace. • Indirect co-firing: Biomass is gasified, and the syngas is co-fired with coal. This action is relevant for coal-fired power plants and industrial facilities with significant heat demand. <p>For further information visit:</p> <ul style="list-style-type: none"> • European Commission Bioenergy Strategy  	<p>The mitigation effect of this measure is based on the reduction of the emission factors through replacement of a portion of fossil fuels with biomass. When local data is not available, specific values can be used for the emission factor for thermal plants. Values can also be attributed in line with the plant's efficiency, and transmission and distribution losses. The emission savings depend on the portion of fossil fuels switched to biomass, and the efficiency of the plant. (User Manual v.6 of MITICA section 4.1.3. </p>	<ul style="list-style-type: none"> • 61,84-167,27 USD/tCO₂-eq 2021 • 16-50 EUR/tCO₂-eq 2014 • 86-129 EUR/tCO₂-eq 2019
Development of Advanced Metering Infrastructure (AMI) in the Electricity Grid	<p>Advanced Metering Infrastructure (AMI) consists of smart meters, communication networks, and data management systems that allow for real-time monitoring of electricity use. It helps reduce peak demand and optimizes electricity consumption.</p> <p>Technologies include:</p> <ul style="list-style-type: none"> • Smart meters: Installed at consumer premises to track and transmit energy consumption data in real time. • Demand response systems: Allow utilities to adjust electricity supply and demand more efficiently. • Grid management systems: Use AI and data analytics to optimize electricity distribution and reduce losses. 	<p>The mitigation effect of this measure is based on the improvement of energy efficiency through the improvement of monitoring by providing real-time data, which helps identify loss points and optimize grid performance. With enhanced data analysis, utilities can reduce energy waste, enhance efficiency, and ensure more electricity reaches consumers. This reduces transmission losses and supports a more sustainable energy system. This action falls under CRT category 1A1a (Electricity and Heat Production), with both ex-post and ex-ante methods available for assessing impact. The mitigation effect of AMI is based on reducing grid losses through enhanced monitoring. Transmission and distribution losses can be minimized, leading to lower emissions from electricity generation. The reduction potential depends on the initial loss percentage, target loss after implementation, the grid CO₂ emission factor, and total electricity consumption. Electricity transmission and distribution losses can range from 2% to over 20% (varies per country), primarily due to grid line and conversion inefficiencies. The introduction of AMI is expected to be especially efficient in countries that have poor communication networks ((User Manual v.6 of MITICA section 4.1.4. </p>	<p>No relevant studies found</p>

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
<p>Commissioning of New Efficient Plants and/ or Fuel Switch to Less Carbon-Intensive Fuels</p>	<p>This action involves the construction of new, more energy-efficient plants or the retrofitting of existing plants to switch to less carbon-intensive fuels, such as switching from coal to natural gas or biomass.</p> <p>Technologies include:</p> <ul style="list-style-type: none"> • Combined-cycle gas turbines (CCGT): More efficient than traditional coal plants. • Biomass combustion technologies: Replacing coal with biomass. • Waste-to-energy plants: Using municipal solid waste as fuel. This action applies to the power generation sector and heavy industries such as cement, steel, and chemicals. <p>For further information visit:</p> <ul style="list-style-type: none"> • IEA Energy Technology Perspectives (2020) • McKinsey Global GHG Abatement Curve 	<p>The mitigation effect of this measure is based on the reduction of the emission factors through the replacement of old inefficient fossil fuel plants with less carbon intensive alternatives. The mitigation effect of this measure is thus based on the replacement of fossil fuel plants with fuels with lower carbon content.</p> <p>To estimate the mitigation effect, the emissions factors of the specific power plants are considered. When local data is not available, default values can be used for the emission factor for thermal plants. These values are also influenced by the plant's efficiency, and transmission and distribution losses. The emission savings depend on the plants retrofitting, and the efficiency of the plant (User Manual v.6 of MITICA section 4.1.2.)</p>	<ul style="list-style-type: none"> • 200 USD/tCO₂-eq 2007 • 25-133 USD/tCO₂-eq 2019 • 18,3-75 USD/tCO₂-eq 2021
<p>Iron and steel industry</p>			
<p>High-Efficiency Slag Recycling in Steelmaking</p>	<p>In steel production, slag is a by-product that can either be disposed of or recycled. Recycling slag reduces emissions from mining new raw materials, and it can be used in cement production, reducing the need for clinker.</p> <p>Technologies include:</p> <ul style="list-style-type: none"> • Slag granulation: Converting slag into a usable material for construction. • Slag reprocessing: Recovering valuable metals from slag and reducing the need for virgin ores. This action applies to steelmakers and industries involved in the recycling of construction materials. <p>For further information visit:</p> <ul style="list-style-type: none"> • World Steel Association on Slag Use • IEA Iron and Steel Roadmap 	<p>The mitigation effect of this measure is based on the increase in the efficiency of the steelmaking process through the enhanced recycling and utilization of steel slag. Studies show that the CO₂ reduction potential for steel slag resource utilization ranges between 340–826 kg-t⁻¹. Additionally, integrating steel slag waste heat recovery and carbon sequestration can enhance the mitigation effect, with CO₂ reductions reaching up to 918.5 kg-t⁻¹ (Fan et al., 2024). The impact of this mitigation effect depends on the specific conditions of the steelmaking process, including the technologies implemented for slag recycling, heat recovery, and carbon sequestration.</p>	<ul style="list-style-type: none"> • 0-40 USD/tCO₂-eq, 2023 • 433 RMB/tCO₂-eq, 2021 • 9,8-115,8 USD/tCO₂-eq, 2017

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
<p>Hydrogen-Based Direct Reduced Iron (DRI) Production</p>	<p>Direct reduced iron (DRI) is produced by reducing iron ore using hydrogen instead of carbon-based fuels like coal or coke, which are traditionally used in blast furnaces. Hydrogen-based DRI results in the emission of water vapor (H₂O) instead of CO₂. This technology is particularly relevant for the steel industry, one of the largest emitters of greenhouse gases.</p> <ul style="list-style-type: none"> Hydrogen DRI plants: Replace carbon-intensive blast furnaces in steel production. <p>For further information visit:</p> <ul style="list-style-type: none"> IEA Iron and Steel Roadmap McKinsey Green Steel Report 	<p>The mitigation effect of this measure is based on the reduction of the emission factors through the replacement of coke with hydrogen in steelmaking, dramatically reducing CO₂ emissions. The emissions reductions are calculated by applying the CO₂ emission factor of coke to the reduction in fossil fuel use compared to the emission factor of the hydrogen which depends on its production – green hydrogen produced through renewables does not have emissions, while hydrogen generated from fossil fuels emits. The result provides the annual mitigation impact in kilotons of CO₂. This technology is a key innovation for decarbonizing steel production, and feasibility crucially depends on the availability and costs of hydrogen production (User Manual v.6 of MITICA section 4.2.6).</p>	<ul style="list-style-type: none"> 40 EUR/tCO₂-eq, 2019 30 EUR/tCO₂-eq, 2020 64-180 USD/tCO₂-eq, 2022
<p>Electric Arc Furnaces for Steel Production</p>	<p>Electric arc furnaces (EAFs) are used to produce steel by melting scrap steel using electric currents, as opposed to blast furnaces that require coal for iron ore reduction. EAFs are significantly less carbon-intensive and can be powered by renewable electricity.</p> <p>Key technologies include:</p> <ul style="list-style-type: none"> Direct arc heating: To melt steel scrap efficiently using electric arcs. Induction furnaces: An alternative method for melting metals using electrical induction. This action is applicable to steel manufacturers looking to reduce emissions by increasing their use of recycled steel and renewable energy. <p>For further information visit:</p> <ul style="list-style-type: none"> IEA Iron and Steel Roadmap 	<p>The mitigation effect of this measure is based on an increase in the energy efficiency due to the deployment of electric furnaces which reduce the energy input requirement while maintaining the required output of the industrial process as well as on a change in the emission factor, due to the utilization of grid or on-site generated renewable electricity instead of carbon intensive fossil fuels. Electric arc furnaces (EAF) in steel production, for example, offer a much more energy-efficient alternative compared to traditional methods, such as the blast furnace-basic oxygen furnace (BF-BOF) process. The EAF process typically consumes about one-third of the energy required by the BF-BOF process and can reduce carbon emissions to just 10%–20% of those produced by conventional methods (Tian et al., 2023).</p>	<ul style="list-style-type: none"> 110 USD/tCO₂-eq, 2021 60 EUR/tCO₂-eq, 2023 30 EUR/tCO₂-eq, 2024

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
Scrap Preheating in Steel Production	<p>Preheating scrap metal before it enters the furnace reduces the energy required for melting. Preheated scrap reduces fuel consumption and lowers overall CO₂ emissions in steel production.</p> <p>Technologies include:</p> <ul style="list-style-type: none"> • Conveyor-based preheating systems: Use waste heat from the furnace to preheat incoming scrap. • Rotary kiln preheating: Preheats scrap in a rotating kiln using exhaust gases. This is applicable in steel recycling plants and facilities using electric arc furnaces. <p>For further information visit:</p> <ul style="list-style-type: none"> • IEA Iron and Steel Roadmap 	<p>The mitigation effect of this measure is based on an increase in the efficiency of the steel production process through the preheating of scrap metal. Studies show that preheating scrap reduces the energy required for melting, resulting in a 2.83% energy savings and up to 5.7% heat recovery improvement when optimized (Selvaraj et al., 2014).</p> <p>The overall impact of this measure depends on the specific conditions of the steel production process, including the scale of operations, the efficiency of the preheating technology, and the integration of the recovery system. Furthermore, the savings can be substantial, with significant reductions in energy consumption and CO₂ emissions when applied on a larger scale.</p>	<ul style="list-style-type: none"> • 50 EUR/tCO₂-eq, 2021 • 118 USD/tCO₂-eq, 2021 • 56 EUR/tCO₂-eq, 2022
Electrolysis of Iron Ore in Steelmaking	<p>The traditional steelmaking process relies on coal as a reducing agent in blast furnaces, which results in large CO₂ emissions. Electrolysis of iron ore, also known as Direct Electrolytic Reduction, is an emerging technology that uses electricity (preferably from renewable sources) to reduce iron ore into iron, eliminating the need for coal. This results in a substantial reduction in CO₂ emissions.</p> <ul style="list-style-type: none"> • Electrolytic reduction cells: Replace traditional blast furnaces, utilizing electrical energy instead of carbon for the reduction process. This technology is most relevant in the steel production sector, particularly in greenfield plants or as a long-term retrofit option. <p>For further information visit:</p> <ul style="list-style-type: none"> • IEA Iron and Steel Roadmap 	<p>The mitigation effect of this measure is based on the reduction of the emission factor, by replacing carbon as a reducing agent with electricity in the electrolysis of iron ore. This process eliminates the need for coal, resulting in a significant reduction in CO₂ emissions typically generated in traditional blast furnaces. The use of electrolytic reduction cells can substantially lower the direct emissions of carbon dioxide during the reduction process. The total impact of this measure depends on several factors, including the source of electricity used with renewable sources providing the greatest reduction in emissions, the efficiency of the electrolytic reduction cells, and the scale of implementation within the steel production facility. Additionally, the overall effect is influenced by whether the technology is applied in greenfield plants or as a retrofit in existing facilities. The reduction in emissions will vary based on the extent to which coal is replaced and the specific operating conditions of the electrolytic process.</p>	<ul style="list-style-type: none"> • 73-166 EUR/tCO₂-eq, 2021 • 55-250 USD/tCO₂-eq, 2023 • 70-100 USD/tCO₂-eq, 2019



Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
Electrification of Annealing in Metalworking	<p>Annealing is a heat treatment process used in metalworking to soften metals and improve ductility. Traditionally, this process relies on fossil fuels for heat generation. Electrification of annealing involves replacing gas-fired or coal-fired furnaces with electric heating elements, especially when combined with renewable electricity, to reduce emissions.</p> <p>This mitigation action is applicable to industries involved in metalworking, including automotive and aerospace sectors.</p> <p>For further information visit:</p> <ul style="list-style-type: none"> • European Commission Industrial Heat Decarbonization  	<p>The mitigation effect of this measure is based on the reduction of the emission factor through the replacement of fossil fuels for heat generation with renewable electricity alternatives. Electrifying the annealing process in metalworking reduces fossil fuel consumption, particularly from solid, liquid, and gaseous fuels. This shift lowers CO₂ emissions, and the impact depends on the reduction in fuel consumption (measured in TJ) and the corresponding CO₂ emission factors for the displaced fuels. The CO₂ emission factors are based on the 2006 IPCC Guidelines. The total emissions reduction is calculated by multiplying the fuel reduction by its respective CO₂ emission factor. This action contributes to emissions reductions in industrial processes, particularly metalworking (User Manual v.6 of MITICA section 4.2.6. .</p>	<ul style="list-style-type: none"> • 150 EUR/tCO₂-eq, 2024
Advanced Metal Recovery from Slag and Dust	<p>In metallurgical industries, a significant amount of valuable metals is lost in by-products such as slag and dust. Advanced recovery technologies can extract metals such as zinc, copper, and lead from slag and dust, reducing the need for virgin raw material extraction and associated emissions.</p> <p>Technologies include:</p> <p>Hydrometallurgical processes: Use aqueous solutions to leach metals from slag or dust.</p> <p>Pyrometallurgical processes: Use heat to recover metals from by-products. This action is relevant for steelmakers, zinc smelters, and non-ferrous metal industries.</p> <p>For further information visit:</p> <ul style="list-style-type: none"> • Glass Alliance Europe Recycling Guidelines  	<p>The mitigation effect of this measure is based on the increase in the efficiency of the industrial process through the advanced recovery of valuable metals from slag and dust. For example, hydrometallurgical processes have been shown to achieve recovery rates of approximately 91.4% for lithium from spent lithium-ion batteries, with minimal loss of other metals such as aluminum (0.1%) and transition metals. Additionally, pyrometallurgical processes contribute to the recovery of metals with improved efficiency, reducing energy consumption compared to traditional methods (Yang et al., 2024 .</p> <p>The mitigation effect of this measure depends on the current conditions of the industry, including the scale and efficiency of the recovery technologies employed, the type and composition of slag and dust being processed, and the effectiveness of the materials recovery process in terms of purity and yield.</p>	<p>No relevant studies found.</p>
Energy Efficiency Improvements in Steel Rolling Mills	<p>Steel rolling mills are used to shape steel into various products, such as sheets and bars. These processes are energy-intensive and often rely on outdated equipment. Energy efficiency improvements in steel rolling mills can include:</p> <p>Improved rolling techniques: Such as hot charging, which reduces energy needed to reheat steel.</p> <ul style="list-style-type: none"> • Installation of variable-speed drives (VSDs): To optimize motor speeds based on demand. • Waste heat recovery systems: To capture heat from exhaust gases and reuse it within the process. This action is relevant in steel manufacturing plants with rolling operations. <p>For further information visit:</p> <ul style="list-style-type: none"> • IEA Iron and Steel Roadmap  	<p>The mitigation effect of this measure is based on the improvement of energy efficiency through the optimization of processes and the introduction of new technologies, leading to the reduction of GHG.</p> <p>The estimation of the mitigation effect depends on factors such as the current technology used in the rolling mill, the energy savings from the implementation of new processes, and the effectiveness of the introduced technologies.</p> <p>For example, the use of improved rolling techniques like hot charging, installation of variable-speed drives (VSDs), and waste heat recovery systems can reduce energy consumption by minimizing the need for reheating, optimizing motor speeds, and reusing heat. The mitigation effect will vary depending on the specific energy savings achieved, the scale of implementation, and the current energy efficiency of the plant.</p>	<ul style="list-style-type: none"> • (-200)-0 RMB/tCO₂-eq, 2016 • 11-16 EUR/tCO₂-eq, 2010




Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
Recycling and Material Efficiency in the Aluminum Industry	<p>Aluminum production is energy-intensive, especially during the electrolysis process used in primary production. However, recycling aluminum uses only a fraction of the energy required to produce primary aluminum. Improving material efficiency and increasing the recycling rate can significantly reduce CO₂ emissions.</p> <p>Measures include:</p> <ul style="list-style-type: none"> Scrap collection and sorting: Enhancing the collection and processing of aluminum scrap for recycling. Closed-loop recycling: Ensuring that aluminum waste is returned to the production cycle with minimal contamination. This action is relevant to the aluminum production industry and sectors that use aluminum, such as automotive, construction, and packaging. <p>For further information visit:</p> <ul style="list-style-type: none"> European Aluminum Industry Report 	<p>The mitigation effect of this measure is based on an increase in the efficiency of the industrial process, as recycled aluminum requires significantly less energy for processing compared to primary aluminum production. The total impact of this measure is conditioned by factors such as the recycling rate, the quality of the recycled material, and the efficiency of the recycling process.</p> <p>The effectiveness of this measure depends on the extent to which aluminum scrap is collected, processed, and reintegrated into the production cycle with minimal contamination, as well as the overall capacity to replace primary aluminum with recycled material in the production process.</p>	<ul style="list-style-type: none"> -65 USD/tCO₂-eq, 2024 84-400 NDZ/tCO₂-eq, 2020
Use of Recycled Steel in Manufacturing	<p>Steel production using recycled steel (also known as scrap steel) through the electric arc furnace (EAF) method is significantly less carbon-intensive than producing steel from iron ore in a blast furnace.</p> <p>Key processes include:</p> <ul style="list-style-type: none"> Electric arc furnaces (EAFs): Used for melting scrap steel to produce new steel products. Closed-loop recycling: Collecting and reusing steel waste within the manufacturing process. This action is applicable to industries such as automotive, construction, and appliances that use steel extensively. <p>For further information visit:</p> <ul style="list-style-type: none"> IEA Iron and Steel Roadmap 	<p>The mitigation effect of this measure is based on the increase in the efficiency of the steelmaking process using recycled steel. Studies have demonstrated that recycling scrap steel is significantly less carbon-intensive compared to traditional iron ore-based production methods (Hao et al., 2024). Recycled steel can save 86% of greenhouse gas emissions, 85% of energy, 76% of water pollution, and 40% of water consumption when using the electric arc furnace route, compared to primary extraction and blast furnace methods (UCL, 2021). The mitigation effect depends on the current conditions of the industry, including factors such as the efficiency of the recycling process, the energy mix used in the furnace technology, and the quality of the scrap steel being processed. Additionally, the effect is influenced by the technological advancements in recycling practices and the overall scale of scrap steel recycling in each region or sector.</p>	<p>No relevant studies found</p>


Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
Cement industry			
Reduction of Process-Related CO₂ Emissions in Cement Production	<p>Cement production generates large amounts of CO₂ through the calcination process, in which limestone (calcium carbonate) is heated to produce lime (calcium oxide), releasing CO₂. Process-related CO₂ emissions can be reduced through various strategies, such as:</p> <ul style="list-style-type: none"> • Carbon capture and storage (CCS): Capturing CO₂ emissions from the cement kiln. • Use of alternative materials: Replacing clinker with supplementary cementitious materials reduces calcination-related emissions. • Innovative cements: Developing new types of cement that require less lime or release fewer emissions during production. This action is relevant in the cement industry, particularly in countries with large infrastructure projects. <p>For further information visit:</p> <ul style="list-style-type: none"> • IEA Cement Industry Report 	<p>The impact of this measure depends on factors such as the proportion of clinker replaced with alternative materials and the efficiency of the substitution process. The effectiveness of this measure is directly related to the scale of clinker replacement and the specific characteristics of the materials used (User Manual v.6 of MITICA section 4.2.4).</p>	<ul style="list-style-type: none"> • 81 EUR/tCO₂-eq 2022 • 5-120 EUR/tCO₂-eq 2023 • 29-52 USD/tCO₂-eq 2022
Carbon Capture and Storage (CCS) in the Cement Industry	<p>Cement production emits large amounts of CO₂ during the calcination process and from fuel combustion in kilns. Carbon capture and storage (CCS) involves capturing CO₂ emissions directly from the kiln and storing it underground or using it in other industrial processes.</p> <p>Technologies include:</p> <ul style="list-style-type: none"> • Post-combustion capture: Captures CO₂ from flue gases after cement production. • Pre-combustion capture: Captures CO₂ before it is emitted during combustion. • Oxy-fuel combustion: Burns fuels in a high-oxygen environment to make CO₂ capture more efficient. This action is highly relevant to the cement industry. <p>For further information visit:</p> <ul style="list-style-type: none"> • IEA Cement Industry Report • Global CCS Institute Reports on CCS Costs • IPCC Special Report on CCS 	<p>The impact of this measure on GHG emissions is equivalent to the total amount captured as emissions once released are removed or withheld from the atmosphere. Implementing Carbon Capture, Utilization, and/or Storage (CCS/CCUS) can reduce the emissions of industrial processes by capturing up to 90% of CO₂ emissions (Climate Portal MIT, 2021), depending on the technology and project conditions. Furthermore, CCS/CCUS has a net CO₂ abatement potential ranging between 47% and 91% (Emborg et al., 2024), as the captured CO₂ is either stored permanently or utilized in industrial applications.</p>	<ul style="list-style-type: none"> • 90-130 USD/tCO₂-eq 2024 • 120 EUR/tCO₂-eq 2023 • 59-107 EUR/tCO₂-eq 2008 • 290 NTD/tCO₂-eq 2021

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
<p>Low Carbon Cement Alternatives</p>	<p>Traditional cement production relies heavily on clinker, which is highly carbon-intensive due to the calcination process. Low-carbon cement alternatives reduce or replace clinker with alternative materials such as:</p> <ul style="list-style-type: none"> • Limestone calcined clay cement (LC3): Uses calcined clay and limestone as substitutes for clinker, reducing process emissions. • Geopolymer cement: Uses industrial by-products like fly ash and slag instead of clinker. • Magnesium-based cements: Use magnesium silicates, which release less CO₂ during production. These technologies are applicable in construction, where cement is a fundamental building material. <p>For further information visit:</p> <ul style="list-style-type: none"> • IEA Cement Industry Report • European Commission Transition Pathways 	<p>The mitigation effect of this efficiency measure, Low Carbon Cement Alternatives, is based on a reduction in clinker content in cement production. When plant specific data is unavailable, a clinker share reduction from 70% to 50% can be assumed as default values, along with standard values of 3.7 GJ/t for thermal energy use and 94.6 tCO₂/TJ for coal emissions. The actual emission savings depend on cement production volume, current clinker content, available substitutes, and plant energy use. This measure works best for cement plants with high clinker ratios and may be less effective where alternatives are already in use (User Manual v.6 of MITICA section 4.2.4).</p>	<ul style="list-style-type: none"> • (-5)-175 USD/tCO₂-eq 2020 • (-15)-8 USD/tCO₂-eq 2022 • 0-52 USD/tCO₂-eq 2022
<p>Use of Waste-Derived Fuels in Cement Production</p>	<p>Cement production is highly energy-intensive, relying on fossil fuels such as coal or natural gas. Replacing these fuels with waste-derived fuels such as municipal solid waste (MSW), industrial waste, or tires can reduce CO₂ emissions and help manage waste streams. This can include:</p> <ul style="list-style-type: none"> • Co-processing: Using waste as fuel in cement kilns. • Alternative fuels: Converting waste materials like plastics or biomass into fuels for cement production. This action is particularly relevant in the cement industry. <p>For further information visit:</p> <ul style="list-style-type: none"> • IEA Cement Industry Report 	<p>The mitigation effect of this measure is based on reducing the emission factor through the replacement of fossil fuels with waste-derived fuels in cement production. When plant specific data is unavailable, default emission values for different fuel types can be used. The actual emission savings depend on the quantity of waste-derived fuels used in the production process. This measure is most effective for plants that do not currently use waste-derived fuels in their cement production. For companies already using such fuels, the efficiency improvements may be less significant (User Manual v.6 of MITICA section 4.2.6).</p>	<ul style="list-style-type: none"> • -19,18 USD/tCO₂-eq 2010 • 100 ZAR/tCO₂-eq 2020 • 75-150 EUR/tCO₂-eq 2022

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
<p>Electrification of Cement Production</p>	<p>Cement production is highly energy-intensive, particularly in the calcination process, which typically relies on fossil fuels. Electrifying the cement production process, particularly the kilns used for calcination, can reduce emissions significantly, especially if powered by renewable electricity.</p> <p>Key technologies include:</p> <ul style="list-style-type: none"> • Electric kilns: To replace fossil fuel-fired kilns for cement calcination. • Plasma torches: For high-temperature electric heating in cement production. This action is relevant in the cement manufacturing industry. <p>For further information visit:</p> <ul style="list-style-type: none"> • IEA Cement Industry Report 	<p>Electrification of kilns in the ceramics industry leads to significant improvements in energy efficiency compared to traditional fossil fuel-based heating. By replacing combustion-based technologies with electric alternatives, the overall energy consumption of the process is reduced. For example, in the case of the Rotary Kiln Electric Furnace (RKEF) process, energy efficiency can reach up to 53% (Rong et al., 2017), compared to the 13%–15% efficiency typically seen with fossil fuel combustion kilns (Zhou, Kin, 2017).</p> <p>The reduction in the emission factor depends on the current fuel used and the emission intensity of the electricity supply. As the grid becomes cleaner, with a greater share of renewable energy, the reduction in emissions from electrified processes can be substantial. In sectors like cement, electrification has already shown significant reductions in CO₂ emissions, with some technologies achieving reductions of up to 92.8% compared to traditional fossil fuel-based systems (Parra, Romano, 2023). Thus, the electrification of kilns not only improves process efficiency but also contributes to a considerable reduction in emissions. However, the extent of these benefits is closely linked to the local energy mix, with regions powered predominantly by renewable sources seeing the greatest environmental impact.</p>	<ul style="list-style-type: none"> • 55-877 USD/tCO₂-eq 2022 • 100-138 EUR/tCO₂-eq 2023 • 110-130 EUR/tCO₂-eq 2018
<p>Enhanced Glass Recycling in Manufacturing</p>	<p>Glass production is energy-intensive, as it requires high temperatures to melt raw materials. Recycling glass significantly reduces the need for virgin raw materials and the energy required for production.</p> <p>This action involves:</p> <ul style="list-style-type: none"> • Glass cullet recycling: Using recycled glass as a raw material in the production process. • Closed-loop recycling: Collecting and processing used glass for direct reuse in the same or similar products. This action is applicable in glass manufacturing, packaging, and building materials industries. <p>For further information visit:</p> <ul style="list-style-type: none"> • Glass Alliance Europe Recycling Guidelines 	<p>The mitigation effect of this measure is based on an increase in the efficiency of the production process, as recycling glass requires less energy compared to producing new glass from raw materials. The total impact of this measure depends on several factors, including the percentage of glass that can be recycled within the production process, the efficiency of the recycling systems, and the energy mix used during the recycling process. The reduction in energy consumption will vary based on the scale of glass recycling and the integration of closed-loop recycling systems, which directly reuse glass in the production of similar products. The effectiveness of this measure is also conditioned by the availability of recycled glass and the overall recycling infrastructure in the region or industry, as well as the energy efficiency of the manufacturing plant.</p>	<ul style="list-style-type: none"> • 20 EUR/tCO₂-eq 2023 • 200 EUR/tCO₂-eq 2023 • 45-157 USD/tCO₂-eq 2022

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
Electrification of Process Heating in Glass Manufacturing	<p>Glass production requires high temperatures, typically generated by fossil fuel combustion. Electrification of process heating in glass manufacturing can reduce emissions, especially when powered by renewable electricity.</p> <p>Key technologies include:</p> <ul style="list-style-type: none"> • Electric furnaces: To replace traditional gas-fired furnaces for glass melting. • Electric batch preheaters: Reduce the energy required for glass melting by preheating the raw materials using electricity. This action is relevant to the glass manufacturing industry. 	<p>The mitigation effect of this measure is based on a change in the emission factor and an increase in the efficiency of the industrial process. This is due to the shift in the energy source from fossil fuels to electricity, which generally results in higher efficiency, as electric furnaces and electric batch preheaters typically have a higher coefficient of performance compared to traditional gas-fired systems. The total estimation of this effect depends on several factors, including the energy mix used to power the electric systems, the efficiency of the electric furnaces and preheaters, and the specific conditions of the glass manufacturing process. The mitigation effect will vary depending on the degree to which fossil fuels are replaced by renewable electricity, as well as the current energy consumption levels and emission factors associated with the existing fossil-fuel-based heating methods.</p>	<ul style="list-style-type: none"> • 261-367 EUR/tCO₂-eq 2022 • 75-91 EUR/tCO₂-eq 2019 • 100 EUR/tCO₂-eq 2016
Chemical industry			
Abatement of N₂O Emissions in Nitric and Adipic Acid Production	<p>Nitrous oxide (N₂O) is a by-product of nitric acid (used in fertilizers) and adipic acid (used in nylon production). N₂O is a potent greenhouse gas with a global warming potential 298 times that of CO₂.</p> <p>Technologies to reduce N₂O emissions include:</p> <ul style="list-style-type: none"> • Catalytic reduction systems: Decompose N₂O into nitrogen and oxygen. • Non-catalytic abatement technologies: Break down N₂O at high temperatures during production. Applicable to chemical industries, particularly those producing fertilizers and polymers. <p>For further information visit:</p> <ul style="list-style-type: none"> • IEA Abatement Technologies Tracker  	<p>The mitigation effect of this measure is based on the reduction of the emission factor through the breakdown and decomposition of N₂O. N₂O emissions from nitric acid plants can be significantly reduced using non-selective catalytic reduction (NSCR), which also lowers NOX emissions. NSCR can mitigate greenhouse gas emissions and improve environmental performance in nitric acid production, falling under CRT category 2B2. Both ex-post and ex-ante methods can be applied to estimate its impact. The mitigation effect depends on reducing N₂O emissions per ton of nitric acid produced. Installing NSCR reduces the emission factor to 2 kg N₂O/ton of nitric acid.</p> <p>The reduction potential depends on the initial N₂O emission factor, the abated emission factor after NSCR installation, the total nitric acid production, and the global warming potential of N₂O. Particularly effective in the chemical industry and other industries working with nitric acid (User Manual v.6 of MITICA section 5.2.. .</p>	<ul style="list-style-type: none"> • 0,5-5 EUR/tCO₂-eq 2022 • 1-5 EUR/tCO₂-eq 2007 • 0,2-3 EUR/tCO₂-eq 2003

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
<p>Carbon Capture and Utilization in the Chemical Industry</p>	<p>Carbon capture and utilization (CCU) involves capturing CO₂ emissions from industrial processes and using them to create valuable products, such as:</p> <ul style="list-style-type: none"> • Synthetic fuels: Produced by combining captured CO₂ with hydrogen. • Carbonates: CO₂ can be converted into carbonates used in construction materials. • Chemicals: CO₂ can serve as a feedstock for various chemical processes. This action is applicable in energy-intensive industries such as petrochemicals, fertilizers, and cement, where capturing and utilizing CO₂ can reduce emissions while providing economic benefits. <p>For further information visit:</p> <ul style="list-style-type: none"> • IEA Abatement Technologies Tracker  	<p>The impact of this measure on GHG emissions is equivalent to the total amount captured as emissions once released are removed or withheld from the atmosphere. By replacing fossil-fuel-based raw materials and energy sources with captured CO₂, the emissions of the chemical production process can be significantly reduced.</p> <p>The extent of emissions reduction depends on factors such as the level of CO₂ captured, the technology used for CO₂ conversion, and the scale of market adoption of CCU technologies. For instance, the use of CCU in the petrochemical industry has the potential to reduce fossil fuel consumption by up to 32%, which can substantially lower CO₂ emissions associated with chemical production (Kawai et al., 2024 ). However, the mitigation effect will vary based on factors such as the efficiency of CO₂ conversion technologies, the scale of CCU deployment, and the market demand for chemicals produced using captured CO₂.</p>	<ul style="list-style-type: none"> • 237,81-253,51 CNY/tCO₂-eq 2023 • 429 USD/tCO₂-eq 2023 • 250-600 RMB/tCO₂-eq 2024
<p>Nitrogen Use Efficiency in Fertilizer Production</p>	<p>Fertilizer production, particularly nitrogen-based fertilizers, results in significant emissions of nitrous oxide (N₂O), a potent greenhouse gas with a global warming potential 298 times higher than CO₂. Increasing nitrogen use efficiency can reduce emissions during production and application.</p> <p>Technologies and strategies include:</p> <ul style="list-style-type: none"> • Optimized fertilizer formulations: Using inhibitors that reduce N₂O emissions. • Precision agriculture: Applying fertilizers based on the exact needs of crops, minimizing excess nitrogen. • Improved production processes: Reducing N₂O emissions during nitric acid and ammonia production. This action is highly relevant for the agriculture and chemical sectors. 	<p>The mitigation effect depends on the technologies and strategies applied, as these can either the emission factor or process efficiency, thereby affecting the activity variable.</p> <p>For instance, optimized fertilizer formulations reduce the emission factor through the minimization of nitrogen emissions. The direct and indirect N₂O emissions from managed soils required for estimation can be obtained from the projected emissions in the latest inventory. When specific data is not available, an assumption of 39% is attributed to AN and 69% to Urea. The emission savings vary based on crop type, fertilizer efficiency, and local conditions (User Manual v.6 of MITICA section 6.3.15 .</p>	<ul style="list-style-type: none"> • 5-1600 EUR/tCO₂-eq 2018 • 55 EUR/tCO₂-eq 2001 • 10-50 USD/tCO₂-eq 2019

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
Use of Biomass Feedstock in Chemical Industry	<p>The chemical industry relies heavily on fossil fuels, particularly for feedstocks. Replacing fossil fuel-derived feedstocks with biomass-derived materials can significantly reduce CO₂ emissions.</p> <p>Examples include:</p> <ul style="list-style-type: none"> • Bio-based plastics: Made from renewable resources such as corn, sugarcane, or cellulose. • Biochemicals: Using biomass to produce chemicals like ethanol, ethylene, and glycerol. • Biopolymers: Using renewable raw materials to produce polymers used in packaging and other applications. This action is relevant to the petrochemical, plastics, and packaging industries. 	<p>The mitigation effect of this measure is based on the change in the emission factor, as replacing fossil fuel-derived feedstocks with biomass-derived materials leads to a reduction in CO₂ emissions. Biomass-based materials, such as bio-based plastics, biochemicals, and biopolymers, generally have lower carbon footprints compared to their fossil fuel-derived counterparts, thus contributing to a reduction in greenhouse gas emissions in the chemical industry.</p> <p>The overall effect of the measure depends on several factors, including the current feedstocks being used, their emission factors in the industrial sector, and the emission factors of the biomass-derived materials used as replacements. Additionally, the emission reductions depend on the scale of the switch from fossil-based to biomass-based materials within the industry.</p>	<ul style="list-style-type: none"> • -50-450 EUR/tCO₂-eq 2023 • 170-210 EUR/tCO₂-eq 2023 • 75-133 EUR/tCO₂-eq 2023
Green Ammonia Production in Chemical Industry	<p>Ammonia is a key industrial chemical used in fertilizers and other products, and its traditional production process (Haber-Bosch) is highly energy-intensive, relying on natural gas or coal. Green ammonia is produced using renewable electricity for electrolysis to generate hydrogen, which is then combined with nitrogen to produce ammonia. This reduces CO₂ emissions significantly.</p> <p>Key technologies include:</p> <ul style="list-style-type: none"> • Electrolyzers: To produce hydrogen from renewable electricity. • Ammonia synthesis: Using green hydrogen to replace fossil-fuel-based feedstocks. This action is relevant in the chemical and agricultural industries. <p>For further information visit:</p> <ul style="list-style-type: none"> • IEA Ammonia Production Report  	<p>The mitigation effect of this measure is based on the reduction of the emission factor, as green ammonia production replaces fossil fuel-based feedstocks with renewable electricity for hydrogen production. This shift significantly lowers CO₂ emissions in the ammonia production process. The estimation of the mitigation effect depends on several factors, including the emission factor of the electricity used to power the electrolysis process, the efficiency of the electrolyzers, and the scale at which green ammonia is produced. Additionally, the impact depends on the current emissions from the traditional ammonia production process, the energy mix of the region and the technological advancements in electrolysis and ammonia synthesis.</p>	<ul style="list-style-type: none"> • 250-400 EUR/tCO₂-eq 2023 • 0-300 EUR/tCO₂-eq 2023 • 50 USD/tCO₂-eq 2020

Name of the PAM	Description and applications	Estimation methodology	Marginal Abatement Costs
Advanced Catalysts for Petrochemical Processes	<p>Petrochemical processes such as cracking, reforming, and polymerization are energy-intensive and produce significant CO₂ emissions. Advanced catalysts can improve the efficiency of these processes, reducing energy use and emissions.</p> <p>Key measures include:</p> <ul style="list-style-type: none"> • Zeolite catalysts: Improve selectivity and conversion efficiency in cracking and reforming processes. • Heterogeneous catalysts: Enhance reaction rates and lower the energy needed for chemical processes. This action is relevant for refineries and petrochemical plants producing fuels, plastics, and chemicals. 	<p>The mitigation effect of this measure is based on the increase in the efficiency of the petrochemical processes. Advanced catalysts, such as zeolite and heterogeneous catalysts, enhance the efficiency of chemical reactions in processes like cracking, reforming, and polymerization.</p> <p>These catalysts improve selectivity, conversion efficiency, and reaction rates, allowing for energy savings and emission reductions. The impact of this mitigation effect depends on the conditions of the industrial process, such as the scale of the operation, the specific requirements of each process, and the effectiveness of the technology implemented. Additionally, the efficiency of the catalyst and the required quality level of the final product play a crucial role in determining the overall impact (Parangi, 2025).</p>	<p>No relevant studies found</p>
Fuel Switching to Green Hydrogen in the Chemicals Industry	<p>The chemicals industry often relies on natural gas or other fossil fuels as feedstocks or for high-temperature heating. Switching to green hydrogen produced via electrolysis using renewable energy can significantly reduce CO₂ emissions.</p> <p>Key applications include:</p> <ul style="list-style-type: none"> • Hydrogen-based chemical synthesis: For the production of ammonia, methanol, and other chemicals. • Hydrogen for process heating: Replacing fossil fuel-based heat with hydrogen combustion. This action is relevant in the chemicals, fertilizers, and petrochemical industries. <p>For further information visit:</p> <ul style="list-style-type: none"> • IEA Hydrogen for Industry Report • European Commission Hydrogen Strategy 	<p>The mitigation effect of this measure is based on a change in the emission factor, as switching from fossil fuels to green hydrogen produced via electrolysis using renewable energy significantly reduces CO₂ emissions. The total estimation of this effect depends on several factors, including the current feedstock and energy sources used in the chemicals industry, the emission factors associated with these conventional fuels, and the carbon intensity of the green hydrogen used. The mitigation effect will also vary based on the scale of the transition to green hydrogen, the efficiency of the electrolysis process, and the degree of hydrogen integration into existing production processes. Additionally, the energy mix and efficiency of the hydrogen production system will influence the overall impact on CO₂ emissions.</p>	<ul style="list-style-type: none"> • 500-1250 USD/tCO₂-eq 2024 • (-50)-250 EUR/tCO₂-eq 2023 • 200 USD/tCO₂-eq 2023
Abatement of Nitrous Oxide (N₂O) Emissions in Fertilizer Production	<p>Nitrous oxide (N₂O) is a potent greenhouse gas emitted during the production of nitrogen-based fertilizers, particularly during the nitric acid production process. N₂O abatement technologies can reduce emissions from fertilizer production by capturing or converting N₂O before it is released into the atmosphere.</p> <p>Technologies include:</p> <ul style="list-style-type: none"> • Selective catalytic reduction (SCR): Using a catalyst to convert N₂O into nitrogen and water. • Non-catalytic reduction: Reducing N₂O emissions through process modifications or chemical inhibitors. This action is highly relevant for fertilizer manufacturers and the chemical industry. 	<p>The mitigation impact of this efficiency measure is based on the optimization of fertilizer application rates, methods, and timing. Information on direct and indirect N₂O emissions from managed soils are needed and can be obtained from the projected emissions in the latest inventory. When such data is not available, an assumption of 39% is attributed to AN and 69% to Urea. The emission savings vary based on crop type, fertilizer efficiency, and local conditions. This approach works best in areas still using traditional fertilizers rather than efficient ones (User Manual v.6 of MITICA section 6.3.15).</p>	<ul style="list-style-type: none"> • (-60)-115 USD/tCO₂-eq 2024 • 5-1600 EUR/tCO₂-eq 2018

Annex D. Exploring Additional Sources of Industry Sector Measures (PAMs)

While this guidebook provides a comprehensive list of industrial decarbonization measures, there is a plethora of additional PAMs that may be considered to drive ambitious emissions reduction in the industry sector. In this context, several international databases and inventories provide complementary laws, policies, incentives, taxes, actions and measures that can be contemplated to expand the selection featured in the guidebook.

In continuation, a concise table is provided detailing the following key information for the additional sources:

- Name of the source and link to the datasets
- Responsible institution/publisher
- Approach/Scope of the data included
- Type of instruments driving the PAMs
- Time coverage
- Country coverage

Note, the databases included contain decarbonization PAMs beyond the industry sector as they represent major inventories for climate measures.

Table 7 Overview of key databases and sources for the identification of additional PAMs.

Name	Responsible institution	Data approach and scope	Type of instruments	Time coverage	Country coverage	Link to source
Climate Policy Database	NewClimate Institute, Wageningen University, PNL, Netherlands Environmental Agency	Inventory of selected national climate mitigation policies adopted in a given year with taxonomy and implementation date	Regulatory instruments, market-based instruments, targets, information instruments R&D, institutions	First release: 2019 Oldest entry: 1927 Release frequency: annual	42 countries and EU	Climate Policy Database
Climate Change Laws of the World	Grantham Research Institute at LSE, Sabin Center at Columbia Law School	Inventory of selected national climate mitigation legislation and policies adopted in a given year and implementation date	Climate and climate-related laws, laws promoting low-carbon transitions	First release: 2010 Oldest entry: 1947 Release frequency: on rolling basis	196 countries and EU	Climate Change Laws of the World
Policy Instruments for the Environment (PINE) Database	Organization for Economic Co-operation and Development (OECD)	Inventory of selected national climate mitigation policies adopted in a given year with taxonomy and implementation date	Taxes and fees, tradeable permits, subsidies, deposit-refund schemes, and voluntary approaches	First release: 1991 Oldest entry: 1917 Release frequency: on rolling basis	130 countries	Policy Instruments for the Environment (PINE) Database
EEA database on greenhouse gas policies and measures in Europe	European Environment Agency (EEA)	Inventory of selected planned and adopted climate policies and measures with taxonomy and implementation date	Regulations, market-based instruments, voluntary approaches, fiscal policies, education	First release: 2021 Oldest entry: 1930 Release frequency: annual	EU	EEA database on greenhouse gas policies and measures in Europe
IEA Policies and Measures (PAMS) Database	International Energy Agency (IEA)	Inventory of selected past, existing or planned government policies and measures with taxonomy and implementation date	Taxes, regulations, grants, performance-based policies, targets	First release: 1999 Oldest entry: 1948 Release frequency: periodically	154 countries and EU	IEA Policies and Measures Database
Climate Actions and Policies Measurement Framework (CAPMF)	Organisation for Economic Co-operation and Development (OECD)	Structured and harmonized national climate policy database continually tracking defined set of instruments	Market-based instruments, regulations, international commitments, subsidies, institutions	First release: 2023 Oldest entry: 1990 Release frequency: annual	50 countries and EU 27	Climate Actions and Policies Measurement Framework (CAPMF)
Policy Toolbox for Industrial Decarbonisation	International Energy Agency (IEA)	Repository/guide of policy instruments for industrial decarbonisation with taxonomy, design considerations, implementation notes, and illustrative policy examples; not a continuously updated policy database. Built under the Climate Club work programme and expanding on IEA's 2022 toolbox.	Wide set across 3 areas and 9 categories, including: roadmaps/plans/targets, ETS, carbon taxes, tradeable performance standards, just transition planning, public funding and finance tools (guarantees, concessional loans, CfDs, tax credits, PPPs), procurement for near-zero materials, product requirements/ mandates, R&D and demonstration support, innovation networks and sandboxes, material-efficiency measures, CBAM-type measures, international cooperation, infrastructure planning, data and standards.	Published: 14 March 2025. Oldest entry: not applicable (report-style repository). Release frequency: not specified.	Global reference scope with examples from multiple regions; not limited to a fixed country list.	Policy Toolbox for Industrial Decarbonisation – IEA



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