Introduction to Decarbonization

Course No: C03-080
Credit: 3 PDH

Ahmad Hammouz, P.Eng, LEED AP.

CED engineering.ca CANADA
CPD FOR THE PROFESSIONAL

Continuing Education and Development, Inc.

P: (877) 322-5800
info@cedengineering.ca

Table of Contents

1.0 Fundamentals of Decarbonization

1.1 What is Decarbonization?

Decarbonization is the process of reducing net carbon dioxide (CO_2) atmospheric emissions to zero. This is critical for stabilizing climate change because CO_2 remains in the atmosphere for hundreds, if not thousands, of years. When CO_2 emissions exceed the absorption capacity of natural sinks (oceans, forests, and vegetation), atmospheric CO_2 levels will rise, intensifying global warming.

The scientific consensus emphasizes that achieving zero net emissions by 2100 is essential to stabilize warming at 2°C above pre-industrial levels, the maximum acceptable threshold identified by international agreements. The Intergovernmental Panel on Climate Change (IPCC) outlines pathways to achieve this, which focus on decarbonizing electricity, increasing energy efficiency, reducing waste, and improving carbon sinks. These pathways will be explained in more details in the next sections.

1.2 Global Carbon Emissions Trends

Global greenhouse gas (GHG) emissions have been on an upward trajectory since the pre-industrial era, with significant increases observed in recent decades. This rise is primarily attributed to human activities, notably the combustion of fossil fuels and industrial processes.

1.2.1 Primary Greenhouse Gases and Their Sources

The major GHGs contributing to global emissions include:

- Carbon Dioxide (CO_2): The predominant GHG, CO_2 is mainly released through the burning of fossil fuels such as coal, oil, and natural gas.
- Methane (CH_4): Emitted during the production and transport of coal, oil, and natural gas, methane also arises from livestock digestion, agricultural practices, and the decay of organic waste in landfills.
- Nitrous Oxide (N_2O): Primarily released from agricultural activities, especially through the use of synthetic fertilizers, as well as from fossil fuel combustion and certain industrial processes.
- Fluorinated Gases: Synthetic gases, including hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6), are emitted from industrial processes, refrigeration, and the use of various consumer products.

1.2.2 Emissions by Economic Sector

In 2019, global GHG emissions were distributed across key economic sectors as follows:

- Electricity and Heat Production (34%): The largest contributor, this sector's emissions result from burning fossil fuels for power and heat.
- Industry (24%): Emissions stem from on-site energy use and industrial processes such as chemical, metallurgical, and mineral transformations.

- Agriculture, Forestry, and Other Land Use (22%): Emissions arise from agricultural activities, deforestation, and land-use changes.
- Transportation (15%): Primarily involves emissions from road, rail, air, and marine transportation, with the majority of energy sourced from petroleum-based fuels.
- Buildings (6%): Emissions originate from the carbon footprint of on-site electrical consumption and fuel combustion for heating and cooking.

1.2.3 Trends in Global Emissions

Since 1850, global CO_2 emissions have risen substantially, with fossil fuel combustion and industrial activities being the primary drivers. Agriculture, deforestation, and other land-use changes have also contributed notably. Emissions of non-CO_2 GHGs, such as methane and nitrous oxide, have similarly increased over this period.

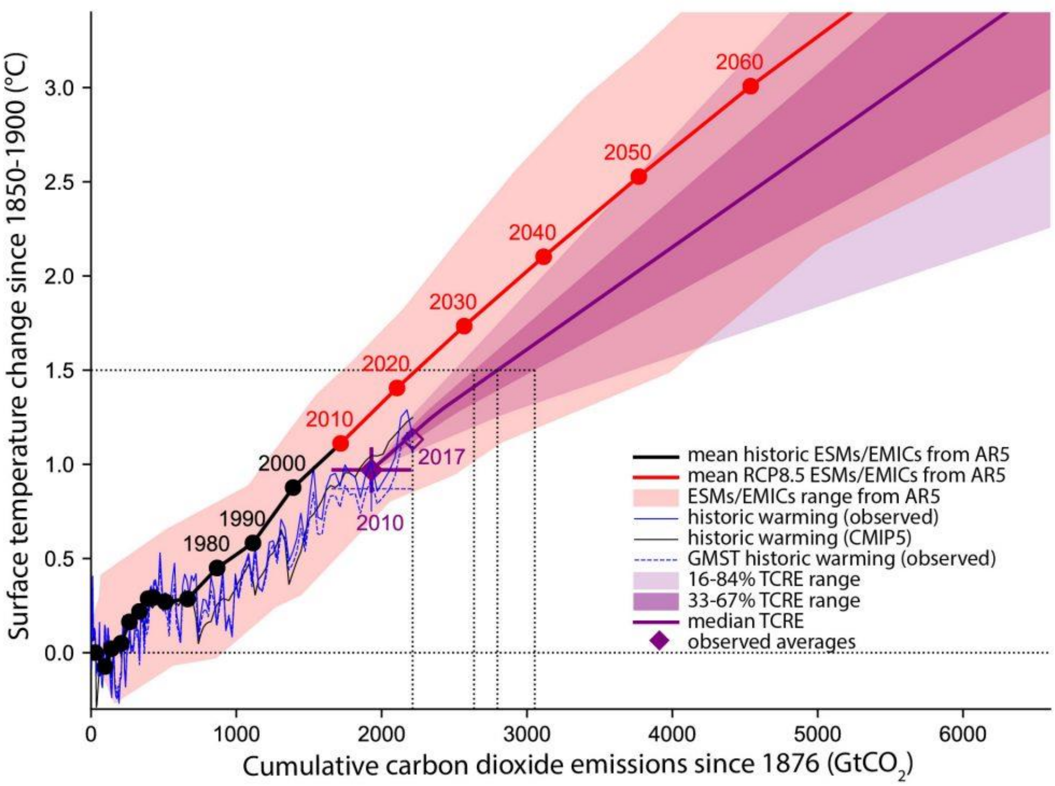

Figure 1: Cumulative CO_2 emissions since 1876

1.3 Importance of Decarbonization in Climate Change Mitigation

The European Union (EU) has recognized this necessity, implementing over 3,000 policies and measures aimed at curbing greenhouse gas emissions across various sectors. These initiatives have led to significant progress. By 2023, the EU achieved a more than 37% reduction in emissions compared to 1990 levels, primarily due to increased adoption of renewable energy and decreased reliance on carbon-intensive fossil fuels.

Despite these advancements, the EU acknowledges the need for more ambitious targets to effectively combat climate change. Current goals include a net reduction of at least 55% below 1990 levels by 2030 and achieving climate neutrality by 2050. Attaining these objectives requires a comprehensive transformation of production and consumption systems, encompassing energy generation, transportation, agriculture, and industrial processes.

2.0 The Science of Carbon Emissions

The carbon cycle is the natural process that circulates carbon among the atmosphere, oceans, soil, plants, animals, and rocks. This cycle plays a crucial role in regulating Earth's climate by controlling the concentration of carbon dioxide (CO_2), a key greenhouse gas, in the atmosphere.

2.1 Natural Carbon Cycle Processes

In the carbon cycle, plants absorb CO_2 from the atmosphere during photosynthesis, converting it into organic matter and storing carbon in their tissues. When plants and animals die and decompose, this carbon is released back into the atmosphere as CO_2 or becomes part of the soil. Oceans also play a significant role by absorbing CO_2 from the atmosphere, where it can be stored in dissolved forms or as carbonate sediments on the seafloor. Additionally, geological processes can store carbon in rocks and fossil fuels over millions of years.

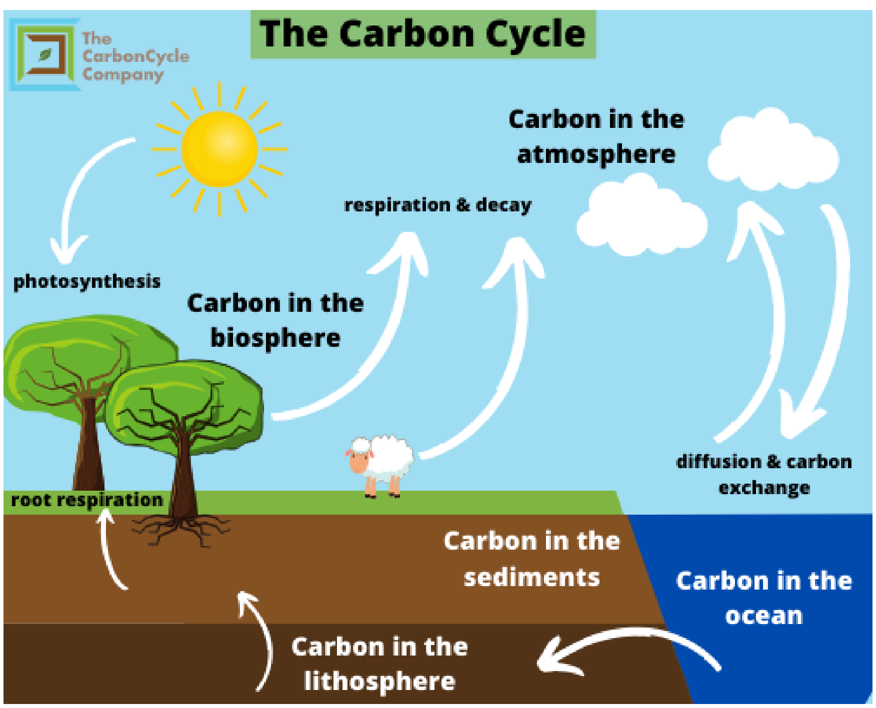

Figure 2: The Natural Carbon Cycle

2.2 Human Impacts on the Carbon Cycle

Human activities have significantly altered the natural carbon cycle, primarily through:

- Burning Fossil Fuels: The combustion of coal, oil, and natural gas for energy and transportation releases large amounts of CO_2 that had been stored underground for millions of years, increasing atmospheric CO_2 levels.
- Deforestation and Land-Use Changes: Clearing forests for agriculture or urban development reduces the number of trees that can absorb CO_2, while the decay or burning of cleared vegetation releases stored carbon back into the atmosphere.
- Industrial Processes: Certain manufacturing activities, such as cement production, emit CO_2 as a byproduct, further contributing to atmospheric carbon levels.

These human-induced changes have led to higher concentrations of CO_2 in the atmosphere, enhancing the greenhouse effect and contributing to global warming.

2.3 Consequences of Altered Carbon Cycle

The disruption of the carbon cycle by human activities has several significant consequences:

- Climate Change: Elevated CO_2 levels increase the greenhouse effect, leading to higher global temperatures, altered weather patterns, and more frequent extreme weather events.
- Ocean Acidification: Increased CO_2 absorption by oceans lowers the pH of seawater, affecting marine life, particularly organisms that rely on calcium carbonate for their shells and skeletons.
- Ecosystem Imbalances: Changes in carbon storage and fluxes can disrupt ecosystems, affecting biodiversity and the services these systems provide, such as clean air and water.

3.0 International Climate Agreements

3.1 Paris Agreement and Net Zero Goals

The Paris Agreement is a landmark international treaty adopted in 2015 under the United Nations Framework Convention on Climate Change (UNFCCC). Its primary objective is to combat climate change and intensify global actions toward a sustainable, low-carbon future. The treaty unites nations in a common cause to limit global warming to well below 2°C above pre-industrial levels, with efforts to restrict temperature rise to 1.5°C.

The Paris Agreement sets crucial goals to curb climate change through collaborative international efforts. Central to its mission is the global temperature target, which aims to cap the increase in global temperatures at 2°C while striving to limit it to 1.5°C. Countries are required to establish their own climate action plans, known as Nationally Determined Contributions (NDCs). These action plans outline specific strategies to reduce greenhouse gas emissions and are updated every five years to enhance ambition and reflect evolving capabilities.

Climate finance plays a pivotal role in ensuring the success of the Agreement. Developed countries pledge to provide financial assistance to developing nations to support climate adaptation and mitigation initiatives. Additionally, a robust transparency framework ensures that countries report their progress and hold each other accountable through regular performance reviews. The Agreement also emphasizes the importance of adaptation and resilience by encouraging countries to implement measures that strengthen their ability to cope with climate impacts, particularly in vulnerable regions.

3.1.1 Net Zero Goals and the Paris Agreement

Achieving net zero emissions is fundamental to meeting the goals of the Paris Agreement. Net zero entails balancing the amount of greenhouse gases emitted into the atmosphere with an equivalent amount removed through various means. This balance is critical for stabilizing global temperatures and reducing the long-term effects of climate change.

The Paris Agreement encourages nations to develop long-term low-emission development strategies that align with the 2050 net-zero target. Many countries have already committed to reaching net-zero emissions by mid-century as part of their national climate action plans. These commitments are designed to create a sustainable pathway toward a climate-resilient future.

3.1.2 Implementation and Progress

The successful implementation of the Paris Agreement relies on international cooperation, with countries working together to share technologies, knowledge, and financial resources. Climate action mechanisms embedded within the treaty facilitate international carbon trading and market-based solutions, allowing nations to reduce emissions more efficiently. To ensure continual progress, countries must periodically review and strengthen their NDCs, taking into account new technological advancements and higher ambitions. These reviews occur every five years, fostering an environment of continuous improvement and accountability.

3.1.3 Challenges and Future Prospects

Despite its significant potential, the Paris Agreement faces several challenges. Political will and policy integration remain essential for translating global commitments into national policies. Success depends on the sustained dedication of governments to integrate climate-focused strategies into their legal and economic frameworks.

Technological innovations in renewable energy, carbon capture, and sustainable agriculture are crucial for achieving net-zero goals. However, disparities in technological access and capabilities can hinder progress. Ensuring equity and climate justice is vital, as countries with differing levels of development and historical emissions have varying responsibilities and capacities for action.

Emissions by Country

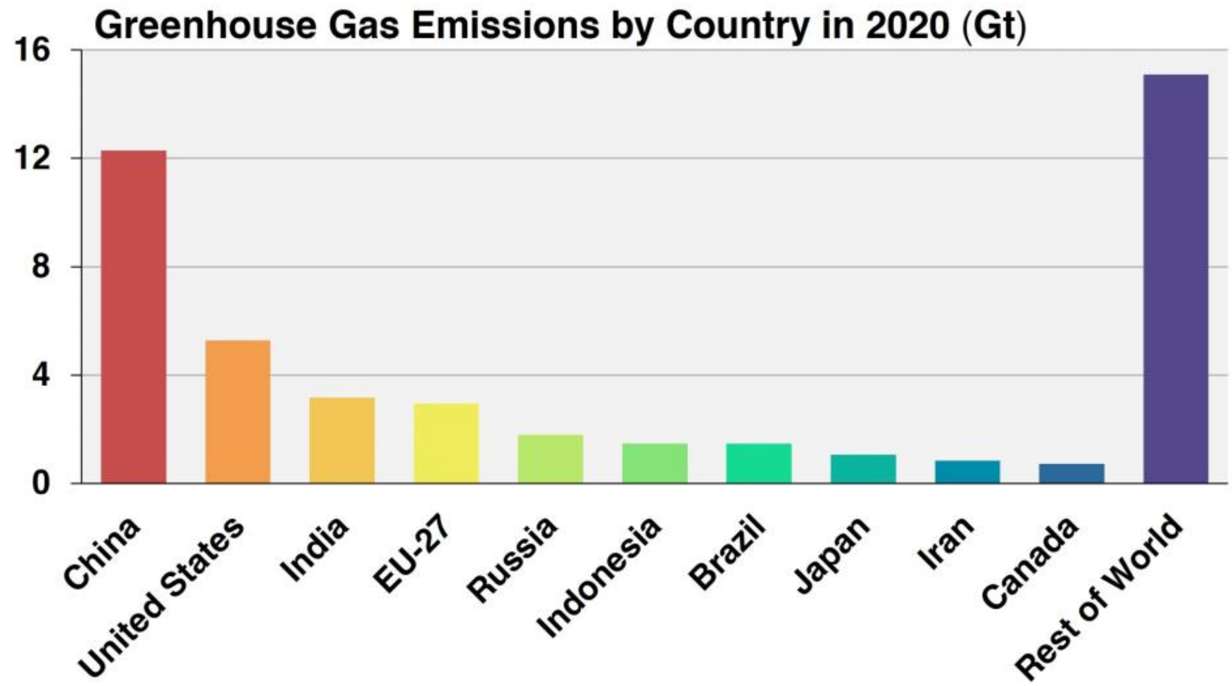

Figure 3: GHG Emissions by Country in 2020

4.0 IPCC and Carbon Budgeting

The Intergovernmental Panel on Climate Change (IPCC) plays a central role in the global response to climate change through its scientific assessments, policy recommendations, and frameworks for climate action. One of the key concepts advanced by the IPCC is carbon budgeting, which provides a science-based approach to managing greenhouse gas emissions and limiting global warming. This chapter explores the role of the IPCC and the critical concept of carbon budgeting in the context of global climate governance.

4.1 The Role of the IPCC

Established in 1988 by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO), the IPCC serves as the leading international body for the scientific assessment of climate change. Its mission is to provide policymakers with objective and comprehensive information on climate science, impacts, and adaptation and mitigation strategies.

4.1.1 Scientific Assessments

The IPCC produces comprehensive assessment reports every five to seven years, summarizing the latest scientific research on climate change. These reports synthesize findings from thousands of peer-reviewed studies and are divided into three working group reports:

- Working Group I: Focuses on the physical science basis of climate change.
- Working Group II: Explores climate change impacts, adaptation, and vulnerability.
- Working Group III: Examines mitigation strategies.

4.1.2 Special Reports and Technical Papers

In addition to major assessment reports, the IPCC publishes special reports on specific topics, such as global warming of 1.5°C, land use, and oceans. These reports guide global climate negotiations and inform national climate policies.

4.1.3 Policy Guidance and International Negotiations

The IPCC's findings play a pivotal role in shaping international climate agreements, including the Paris Agreement. Its scientific assessments underpin the targets for reducing emissions and achieving net-zero goals by mid-century.

4.2 Carbon Budgeting: A Framework for Climate Action

A carbon budget refers to the cumulative amount of carbon dioxide (CO_2) emissions permitted over a specific period while limiting global temperature rise to a target level, typically 1.5°C or 2°C above pre-industrial levels. Carbon budgeting provides a clear framework for emission reduction strategies.

4.2.1 Carbon Budget Components

The total carbon budget consists of several key components:

- Historical Emissions: Past emissions already released into the atmosphere.
- Current Emissions: Ongoing emissions from various human activities.
- Remaining Budget: The allowable emissions left to meet temperature targets.
- Uncertainty Buffers: Adjustments for scientific uncertainties in emissions and climate sensitivity.

4.2.2 Global Carbon Budgets

The IPCC's Special Report on Global Warming of 1.5°C highlights that limiting warming to 1.5°C requires keeping cumulative CO_2 emissions within approximately 420-580 gigatonnes of CO_2 from 2018 onward. Exceeding this budget would increase the likelihood of severe climate impacts.

4.3 Implementing Carbon Budgets

Countries use carbon budgeting to set national emission reduction targets, ensuring alignment with global climate goals. Carbon budgets can be subdivided across economic sectors, including energy, transportation, industry, and agriculture.

- Energy: Transitioning to renewable energy sources and improving energy efficiency.
- Transport: Electrifying vehicle fleets and promoting public transit.
- Agriculture: Enhancing sustainable farming practices and reducing deforestation.

- Industry: Adopting low-carbon technologies and reducing industrial emissions.

4.3.1 Monitoring and Reporting

Robust monitoring frameworks track emissions against carbon budgets. Countries report progress through Nationally Determined Contributions (NDCs) under the Paris Agreement, with periodic updates based on IPCC assessments.

4.4 Challenges in Carbon Budgeting

4.4.1 Scientific Uncertainty

Estimating precise carbon budgets involves uncertainties related to climate sensitivity, feedback mechanisms, and data availability. Addressing these uncertainties requires continuous scientific research and data collection.

4.4.2 Equity and Fairness

Global carbon budgeting must balance fairness and equity among nations with varying historical emissions, economic capabilities, and development needs.

4.4.3 Policy Integration

Implementing carbon budgets requires seamless integration into national policies, legal frameworks, and international agreements. This process involves coordination across multiple sectors and government levels.

5.0 Nationally Determined Contributions (NDCs)

Nationally Determined Contributions (NDCs) are central to the Paris Agreement's framework, representing each Party's commitments to reduce national greenhouse gas (GHG) emissions and adapt to climate change impacts. This chapter delves into the intricacies of NDCs, examining their scope, coverage, implementation timelines, methodologies, and the collective progress toward global climate objectives.

5.1 Scope and Coverage of NDCs

The scope of NDCs encompasses various sectors and GHGs, reflecting each Party's unique circumstances and priorities. Key aspects include:

- Sectors Covered: Parties address emissions from sectors such as energy, transport, agriculture, waste, and industrial processes. The extent of coverage varies, with many Parties aiming for economy-wide emission reductions.
- Greenhouse Gases Included: NDCs typically cover CO_2, CH_4, and N_2O, with some also addressing HFCs, PFCs, SF_6, and NF_3. The selection of gases depends on national emission profiles and capacities.
- Mitigation Targets: Parties set targets ranging from absolute emission reductions to intensity-based goals or deviations from business-as-usual scenarios. These targets are informed by national circumstances and development priorities.

5.2 Time Frames and Implementation Periods

NDCs specify time frames for achieving targets, commonly aligning with 5- or 10-year periods. Most Parties have set implementation periods up to 2030, facilitating synchronization with global stocktake cycles and enabling regular assessment of progress.

5.3 Methodological Approaches

Parties employ various methodologies to estimate and account for GHG emissions and removals:

- Reference Points: Many NDCs use base years, such as 1990 or 2005, as reference points for setting targets. Others utilize projected baselines or intensity metrics (e.g., emissions per unit of GDP).
- Accounting Practices: Approaches to accounting for emissions and removals differ, particularly concerning the land use, land-use change, and forestry (LULUCF) sector. Some Parties apply specific rules for this sector, while others integrate it into broader accounting frameworks.
- Global Warming Potentials (GWPs): Parties often use GWP values from the IPCC's Fifth Assessment Report to convert non-CO_2 gases into CO_2 equivalents, ensuring consistency in reporting.

5.4 Planning and Implementation Processes

The development and execution of NDCs involve comprehensive planning:

- Institutional Arrangements: Parties establish dedicated bodies or frameworks to coordinate NDC planning and implementation, ensuring alignment with national policies.
- Stakeholder Engagement: Inclusive processes involve stakeholders from government, civil society, and the private sector, fostering broad support and facilitating effective implementation.
- Integration with Development Plans: Aligning NDCs with national development strategies ensures that climate actions contribute to sustainable development goals, promoting coherence across policy areas.

5.5 Adaptation Components

Recognizing the importance of resilience, many NDCs include adaptation strategies:

- Vulnerability Assessments: Parties identify sectors and communities most at risk from climate impacts, informing targeted adaptation measures.
- Adaptation Priorities: Actions such as enhancing water resource management, promoting climate-resilient agriculture, and protecting ecosystems are prioritized to reduce vulnerability.
- Monitoring and Evaluation: Establishing systems to assess the effectiveness of adaptation efforts allows for iterative improvements and informed decision-making.

5.6 Means of Implementation

Achieving NDC goals requires support in finance, technology, and capacity-building:

- Financial Resources: Parties outline the need for domestic and international funding, with developing countries emphasizing the necessity for external support to meet their targets.
- Technology Transfer: Access to advanced technologies is crucial for effective mitigation and adaptation, with many NDCs highlighting the importance of international cooperation in this area.
- Capacity-Building: Enhancing institutional and human capacities is essential for planning and implementing NDCs, particularly in developing countries.

5.7 Fairness and Ambition

Parties assess their NDCs concerning fairness and ambition:

- National Circumstances: Considerations include economic capabilities, development levels, and historical contributions to GHG emissions.
- Equity Considerations: Some Parties reference principles like common but differentiated responsibilities and respective capabilities, emphasizing the need for balanced efforts.
- Ambition Levels: Parties strive to reflect their highest possible ambition, with many indicating intentions to enhance efforts in future NDC cycles.

5.8 Collective Progress and Global Goals

The aggregated impact of NDCs is critical for achieving the Paris Agreement's objectives:

- Emission Trajectories: Current NDCs indicate a potential plateauing of global emissions by 2030; however, significant reductions are necessary to align with pathways limiting warming to 1.5°C or 2°C.
- Adaptation Efforts: Collective adaptation actions contribute to global resilience, with Parties sharing best practices and lessons learned to enhance effectiveness.
- Global Stocktake: Regular assessments of collective progress inform the enhancement of NDCs, ensuring that global efforts remain on track to meet long-term climate goals.

6.0 Carbon Emissions Scopes 1, 2, and 3

As the global focus on climate change intensifies, understanding carbon emissions and how they are classified has become critical for businesses, governments, and individuals alike. The Greenhouse Gas (GHG) Protocol established a standardized framework categorizing emissions into three scopes: Scope 1, Scope 2, and Scope 3. This chapter explores these classifications, their significance, and how organizations can manage and reduce their carbon footprints.

6.1 Scope 1 Emissions

Scope 1 emissions are direct greenhouse gas emissions from sources owned or controlled by an organization. These emissions occur from activities that the organization directly manages, such as:

- Stationary Combustion: Emissions from burning fossil fuels on-site, such as in boilers, furnaces, and generators.
- Mobile Combustion: Emissions from company-owned vehicles and machinery.
- Process Emissions: Emissions from chemical processes, such as those in manufacturing and production.
- Fugitive Emissions: Leaks from refrigeration systems or gas pipelines.

Example: A manufacturing plant using natural gas to power its production line contributes to Scope 1 emissions through direct fuel combustion.

6.2 Scope 2 Emissions

Scope 2 emissions are indirect greenhouse gas emissions from the generation of purchased electricity, steam, heating, or cooling consumed by an organization. While these emissions occur off-site, they result from the organization's energy consumption.

Key aspects include:

- Electricity Use: The primary source of Scope 2 emissions, often generated from burning fossil fuels at power plants.
- Heating and Cooling: Purchased thermal energy can also contribute to Scope 2 emissions if derived from non-renewable sources.

Example: An office building powered by grid electricity from a coal-fired power plant is responsible for Scope 2 emissions associated with that energy use.

6.3 Scope 3 Emissions

Scope 3 emissions encompass all other indirect emissions that occur throughout the value chain of an organization. These emissions often represent the largest share of a company's carbon footprint and include emissions from:

- Upstream Activities: Purchased goods and services, business travel, employee commuting, and waste management.

- Downstream Activities: Transportation and distribution of products, use of sold goods, and product end-of-life treatment.

Scope 3 emissions can be challenging to measure due to their complexity and the involvement of third-party organizations.

Example: A clothing manufacturer's Scope 3 emissions may include carbon released during raw material extraction, transportation of products, and customer use of clothing.

6.4 Categorization of Emissions

Categorizing emissions helps organizations understand where their greatest environmental impacts occur and identify strategies to reduce them. This classification also supports transparent reporting, which is increasingly demanded by stakeholders, investors, and regulatory bodies.

Managing and Reducing Emissions

To manage emissions effectively, organizations should:

1. Measure and Report: Use GHG accounting standards to assess emissions across all three scopes.
2. Set Reduction Targets: Establish clear, science-based targets to lower emissions.
3. Invest in Renewable Energy: Transition to renewable energy sources to reduce Scope 2 emissions.
4. Enhance Operational Efficiency: Improve processes and technologies to lower Scope 1 emissions.
5. Engage the Supply Chain: Collaborate with suppliers and customers to minimize Scope 3 emissions.
6. Offset Remaining Emissions: Consider carbon offset projects to neutralize unavoidable emissions.

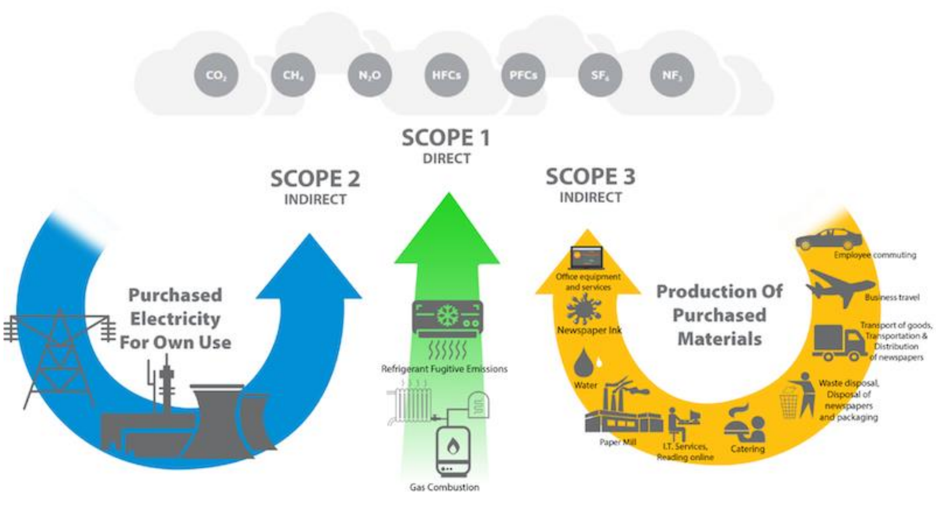

Figure 4: Scopes 1, 2, and 3 Emissions

7.0 Decarbonization of Industries: Concrete

Concrete, a cornerstone of global infrastructure, is second only to water as the most consumed substance on Earth. However, its production is a significant contributor to global greenhouse gas (GHG) emissions due to its reliance on cement, particularly its key ingredient—clinker. Cement production alone accounts for approximately 7% of global GHG emissions, largely due to the energy-intensive process of converting limestone into clinker through calcination. Addressing these emissions is imperative for combating climate change. This chapter outlines a comprehensive roadmap for achieving net-zero carbon concrete by 2050, emphasizing innovation, industry-government collaboration, and the adoption of advanced technologies.

7.1 Decarbonization Opportunities in Cement and Concrete

7.1.1 Clinker and Cement Production

The cement industry's decarbonization strategy focuses on reducing emissions at every stage of the cement production process, particularly during clinker production, which accounts for more than 60% of the total emissions.

- Reducing Clinker Volumes: The key to reducing emissions in cement production lies in reducing the volume of clinker used in cement. This can be achieved by incorporating alternative cementitious materials such as fly ash, slag, natural pozzolans, and fine gradations from recycled concrete. These materials have already undergone calcination or do not emit CO2 when heated, making them ideal substitutes.
- Alternative Fuels: Cement kilns require extremely high temperatures (approximately 1,450°C), traditionally generated using fossil fuels. Transitioning to low-emission alternatives such as biomass, hydrogen, and waste-derived fuels can significantly reduce carbon emissions.
- Clean Electricity and Efficiency: Improving energy efficiency at cement plants is essential. Key measures include upgrading grinding technologies, such as switching from ball mills to vertical roller mills, optimizing process control, and automating production lines. Additionally, transitioning to clean electricity sources such as wind, solar, and hydropower can dramatically lower emissions.
- Carbon Capture, Utilization, and Storage (CCUS): CCUS is considered the most promising technology for reducing process emissions in cement production. Emerging technologies such as direct CO2 injection into concrete and carbon mineralization into synthetic aggregates are also gaining traction. Large-scale CCUS deployment will be critical post-2030 as the industry aims to capture and permanently store CO2 in geological formations.

7.1.2 Concrete Manufacturing and Construction

Concrete manufacturing and construction processes offer additional pathways for decarbonization by improving material efficiency, reducing transportation emissions, and adopting innovative building technologies.

- Mix Optimization: Replacing traditional cement with supplementary cementitious materials (SCMs) such as fly ash, slag, and calcined clays can reduce CO2 emissions while maintaining or enhancing concrete strength. Additionally, advanced chemical admixtures can further improve the performance of low-carbon concrete.
- Manufacturing and Transportation: Electrifying production plants and transportation fleets is essential. Cement manufacturers are encouraged to switch to electric or hydrogen-powered trucks and improve logistical efficiency by sourcing materials locally. This minimizes transportation-related emissions.
- Design and Construction Optimization: Optimizing structural design can minimize concrete usage without compromising safety or performance. Techniques such as 3D printing, modular construction, and smart sensor integration can reduce material waste and enhance project efficiency. Furthermore, designing for adaptive reuse and recycling can prolong a structure's lifespan and reduce its environmental impact.

7.2 Policy and Market Transformation

Policy frameworks play a critical role in driving the adoption of low-carbon technologies and fostering market transformation. Regulatory interventions, procurement policies, and performance standards are among the most effective levers.

- Codes and Standards: Governments should integrate carbon performance criteria into building codes and construction standards. This includes setting mandatory requirements for embodied carbon in construction materials, developing performance-based codes, and accelerating the adoption of low-carbon construction practices.
- Green Procurement: Public sector procurement policies should mandate the use of low-carbon cement and concrete in infrastructure projects. Federal commitments such as Canada's Buy Clean Strategy can drive demand for domestic low-carbon products. This includes requiring life-cycle carbon assessments and setting progressive carbon reduction targets in procurement contracts.

7.3 Industry Innovations

Research and development (R&D) play a central role in achieving net-zero carbon concrete. The development of breakthrough technologies, process improvements, and innovative construction methods will be crucial.

- R & D: The cement industry must invest in R&D to develop next-generation materials, including carbon-neutral binders and CO2-capturing aggregates. Research hubs are already working on projects such as synthetic aggregate production and advanced admixture development.
- Financial Mechanisms: Financial incentives such as investment tax credits for CCUS projects, carbon pricing schemes, and carbon contracts for difference can accelerate industry transition. Government-funded grants for technology demonstration projects and pilot programs can further support innovation.

7.4 Action Plans to 2030 and 2050

7.4.1 Action Plan to 2030

By 2030, the industry aims to achieve cumulative GHG reductions through the following initiatives:

- Blended Cements: Market adoption of low-carbon cement types such as Portland Limestone Cement (PLC).
- Clinker Reduction: Reduction in clinker content through the use of alternative materials.
- Emissions Reductions: Deploy pilot projects for carbon capture and explore CO2 mineralization applications.

7.5 Action Plan to 2050

The long-term vision for 2050 includes full-scale deployment of CCUS technologies, 100% renewable power supply, and zero-emission transportation fleets. These efforts aim to achieve net-zero carbon emissions across the entire cement and concrete value chain.

7.6 Collaboration and Governance

7.6.1 Governance Framework

Effective implementation requires a multi-stakeholder governance model comprising industry leaders, government bodies, environmental organizations, and academic institutions. Regular monitoring, transparent reporting, and adaptive policy adjustments will ensure steady progress.

7.6.2 Industry and Government Partnerships

Industry-government partnerships should prioritize knowledge sharing, joint R&D initiatives, and international collaboration on carbon reduction technologies.

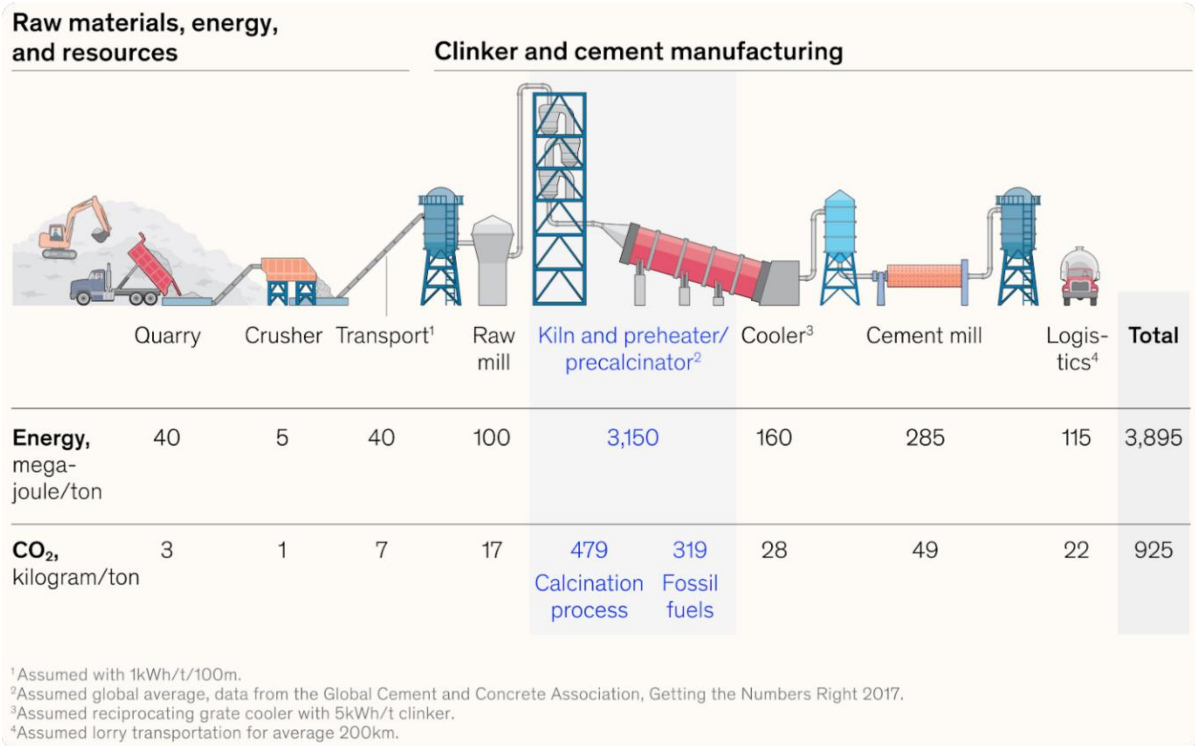

Figure 5: Clinker and cement manufacturing carbon emissions and energy consumption at each stage

8.0 Decarbonization of Industries: Steel Manufacturing

The steel industry is a cornerstone of global infrastructure and economic development, yet it stands as one of the most significant industrial contributors to greenhouse gas (GHG) emissions. Traditional steel production methods, particularly those utilizing blast furnaces (BF) and basic oxygen furnaces (BOF), are heavily reliant on carbon-intensive processes. As the world intensifies efforts to combat climate change, decarbonizing steel production has become imperative. This chapter explores viable pathways for reducing carbon emissions in steel manufacturing, focusing on fuel shifts, electrification of process heat, and waste heat recovery solutions.

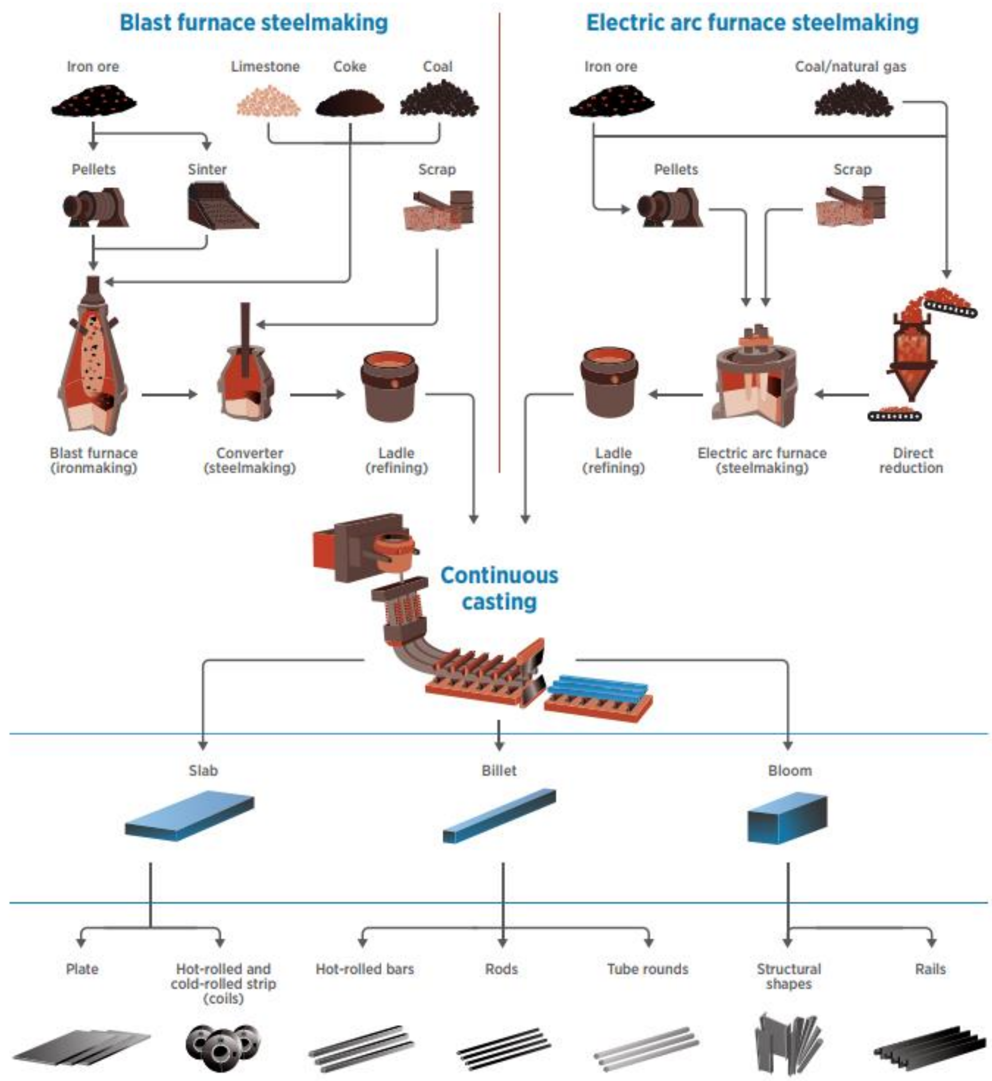

Figure 6: Overview of the primary steelmaking processes

8.1 Fuel Shift

Transitioning from carbon-intensive fuels to low-carbon alternatives is a pivotal strategy in decarbonizing steel production. This section examines two primary approaches: partial decarbonization through hydrogen injection in blast furnaces and full decarbonization via hydrogen-based direct reduced iron (DRI) processes.

8.1.1 Partial Decarbonization: Hydrogen Injection to Replace Pulverized Coal Injection in Blast Furnaces

In traditional blast furnace operations, pulverized coal injection (PCI) is employed to reduce iron ore. Introducing hydrogen as a substitute for PCI offers a promising route to lower CO_2 emissions. Hydrogen, when used as a reducing agent, reacts with iron ore to produce iron and water vapor, thereby eliminating CO_2 emissions associated with coal combustion.

Implementation Considerations:

- Infrastructure Adaptation: Modifying existing blast furnaces to accommodate hydrogen injection necessitates significant alterations to infrastructure. This includes upgrading injection systems and ensuring materials can withstand the different chemical environment introduced by hydrogen.
- Hydrogen Supply: Establishing a reliable and sustainable hydrogen supply chain is critical. This involves scaling up hydrogen production, preferably through green methods such as electrolysis powered by renewable energy sources, and developing storage and distribution networks.
- Economic Factors: The transition to hydrogen injection entails substantial capital expenditure (CAPEX) and operational expenditure (OPEX). However, it can serve as an interim solution, allowing for incremental emission reductions while more comprehensive decarbonization technologies are developed.

8.1.2 Full Decarbonization: Hydrogen-Based Direct Reduced Iron (DRI)

Hydrogen-based DRI represents a transformative approach to steel production, enabling near-complete decarbonization. In this process, hydrogen serves as the sole reducing agent, converting iron ore into direct reduced iron without generating CO_2 emissions.

Implementation Considerations:

- Process Redesign: Transitioning to hydrogen-based DRI requires a fundamental redesign of the steel production process. This includes the construction of new DRI facilities equipped to handle hydrogen as the primary reducing agent.
- Energy Demand: The hydrogen-based DRI process is energy-intensive, necessitating substantial amounts of hydrogen. Ensuring that hydrogen production is powered by renewable energy is essential to achieve true decarbonization.
- Economic Viability: While offering significant emission reductions, the high costs associated with hydrogen production and infrastructure development pose economic challenges. Policy support, such as subsidies and carbon pricing mechanisms, can enhance the competitiveness of hydrogen-based DRI.

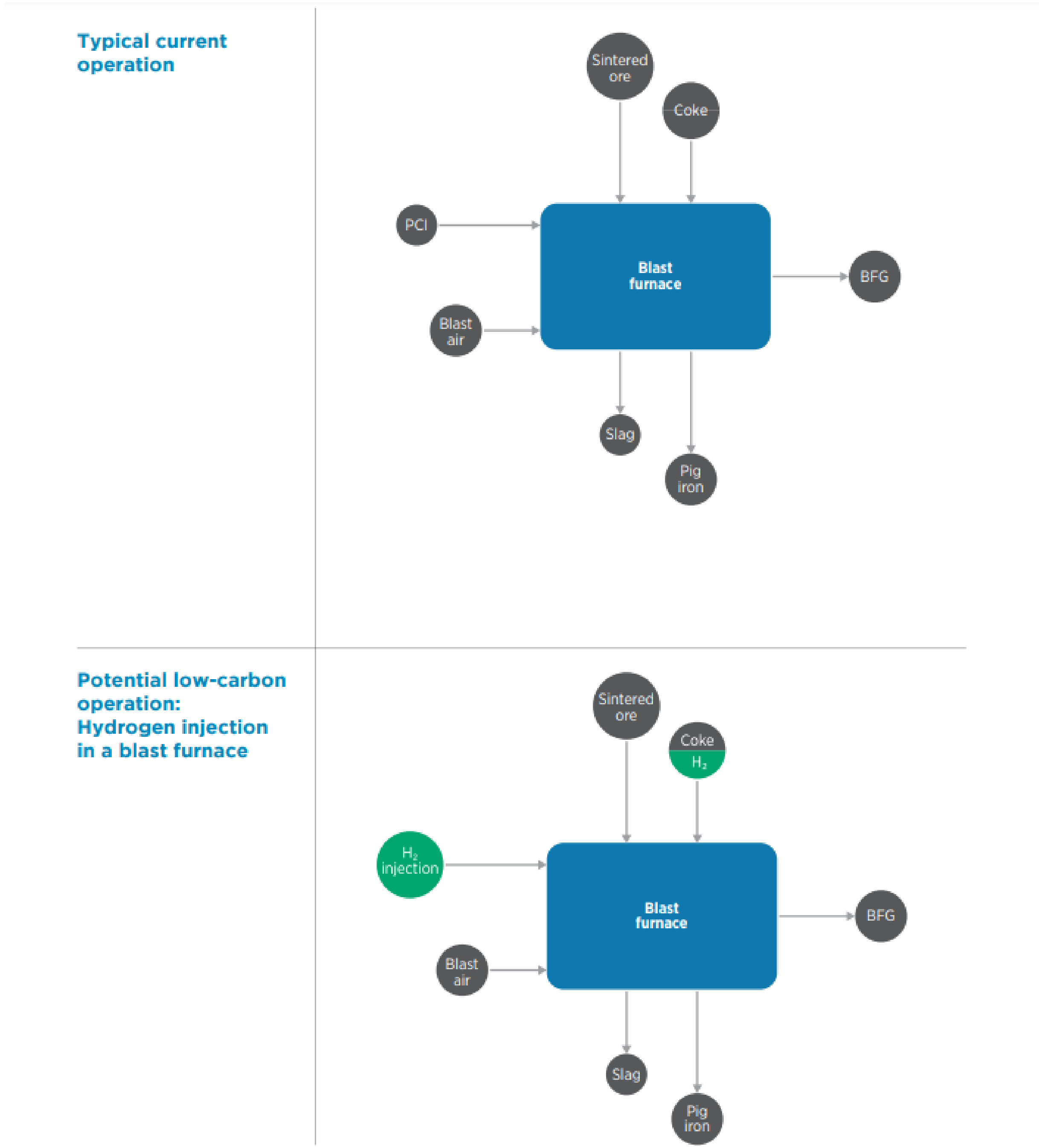

Figure 7: Partial Steel Manufacturing Decarbonization - Hydrogen injection to replace pulverised coal injection for blast furnaces

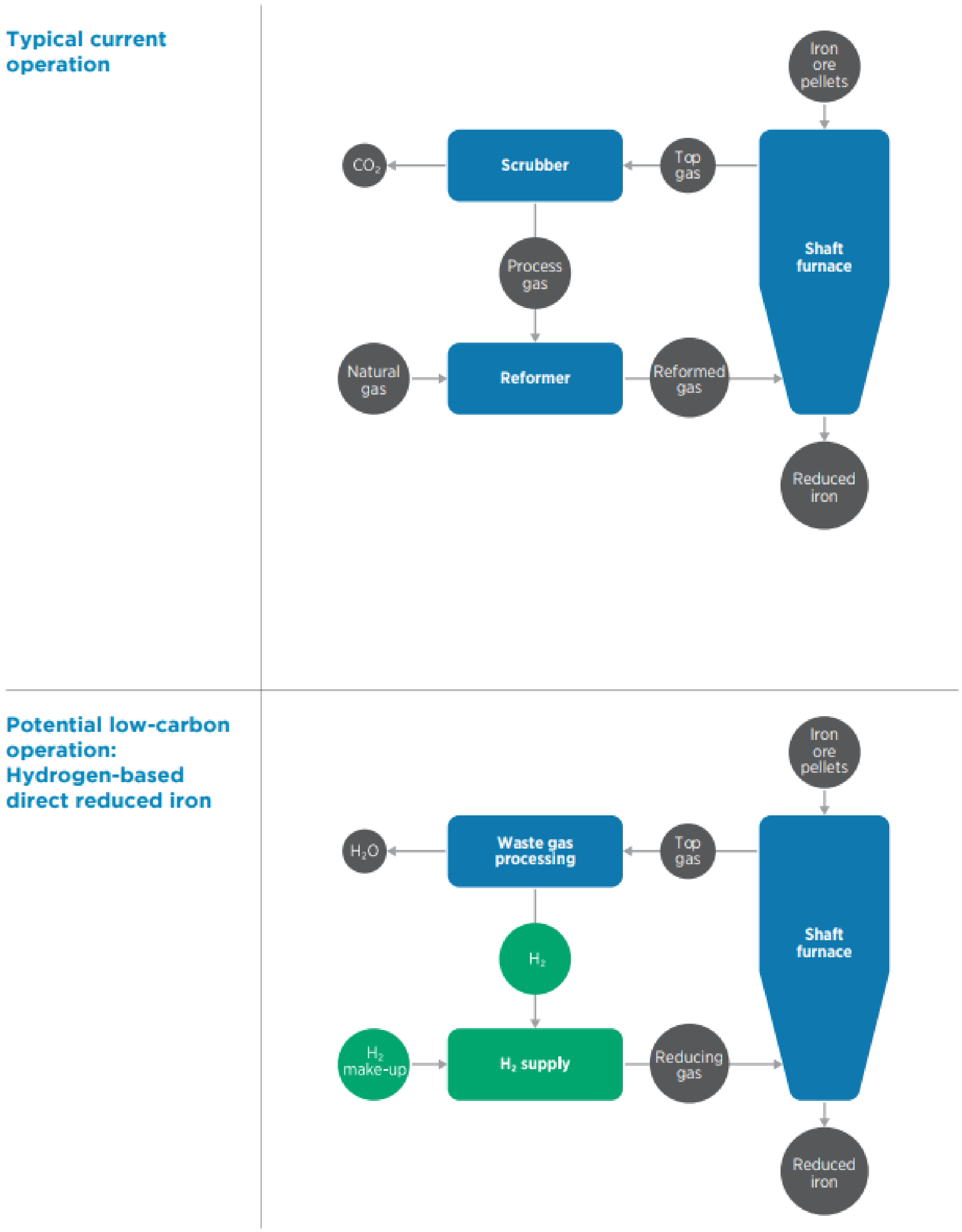

Figure 8: Full Steel Manufacturing Decarbonization - Hydrogen-based direct reduced iron

8.2 Electrification of Process Heat

Electrifying the heat required in steel production processes presents another avenue for decarbonization. Utilizing renewable electricity to generate process heat can substantially reduce GHG emissions.

Implementation Considerations:

- Technological Adaptation: Shifting from fossil fuel-based heat sources to electric alternatives necessitates the development and integration of technologies such as electric arc furnaces (EAF) and induction heating systems.
- Renewable Energy Integration: The effectiveness of electrification hinges on the availability of renewable electricity. Investments in renewable energy generation and grid infrastructure are crucial to support the increased electrical demand.
- Operational Adjustments: Operators must adapt to the distinct characteristics of electric heating, which may differ from traditional methods in terms of heat distribution and control.

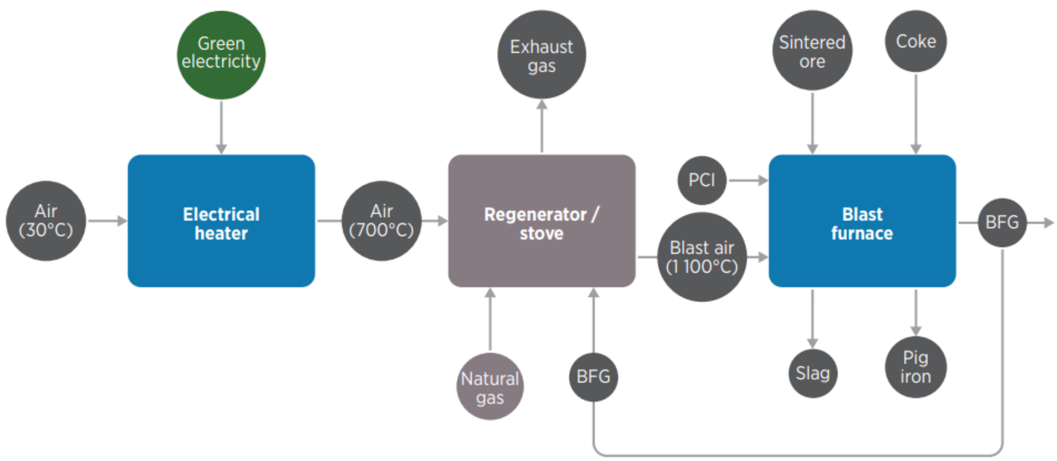

Figure 9: Potential Low-carbon Steel Manufacturing Operation: Electrification in a blast furnace

8.3 Waste Heat Recovery Solutions

Implementing waste heat recovery systems enables the capture and reuse of heat generated during steel production, enhancing energy efficiency and reducing emissions.

Implementation Considerations:

- System Integration: Designing and installing waste heat recovery systems, such as heat exchangers and regenerators, require careful integration into existing production lines to maximize efficiency.

- Economic Assessment: Evaluating the cost-effectiveness of waste heat recovery involves analyzing the potential energy savings against the investment and maintenance costs of the systems.
- Environmental Impact: Beyond energy savings, waste heat recovery contributes to emission reductions by decreasing the need for additional fuel combustion.

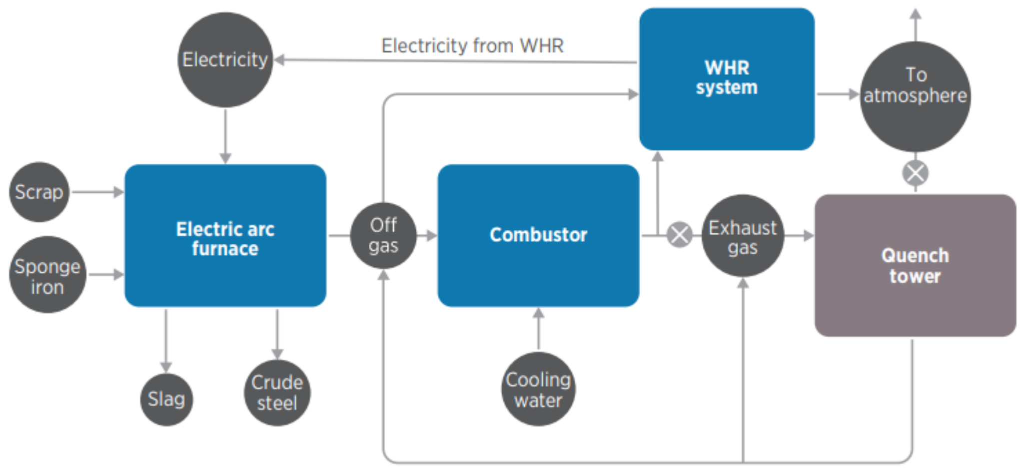

Figure 10: Potential Low-carbon Steel Manufacturing Operation: Waste heat recovery in an electric arc furnace

8.4 Carbon Capture, Utilization, and Storage (CCUS)

CCUS technologies are central to reducing CO_2 emissions in the steel industry. They involve capturing CO_2 produced during steelmaking, using it in various industrial processes, or storing it in geological formations to prevent its release into the atmosphere. Steel production generates CO_2 primarily from blast furnace-basic oxygen furnace (BF-BOF) operations. CCUS technologies can capture emissions directly from these processes.

- Post-Combustion Capture: This technology captures CO_2 from flue gases emitted by BF-BOF systems. Solvents such as amines absorb CO_2, which is then separated, compressed, and prepared for storage or utilization.
- Pre-Combustion Capture: This method involves gasifying coal or other carbon-based fuels before combustion, producing a mix of hydrogen and CO_2. The CO_2 is separated and captured before the hydrogen is used as fuel.
- Oxy-Fuel Combustion: This process burns fuels in an oxygen-rich environment, resulting in a concentrated CO_2 stream that is easier to capture.

8.4.1 CO_2 Utilization

- Mineral Carbonation: CO_2 can be used in mineral carbonation, producing valuable materials like construction aggregates. This process chemically binds CO_2 into stable carbonates, reducing emissions while creating useful by-products.
- Synthetic Fuels and Chemicals: Captured CO_2 can be converted into synthetic fuels or chemical feedstocks through catalytic processes powered by renewable energy.
- Steelmaking By-Products: CO_2 can be used to enhance by-products such as slag in cement production, turning a waste product into a valuable resource.

8.4.2 CO_2 Storage

- Geological Sequestration: CO_2 can be injected into deep geological formations, including saline aquifers and depleted oil and gas reservoirs, for long-term storage. Site monitoring ensures the gas remains securely trapped.
- Enhanced Oil Recovery (EOR): Captured CO_2 can be used in EOR processes, where it is injected into oil reservoirs to increase extraction efficiency while storing the gas underground.

8.5 Implementation Challenges and Opportunities

- Infrastructure Development: Expanding pipeline networks for CO_2 transport and creating centralized storage hubs are essential.
- Economic Viability: The high costs of CCUS technologies can be offset through government subsidies, carbon pricing mechanisms, and international climate finance.
- Policy and Regulation: Strong regulatory frameworks must support CCUS deployment by defining clear legal responsibilities and ensuring public acceptance through transparent monitoring.

8.6 Case Studies and Global Initiatives

- European Initiatives: Europe has been at the forefront of CCUS implementation with projects like Norway’s Longship and the UK’s Net Zero Teesside, integrating CO_2 capture from industrial clusters.
- Industry Collaboration: Global steel producers have formed alliances like the Mission Possible Partnership to accelerate CCUS technology adoption through shared research and development (R&D).

9.0 Decarbonizing Global Power Systems: Strategies and Pathways

The global power sector is a significant contributor to greenhouse gas (GHG) emissions, accounting for approximately 30% of global CO_2 emissions. Transitioning to a decarbonized power system is essential to mitigate climate change and achieve net-zero emissions by 2050. This transition involves integrating renewable energy sources, enhancing system flexibility, and implementing supportive policies and technologies.

9.1 Integration of Renewable Energy Sources

Renewable energy sources, particularly wind and solar power, have become economically competitive with traditional fossil fuels due to significant cost reductions—solar power costs have decreased by up to 80%, and wind power by about 40% over the past decade. As a result, renewables accounted for the majority of new power-generation capacity in 2018. However, their inherent intermittency poses challenges to ensuring a reliable and consistent power supply.

9.1.1 Expansion of Wind and Solar Power

Scaling up wind and solar installations is crucial for decarbonization. These sources have become the least expensive options for adding new capacity in many markets. Investments in large-scale wind farms and solar photovoltaic (PV) systems can significantly reduce GHG emissions. However, their variable nature requires complementary strategies to maintain grid stability.

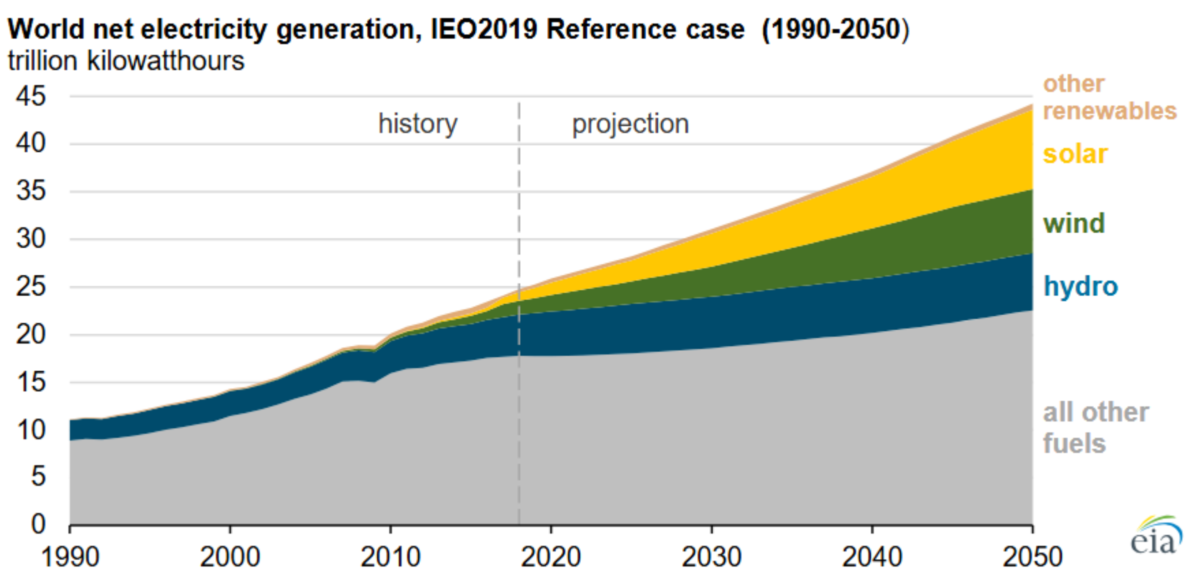

Figure 11: World Net Electricity Generation

9.1.2 Development of Energy Storage Solutions

Energy storage systems, such as batteries, play a pivotal role in mitigating the intermittency of renewables. They store excess energy generated during periods of high renewable output and release it during low production periods, ensuring a balanced supply and demand. Advancements in battery technology and cost reductions are making storage solutions more viable for large-scale deployment.

9.2 Enhancing System Flexibility

Flexibility is essential to accommodate the variability of renewable energy sources. A flexible power system can effectively manage fluctuations in supply and demand, ensuring reliability. Traditional power plants, such as those fueled by natural gas, can adjust their output to compensate for the variability of renewables. These plants can ramp up production when renewable output is low and decrease it when renewable generation is high, providing essential grid stability.

Additionally, encouraging consumers to modify their energy usage patterns can help balance supply and demand. Demand-side management programs incentivize users to reduce consumption during peak periods or shift it to times when renewable energy is abundant, thus enhancing system flexibility. Furthermore, investing in grid infrastructure is vital to transmit electricity from renewable-rich areas to demand centers. Enhanced transmission networks facilitate the integration of dispersed renewable energy sources and improve overall system resilience.

9.3 Technological Innovations

Advancements in technology are central to overcoming the challenges associated with decarbonizing power systems. Innovations enhance efficiency, reduce costs, and enable the integration of higher shares of renewable energy.

9.3.1 Smart Grid Technologies

Smart grids utilize digital communication technologies to monitor and manage the transmission of electricity. They enable real-time balancing of supply and demand, integration of distributed energy resources, and improved reliability and efficiency of the power system.

9.3.2 Long-Duration Energy Storage

Developing long-duration energy storage solutions is crucial for maintaining energy supply during prolonged periods of low renewable generation. Technologies such as pumped hydro storage, advanced battery systems, and emerging solutions like hydrogen storage can provide the necessary backup to ensure grid reliability.

9.3.3 Power-to-X Technologies

Power-to-X refers to converting surplus renewable electricity into other forms of energy carriers, such as hydrogen (Power-to-Hydrogen) or synthetic fuels (Power-to-Liquids). These technologies enable the storage of excess renewable energy and its utilization across various sectors, facilitating deeper decarbonization.

9.4 Policy and Regulatory Support

Supportive policies and regulatory frameworks are critical to drive the decarbonization of power systems. Governments and regulatory bodies play a significant role in setting targets, providing incentives, and ensuring a conducive environment for the transition.

Establishing clear and ambitious decarbonization goals provides direction and urgency. For instance, some regions aim for up to 100% decarbonization by 2040, guiding investments and policy measures towards achieving these targets.

9.4.1 Incentives for Renewable Energy Adoption

Financial incentives, such as subsidies, tax credits, and feed-in tariffs, encourage the adoption of renewable energy technologies. These incentives reduce the financial barriers for investors and accelerate the deployment of clean energy solutions.

9.4.2 Carbon Pricing Mechanisms

Implementing carbon pricing, through taxes or cap-and-trade systems, internalizes the environmental costs of carbon emissions. This approach makes fossil fuel-based generation less competitive compared to renewables, promoting cleaner energy sources.

9.5 Economic Considerations

The transition to a decarbonized power system involves significant investments but also offers economic opportunities. Understanding the cost implications and potential benefits is essential for informed decision-making. Substantial capital is required to develop renewable energy projects and associated infrastructure. However, declining technology costs and supportive policies can make these investments economically viable and attractive. Furthermore, the renewable energy sector has the potential to create jobs and stimulate economic growth. Investments in renewable energy projects, grid infrastructure, and related industries can lead to employment opportunities and contribute to economic development.

Failing to decarbonize power systems can result in long-term economic costs due to climate change impacts, health-related expenses from pollution, and potential regulatory penalties. Proactively investing in decarbonization can mitigate these risks and lead to a more sustainable economic future.

10.0 Global Transportation Decarbonization

The transportation sector is a major contributor to global greenhouse gas (GHG) emissions, accounting for approximately 24% of total CO_2 emissions worldwide. Addressing transportation decarbonization is crucial to achieving global climate targets and limiting global warming to 1.5°C. This transition requires a comprehensive approach involving technological innovation, infrastructure development, policy reforms, and international collaboration.

10.1 Electrification of the Transport Sector

Electrification is a central pillar of transportation decarbonization. Electric vehicles (EVs), including passenger cars, buses, and trucks, are key to reducing tailpipe emissions. Expanding the global EV fleet has been supported by technological advancements such as decreasing battery costs, extended vehicle ranges, and favorable policies that incentivize consumer adoption. Additionally, electric buses deployed in urban areas reduce air pollution while improving public health and enhancing sustainability. In the freight sector, heavy-duty trucks powered by batteries and supported by fast-charging infrastructure can displace diesel-powered trucks, enabling a cleaner and more efficient logistics network.

To enable widespread EV adoption, a robust charging infrastructure is essential. High-capacity fast-charging stations alleviate range anxiety by supporting long-distance EV travel. Home and workplace charging options, incentivized by government programs, ease reliance on public networks. Furthermore, grid integration through smart charging technologies balances electricity demand, supports renewable energy use, and enables vehicle-to-grid (V2G) systems that can store and return power to the grid.

Technological advancements in batteries further drive EV adoption. Improvements in battery chemistry have increased energy density, enabling longer driving ranges. Battery recycling technologies ensure that valuable resources like lithium and cobalt are reused, reducing environmental impact. Cost reductions driven by scaling up battery production have made EVs increasingly affordable, positioning them as viable alternatives to internal combustion engine vehicles.

10.2 Adoption of Zero-Emission Fuels

Beyond electrification, zero-emission fuels such as hydrogen and biofuels are critical to decarbonizing segments of the transportation sector where battery-electric power is less practical. Hydrogen fuel cell vehicles (FCEVs), with high energy density and fast refueling capabilities, are particularly suited for long-haul trucks, buses, ships, and even airplanes. However, the success of FCEVs depends on building a network of hydrogen refueling stations and scaling up production facilities. Technological advancements in fuel cell design are continuously improving efficiency and reducing costs, making hydrogen an increasingly attractive option.

Sustainable aviation fuels (SAFs) derived from biomass, waste oils, and synthetic processes offer a path to reducing the carbon intensity of air travel. Airlines are committing to long-term SAF contracts and partnerships with fuel producers to secure supply. Supportive regulatory frameworks that mandate blending SAFs with conventional jet fuel, coupled with subsidies and carbon credit programs, incentivize industry-wide adoption.

The maritime sector can benefit from advanced biofuels as a near-term solution for replacing heavy fuel oils. However, ensuring that these biofuels meet stringent sustainability and emissions standards is critical to achieving real environmental benefits. Significant investment in production infrastructure and the development of reliable feedstock supply chains is required to meet the increasing fuel demands of the shipping industry.

10.3 Infrastructure Development and Urban Planning

Efficient transportation infrastructure and urban design are essential for reducing travel demand and supporting low-carbon mobility. Expanding mass transit systems such as metro, rail, and bus networks reduces dependence on private vehicles, curbing emissions while enhancing urban connectivity. Urban planning centered around transit hubs encourages higher-density development, creating walkable communities that promote public transit use.

Active transportation infrastructure, including extensive bike lanes and pedestrian pathways, promotes cycling and walking while improving urban livability. Shared electric micromobility solutions such as scooters and bikes provide convenient last-mile connectivity, reducing urban congestion and enhancing sustainable mobility options.

Freight and logistics optimization also plays a critical role in decarbonization. Intermodal transport that integrates rail, waterways, and road networks can significantly reduce truck dependency. Digital logistics platforms optimize delivery routes, minimize empty runs, and lower fuel consumption, creating greener and more efficient supply chains.

10.4 Policy and Regulatory Frameworks

Supportive policies and regulations are essential drivers of transportation decarbonization. Several countries have established zero-emission vehicle (ZEV) mandates, requiring a phased transition to EVs for passenger and commercial fleets. Stringent fuel efficiency standards push manufacturers to innovate and produce cleaner, more efficient vehicles.

Carbon pricing mechanisms, including carbon taxes and cap-and-trade systems, internalize the environmental costs of GHG emissions, encouraging the adoption of low-carbon technologies. Financial incentives such as subsidies, tax credits, and grants support EV purchases, charging infrastructure deployment, and renewable fuel production. Public-private partnerships (PPPs) accelerate infrastructure development by combining government support with private sector expertise and investment.

Research and development (R&D) funding is another critical policy tool. Government-sponsored R&D programs fuel technological innovation, bringing cutting-edge clean transport technologies to market. These policies create an enabling environment that fosters industry growth while reducing emissions on a global scale.

10.5 International Collaboration and Finance

Global cooperation is indispensable for aligning transportation decarbonization efforts across countries and securing adequate financing. The Paris Agreement has catalyzed international commitments to reduce transport emissions through nationally determined contributions (NDCs). Global coalitions such as the

International Zero-Emission Vehicle Alliance (ZEV Alliance) promote policy alignment and facilitate cross-border collaboration.

Climate finance mechanisms, including green bonds and climate funds, support large-scale transport decarbonization projects and the development of renewable infrastructure. Multilateral development banks provide low-interest loans for building sustainable transport systems in emerging economies, bridging financing gaps and driving inclusive growth.

Technology transfer and capacity building are equally important. Knowledge-sharing platforms enable countries to exchange best practices and technological innovations, accelerating the adoption of clean technologies. Training programs develop a skilled workforce capable of deploying and maintaining advanced transportation systems, ensuring long-term sustainability.

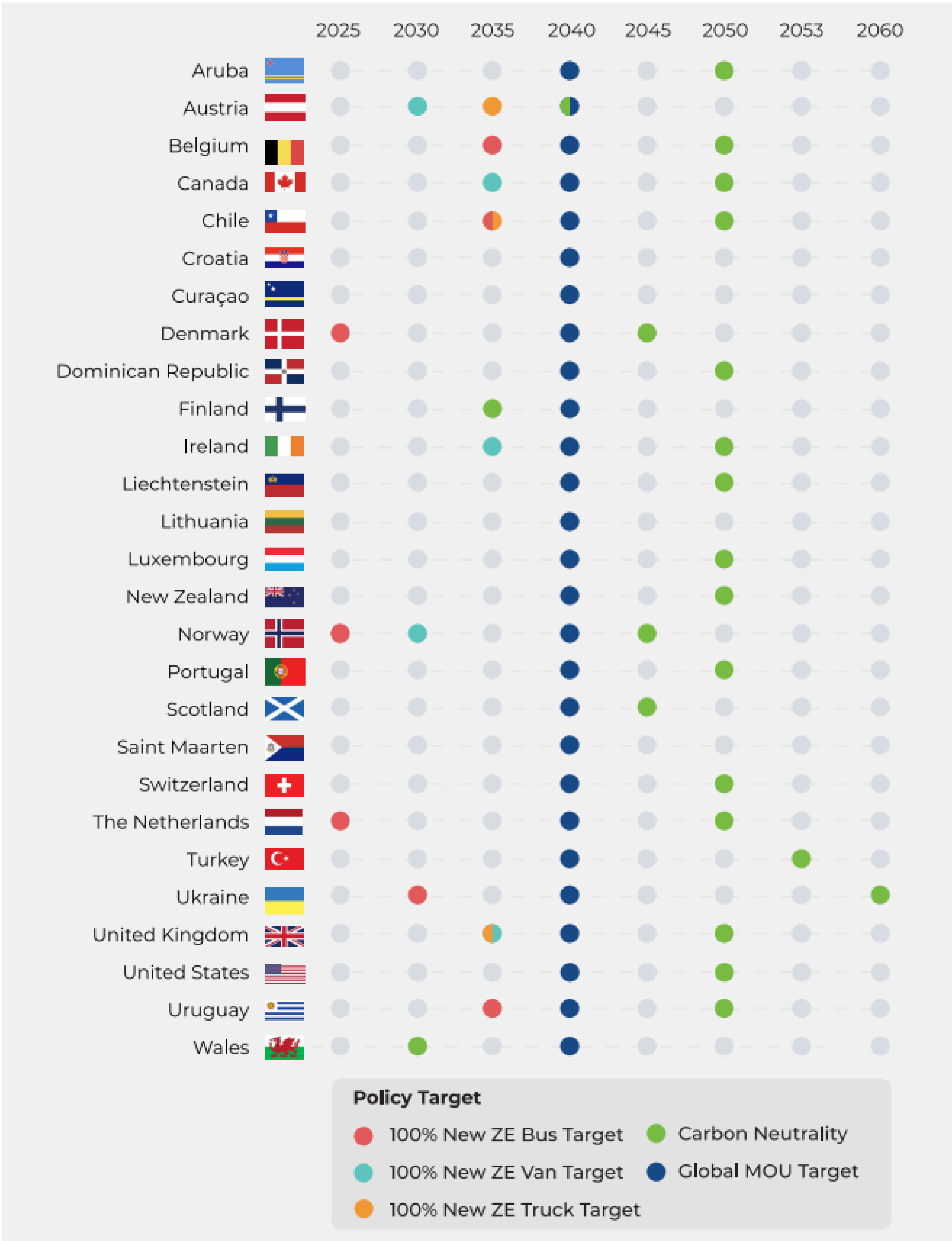

Figure 12: Timeline of Zero Emissions Medium-to-Heavy Duty Vehicle Targets by Governments

11.0 Construction Decarbonization and Sustainable Building Materials

The construction industry is one of the most significant contributors to global greenhouse gas emissions, responsible for nearly 40% of total CO_2 emissions through building operations and material production. Achieving net-zero emissions in this sector requires transformative changes in building practices, materials, and energy systems. This section explores energy-efficient construction practices, sustainable material choices, circular economy principles, renewable energy integration, policy frameworks, and research innovations.

11.1 Energy-Efficient Building Design

Energy-efficient design aims to reduce operational carbon emissions by minimizing the energy required for heating, cooling, and lighting. Key architectural strategies include passive solar orientation, optimal insulation, airtight construction, and the use of high-performance windows. Advanced building management systems (BMS) offer real-time energy monitoring and automated control of heating, ventilation, and air conditioning (HVAC) systems, enabling dynamic energy optimization based on occupancy patterns and weather conditions. Additionally, integrated design approaches that combine architectural features with mechanical systems can reduce energy consumption by up to 60%.

11.2 Sustainable Building Materials

Reducing embodied carbon — the emissions generated during the production of construction materials — is crucial for sustainable building development. The following materials offer significant carbon reduction potential:

- **Low-Carbon Concrete:** Cement production alone accounts for approximately 8% of global CO_2 emissions. Innovations such as geopolymer concrete, carbon-injected concrete, and recycled aggregates are revolutionizing the industry by reducing carbon intensity. Using supplementary cementitious materials like fly ash and slag further reduces emissions.
- **Engineered Wood Products:** Materials like cross-laminated timber (CLT) and laminated veneer lumber (LVL) serve as carbon sinks by storing atmospheric carbon throughout a building's lifecycle. They also offer comparable strength to steel and concrete with significantly lower carbon footprints.
- **Recycled Steel and Aluminum:** Steel and aluminum can be recycled indefinitely without losing structural integrity. Using recycled metals in construction reduces the environmental impact by conserving energy and reducing the need for mining virgin materials.
- **Green Insulation Materials:** Natural insulation options, including hemp, sheep's wool, and cellulose, offer superior thermal performance with minimal environmental impact. These materials reduce heating and cooling demands, enhancing overall building efficiency.

11.3 Circular Economy in Construction

Applying circular economy principles in construction involves designing for disassembly, minimizing waste, and reusing materials. Key strategies include modular construction, which allows for easy deconstruction and repurposing, and prefabrication, which reduces on-site waste by manufacturing components in controlled environments. Demolition waste can be processed into secondary raw materials for new construction, reducing landfill contributions. Moreover, incorporating life cycle assessments (LCAs) ensures that environmental impacts are considered from material extraction through to end-of-life management.

11.4 Renewable Energy Integration

Integrating renewable energy systems into buildings plays a critical role in reducing operational emissions. Solar photovoltaic (PV) panels, wind turbines, and geothermal heating systems provide on-site renewable energy generation. Net-zero energy buildings (NZEBs) produce as much energy as they consume annually, often sending excess power back to the grid. Advanced technologies like building-integrated photovoltaics (BIPV) and solar thermal systems enable seamless renewable energy adoption without compromising building aesthetics.

11.5 Policy and Certification Standards

Government policies and global certification standards are essential for promoting sustainable building practices. Major policy instruments and frameworks include:

- **Building Codes and Standards:** Energy codes set minimum efficiency requirements for new constructions and renovations. Examples include the International Energy Conservation Code (IECC) and the European Union's Energy Performance of Buildings Directive (EPBD).
- **Green Certifications:** Voluntary certifications like LEED (Leadership in Energy and Environmental Design), BREEAM (Building Research Establishment Environmental Assessment Method), and WELL certification recognize high-performing sustainable buildings.
- **Incentives and Subsidies:** Financial mechanisms such as tax credits, grants, and green bonds encourage investment in low-carbon technologies and materials, making sustainability more economically viable.

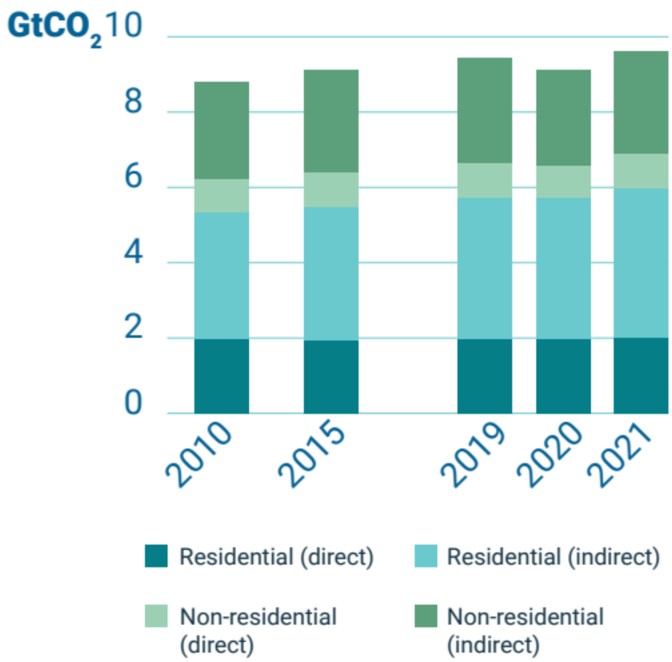

Figure 13: Direct and Indirect CO2 Emissions in Various Types of Buildings

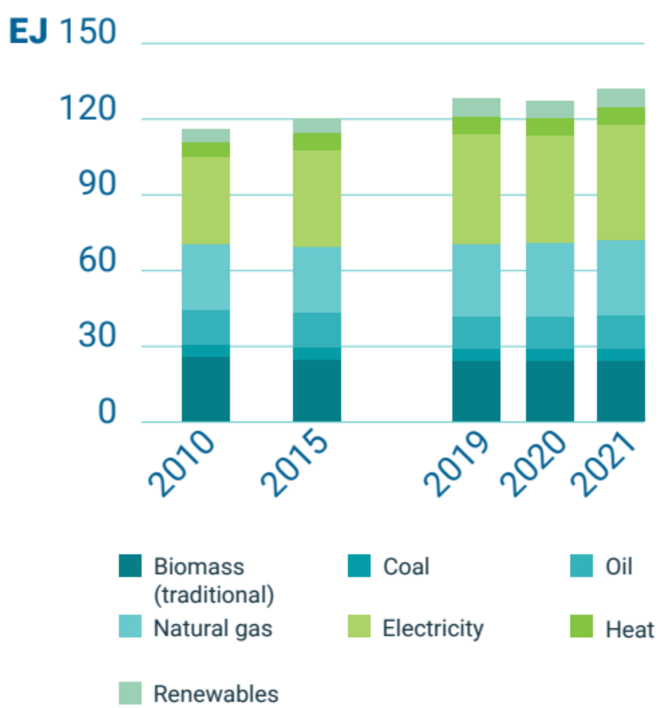

Figure 14: Energy Consumption in Buildings by Fuel

12.0 Decarbonization of the Maritime Industry

The maritime industry plays a crucial role in global trade but is also a significant contributor to greenhouse gas (GHG) emissions, accounting for approximately 3% of global emissions. To align with the Paris Agreement's goal of limiting global warming to 1.5°C, the sector must adopt comprehensive decarbonization strategies. This involves reducing emissions by 45% by 2030 compared to 2010 levels and achieving net-zero emissions by 2050. Maritime decarbonization is a multifaceted endeavor requiring enhancements in energy efficiency, adoption of alternative fuels, and the establishment of supportive regulatory frameworks.

12.1 Enhancing Onboard Energy Efficiency

12.1.1 Improve Hull Optimization and Reduce Water Resistance

Hull optimization is essential for reducing energy consumption in maritime operations. A well-optimized hull design minimizes drag as the ship moves through water, enhancing fuel efficiency. Technologies such as advanced hull coatings, bulbous bows, and air lubrication systems reduce friction, allowing ships to consume less fuel. These measures result in lower operating costs and reduced environmental impact by cutting carbon emissions.

12.1.2 Upgrade Propulsion Systems and Utilize Advanced Propellers

Modern propulsion systems are central to maritime energy efficiency. Using advanced technologies such as contra-rotating propellers and podded drives can enhance thrust and reduce energy loss. Adjustable pitch propellers and hybrid propulsion systems further optimize engine performance by allowing dynamic adjustments based on operational conditions, thereby lowering emissions and boosting efficiency.

12.1.3 Implement Waste Heat Recovery Systems

Maritime engines produce significant amounts of waste heat, which, if left unutilized, represents a loss of potential energy. Waste heat recovery systems such as heat recovery boilers and Organic Rankine Cycle systems capture this energy and convert it into useful power. This approach reduces energy waste, enhances onboard power generation, and cuts overall fuel consumption.

12.1.4 Use Voyage Optimization and Route Planning Tools

Effective route planning can substantially decrease fuel use by minimizing travel distances and avoiding adverse weather. Real-time weather routing and predictive maintenance algorithms help operators choose optimal sailing routes, reducing transit times, fuel consumption, and emissions while improving reliability and profitability.

12.1.5 Adopt Slow Steaming to Reduce Fuel Consumption

Slow steaming refers to operating ships at reduced speeds, a practice that can lead to substantial fuel savings. By adjusting travel schedules and maintaining steady, slower speeds, shipping companies can decrease fuel consumption and associated emissions. Although transit times may increase, the environmental and economic benefits are significant.

12.1.6 Ensure Regular Maintenance of Engines and Hulls

Consistent maintenance ensures that engines and hulls operate at peak efficiency. Regular engine tuning, hull cleaning, and the use of maintenance tracking systems can prevent performance deterioration. Proactive maintenance minimizes fuel consumption, reduces mechanical failures, and ensures compliance with environmental standards.

12.1.7 Foster Industry Collaboration to Share Efficiency Costs and Benefits

Collaboration across the maritime value chain can reduce the financial burden of energy efficiency investments. Shared investment models for retrofitting ships with energy-efficient technologies distribute costs among stakeholders while enabling broader adoption of green practices, making decarbonization economically viable.

12.1.8 Establish Clear Energy Efficiency Regulations Through the IMO

The International Maritime Organization (IMO) plays a critical role in establishing binding international standards for energy efficiency. Frameworks such as the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) set clear performance targets, ensuring consistent industry-wide compliance and long-term sustainability.

12.2 Transitioning to Alternative Fuels

12.2.1 Explore Low-GHG Fuels

Transitioning to low-GHG fuels is critical for reducing maritime emissions. Promising options include bio-methane, e-methane, bio-methanol, e-methanol, ammonia (blue and green), bio-oils, and e-diesel. These fuels offer varying degrees of carbon reduction potential, and their adoption depends on factors such as availability, energy density, and environmental impact.

12.2.2 Scale Up Production Facilities for Alternative Fuels

Expanding fuel production capacity is essential to meet the growing demand for alternative marine fuels. Investments in renewable energy projects, biofuel refineries, and synthetic fuel plants are necessary to secure a reliable fuel supply, reduce dependency on fossil fuels, and ensure sustainable industry growth.

12.2.3 Develop Safe Storage and Bunkering Infrastructure

Safe and efficient fuel storage and refueling infrastructure are crucial for supporting alternative fuels. Advanced bunkering stations and onboard fuel management systems ensure safe handling, reducing operational risks. These developments increase fuel accessibility and operational efficiency across global shipping routes.

12.2.4 Create International Fuel Standards and Regulatory Frameworks

Developing standardized fuel specifications and regulatory frameworks ensures that alternative fuels meet safety and performance criteria. Global fuel standards established through international agreements help maintain consistent operational practices, enhancing fuel reliability and fostering global adoption.

12.2.5 Promote R&D for More Efficient and Cost-Effective Fuel Technologies

Research and development in alternative fuel technologies drive innovation and reduce deployment costs. Areas of focus include hydrogen fuel cells, carbon-neutral synthetic fuels, and advanced energy storage systems. Investing in R&D accelerates technological progress and facilitates widespread adoption of cleaner fuels.

12.2.6 Introduce Carbon Pricing to Incentivize Cleaner Fuel Adoption

Carbon pricing mechanisms, such as carbon taxes, emission trading systems, and offset credits, internalize the environmental costs of emissions. By making fossil fuels more expensive, carbon pricing encourages the adoption of cleaner fuel alternatives, fostering a low-carbon shipping economy.

12.2.7 Secure Government Subsidies, Tax Incentives, and Grants for Innovation

Government-backed financial incentives support industry transitions by reducing the economic risks of adopting new technologies. Subsidies for retrofitting vessels, tax credits for R&D investments, and grants for innovative projects enable broader implementation of decarbonization strategies.

12.2.8 Establish Public-Private Partnerships to Accelerate Fuel Deployment

Collaboration between governments and industry stakeholders can drive large-scale deployment of alternative fuels. Joint ventures focused on fuel production, infrastructure expansion, and research initiatives share costs and risks while accelerating market readiness.

12.3 Regulatory Frameworks and Policy Support

12.3.1 Set Absolute GHG Reduction Targets With Intermediate Milestones

Establishing clear, binding GHG reduction targets ensures accountability and long-term sustainability. Intermediate milestones, such as targets for 2030 and 2040, enable progress tracking and provide a structured roadmap for achieving net-zero emissions by 2050.

12.3.2 Implement Well-to-Wake Emissions Accounting Standards

Comprehensive well-to-wake emissions accounting tracks GHG emissions from fuel production to consumption. International standards set by the IMO ensure transparent emission reporting, enabling industry-wide comparisons and fostering compliance.

12.3.3 Introduce Global Carbon Pricing Mechanisms

Global carbon pricing internalizes the environmental cost of GHG emissions. Mechanisms such as carbon taxes and emission trading schemes incentivize investments in low-emission technologies, creating a financial driver for decarbonization.

12.3.4 Offer National Financial Incentives for Clean Technology Adoption

Governments can stimulate clean technology adoption through investment grants, tax rebates, and low-interest financing. These incentives reduce upfront costs and promote industry investment in energy-efficient systems and alternative fuels.

	Feedstock availability	Fuel production	Fuel storage, logistics & bunkering	Onboard energy storage & fuel conversion	Onboard safety & fuel management	Vessel emissions	Regulation & certification
e-ammonia	Mature	Solutions identified	Major challenges	Major challenges	Major challenges	Major challenges	Major challenges
Blue ammonia	Solutions identified	Solutions identified	Major challenges	Major challenges	Major challenges	Major challenges	Major challenges
e-methanol	Solutions identified	Solutions identified	Solutions identified	Mature	Mature	Mature	Solutions identified
Bio-methanol	Solutions identified	Solutions identified	Solutions identified	Mature	Mature	Mature	Solutions identified
e-methane	Solutions identified	Solutions identified	Mature	Mature	Mature	Solutions identified	Solutions identified
Bio-methane	Solutions identified	Solutions identified	Mature	Mature	Mature	Solutions identified	Solutions identified
e-diesel	Solutions identified	Solutions identified	Mature	Mature	Mature	Mature	Solutions identified
Bio-oils	Solutions identified	Major challenges	Solutions identified	Solutions identified	Mature	Solutions identified	Solutions identified

Mature
Solutions are available, none or marginal barriers identified

Solutions identified
Solutions exist, but some challenges on e.g., maturity and availability

Major challenges
Solutions are not developed or lack specification

Figure 15: Maritime Fuel Pathway Maturity Map

13.0 Decarbonization of Aviation

The aviation sector is a pivotal component of the global economy, facilitating international trade, tourism, and connectivity. However, it significantly contributes to greenhouse gas (GHG) emissions, accounting for approximately 2-3% of global CO_2 emissions. In 2021, the airline industry committed to achieving carbon neutrality by 2050, aligning with the Paris Agreement's objectives. Achieving this ambitious target necessitates a multifaceted approach, encompassing technological innovations, operational enhancements, sustainable fuel adoption, and supportive regulatory frameworks.

13.1 Technological Innovations in Aircraft Design

Advancements in aircraft technology are crucial for reducing fuel consumption and emissions. The development of lighter materials, such as composites, and more efficient aerodynamics can significantly enhance aircraft performance. Innovations like blended wing body designs and laminar flow control contribute to lower drag and improved fuel efficiency. Additionally, the integration of advanced propulsion systems, including geared turbofan engines and open-rotor designs, offers potential reductions in fuel burn and emissions. Continuous investment in research and development is essential to bring these technologies from concept to commercial viability.

Accelerating the replacement of older, less efficient aircraft with newer models can yield immediate environmental benefits. Modern aircraft are designed with fuel efficiency in mind, incorporating the latest technological advancements. For instance, the Airbus A320neo and Boeing 737 MAX families offer substantial fuel savings compared to their predecessors. Fleet renewal not only reduces emissions but also lowers operating costs for airlines. However, the financial implications of large-scale fleet replacement require careful consideration, especially in the context of the industry's recovery from the COVID-19 pandemic.

13.2 Operational Efficiency Improvements

Optimizing flight operations presents significant opportunities for emission reductions. Implementing measures such as single-engine taxiing, continuous descent approaches, and optimized flight planning can decrease fuel consumption. Air traffic management enhancements, including the deployment of performance-based navigation and collaborative decision-making, enable more direct routing and reduced delays. Ground operations also offer potential for efficiency gains through electrification of ground support equipment and improved airport infrastructure. Collectively, these operational strategies contribute to the sector's decarbonization efforts.

13.3 Sustainable Aviation Fuels (SAFs)

The adoption of sustainable aviation fuels is pivotal in the industry's decarbonization strategy. SAFs, derived from renewable sources such as biomass, waste oils, and synthetic processes, can reduce lifecycle CO_2 emissions by up to 80% compared to conventional jet fuel. Scaling up SAF production and integrating them into the fuel supply chain are critical steps. Policies that support SAF development, including subsidies, mandates, and investment in production facilities, are essential to overcome current challenges related to cost and availability. Collaboration among stakeholders, including governments, airlines, and fuel producers, is necessary to establish a robust SAF market.

13.4 Regulatory and Market-Based Measures

Effective regulatory frameworks are vital to drive the aviation sector's transition to carbon neutrality. International agreements, such as the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), aim to stabilize CO_2 emissions from international flights at 2020 levels by requiring airlines to offset growth in emissions. Market-based measures, including carbon pricing and emissions trading systems, incentivize emission reductions by assigning a cost to carbon output. National and regional policies, such as the European Union's Emissions Trading System (EU ETS), further reinforce these efforts. Harmonizing regulations across jurisdictions is crucial to ensure a level playing field and prevent market distortions.

13.5 Research and Development Initiatives

Investing in research and development is fundamental to achieving long-term decarbonization goals. Exploring alternative propulsion technologies, such as electric and hydrogen-powered aircraft, holds promise for substantial emission reductions. Demonstration projects and pilot programs are essential to validate the feasibility and safety of these technologies. Public-private partnerships can facilitate the sharing of knowledge and resources, accelerating innovation. Additionally, fostering collaboration among academia, industry, and government agencies ensures that research efforts are aligned with practical applications and policy objectives.

13.6 International Collaboration and Policy Alignment

The global nature of aviation necessitates coordinated international action. Aligning policies and standards across countries and regions ensures the effectiveness of decarbonization measures. Organizations such as the International Civil Aviation Organization (ICAO) play a pivotal role in facilitating cooperation and setting global standards. Sharing best practices and technological advancements accelerates progress and helps avoid duplication of efforts. Developing countries may require support in building capacity to implement decarbonization initiatives, highlighting the importance of inclusive international collaboration.

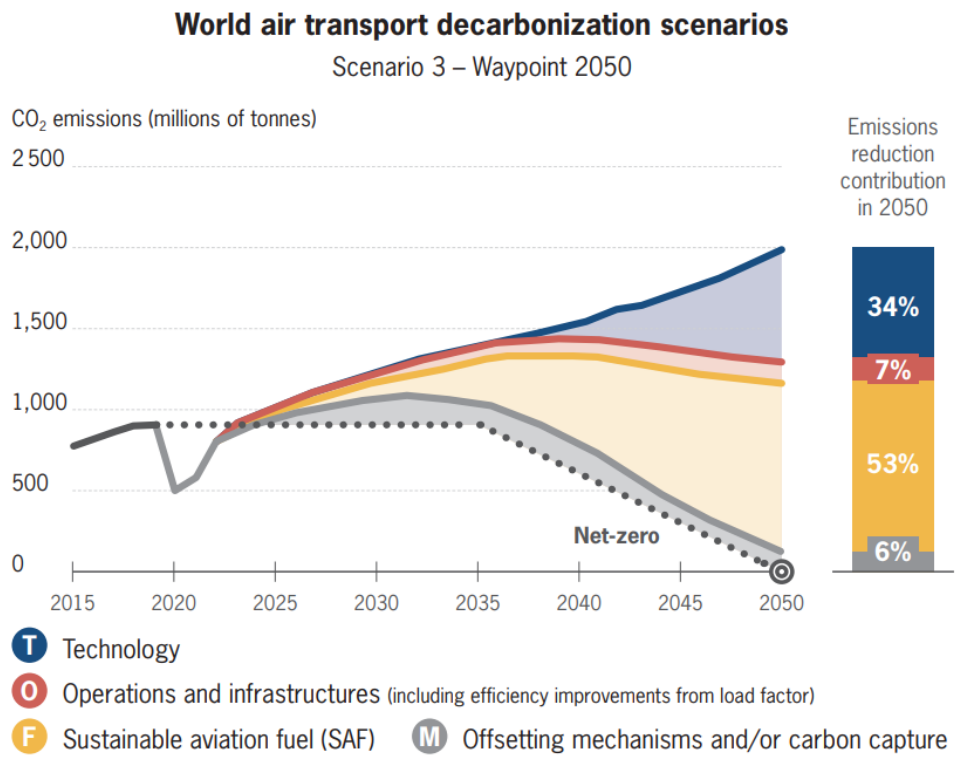

Figure 16: World air transport decarbonization scenarios

Glossary of Terms

Adaptation: Adjustments in systems to reduce vulnerability to climate change impacts.

Alternative Fuels: Low-carbon energy sources like hydrogen, biofuels, and e-methanol used to reduce GHG emissions.

Air Lubrication System: A technology that reduces water friction under a ship's hull to improve fuel efficiency.

Bioenergy: Renewable energy from biological sources like plants and waste.

Blended Cements: Cements mixed with supplementary materials like fly ash and slag to reduce carbon emissions.

Building-Integrated Photovoltaics (BIPV): Solar panels integrated into building structures, serving as both energy generators and architectural components.

Carbon Budget: The allowable amount of CO_2 emissions to keep global temperature rise below a target level.

Carbon Capture, Utilization, and Storage (CCUS): Technologies capturing CO_2 emissions for storage or reuse.

Carbon Neutrality: Achieving net-zero carbon emissions by balancing emitted and absorbed CO_2.

Carbon Pricing: Assigning a monetary value to CO_2 emissions through taxes or cap-and-trade systems.

Carbon Sinks: Natural systems like forests and oceans that absorb more CO_2 than they emit.

Circular Economy: A regenerative system minimizing waste and maximizing material reuse.

Decarbonization: Reducing or eliminating carbon emissions from various sectors.

Demand-Side Management: Adjusting consumer energy use to balance electricity supply and demand.

Direct Reduced Iron (DRI): A method of steel production that uses hydrogen instead of carbon-intensive fuels.

Electrification: Replacing fossil fuel-based energy systems with electricity-powered systems.

Emission Trading System (ETS): A market-based mechanism allowing companies to trade emissions allowances.

Embodied Carbon: Carbon emissions associated with producing and transporting building materials.

Fluorinated Gases: Synthetic gases with high global warming potential used in industrial applications.

Fugitive Emissions: Unintentional releases of greenhouse gases from equipment or facilities.

Geothermal Heating Systems: Renewable heating systems using Earth’s heat.

Global Warming Potential (GWP): A measure of how much heat a GHG traps in the atmosphere relative to CO_2.

Green Bonds: Bonds financing environmentally sustainable projects.

Hydrogen Fuel Cell Vehicles (FCEVs): Vehicles powered by hydrogen fuel cells producing only water vapor as emissions.

Hydrogen Injection: Using hydrogen to reduce CO_2 emissions in industrial processes like steel production.

Infrastructure Development: Building facilities like renewable energy plants, electric charging stations, and smart grids.

Integrated Design: A design approach combining architecture and engineering for enhanced energy efficiency.

Life Cycle Assessment (LCA): Evaluating a product's environmental impact from production to disposal.

Low-Carbon Concrete: Cement alternatives with reduced CO_2 emissions.

Low-GHG Fuels: Fuels with lower greenhouse gas emissions compared to conventional fossil fuels.

Methane (CH_4): A potent greenhouse gas emitted from natural gas systems and agricultural activities.

Modular Construction: Building method using pre-fabricated sections to reduce waste and emissions.

Nationally Determined Contributions (NDCs): Country-specific plans for reducing GHG emissions under the Paris Agreement.

Net-Zero Emissions: Balancing emitted and removed greenhouse gases to achieve zero net emissions.

Nitrous Oxide (N_2O): A powerful GHG emitted from agriculture and industrial processes.

Paris Agreement: A global treaty aiming to limit global warming to below 2°C, ideally 1.5°C.

Photovoltaic (PV) Systems: Solar panels converting sunlight into electricity.

Power-to-X Technologies: Converting renewable electricity into other energy carriers like hydrogen or synthetic fuels.

Renewable Energy: Energy from naturally replenishing sources like wind, solar, and hydropower.

Renewable Portfolio Standards (RPS): Regulations requiring a specific percentage of energy from renewable sources.

Retrofit: Upgrading existing buildings or equipment to improve energy efficiency.

Scope 1, 2, and 3 Emissions: Categorization of emissions by source, from direct emissions to supply chain impacts.

Smart Grid: An energy network using digital technology for efficient electricity management.

Sustainable Aviation Fuel (SAF): Low-carbon jet fuel made from renewable sources.

Transit-Oriented Development (TOD): Urban development focused on maximizing access to public transit.

Transparency Framework: Reporting mechanisms ensuring compliance with international climate agreements.

Waste Heat Recovery: Capturing and reusing heat generated in industrial processes.

Well-to-Wake Emissions: Total GHG emissions from fuel production to its final use.

Zero-Emission Vehicles (ZEVs): Vehicles producing no direct emissions from their power sources.

Zero-Energy Building (ZEB): A building generating as much energy as it consumes over a year.

References

[1] IPCC. (2019). Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. Retrieved from https://www.ipcc.ch/site/assets/uploads/sites/2/2019/02/SR15_Chapter2_Low_Res.pdf

[2] RealClimate.org. (2021). Climate change insights and scientific discussions. Retrieved from https://www.realclimate.org/index.php/archives/2021/08/

[3] European Environment Agency (EEA). (2024). Climate change mitigation: Reducing emissions. Retrieved from https://www.eea.europa.eu/en/topics/in-depth/climate-change-mitigation-reducing-emissions

[4] Environmental Protection Agency (EPA). (2024). Global greenhouse gas overview. Retrieved from https://www.epa.gov/ghgemissions/global-greenhouse-gas-overview

[5] United Nations. (n.d.). The Paris Agreement on climate change. Retrieved from https://www.un.org/en/climatechange/paris-agreement

[6] Carbon Cycle Compost. (2020). What is the carbon cycle? Retrieved from https://carboncyclecompost.com/what-is-the-carbon-cycle/

[7] Intergovernmental Panel on Climate Change (IPCC). (2018). Special Report on Global Warming of 1.5°C. Retrieved from https://www.ipcc.ch/sr15/

[8] IPCC. (2018). Chapter 2: Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. Retrieved from https://www.ipcc.ch/sr15/chapter/chapter-2/

[9] United Nations Framework Convention on Climate Change (UNFCCC). (2021). CMA 2021 Advancing Climate Action Report. Retrieved from https://unfccc.int/sites/default/files/resource/cma2021_08_adv_1.pdf

[10] Innovation, Science and Economic Development Canada. (2022). Roadmap to Net-Zero Carbon Concrete by 2050. Retrieved from https://ised-isde.canada.ca/site/clean-growth-hub/sites/default/files/documents/2022-11/roadmap-net-zero-carbon-concrete-2050_0.pdf

[11] Alliance for Industry Decarbonization. (2024). Solutions to decarbonize the steel industry. Retrieved from https://www.allianceforindustrydecarbonization.org/-/media/Alliance/Files/Publications/AFID_Solutions_decarbonise_steel_industry_2024.pdf

[12] McKinsey & Company. (2020). How to decarbonize global power systems. Retrieved from https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/how-to-decarbonize-global-power-systems

[13] Zero Carbon Shipping. (2022). Maritime Decarbonization Strategy. Retrieved from https://cms.zerocarbonshipping.com/media/uploads/publications/Maritime-Decarbonization-Strategy-2022.pdf

[14] Institut Montaigne. (2022). Decarbonizing aviation: All aboard. Retrieved from https://www.institutmontaigne.org/ressources/pdfs/publications/report-decarbonizing-aviation-all-aboard.pdf

[15] Global Drive to Zero. (2023). Global progress toward transport decarbonization. Retrieved from https://globaldrivetozero.org/site/wp-content/uploads/2023/11/Global-Progress-Toward-Transport-Decarbonization_MCAP-2023-Update_Final-1.pdf

[16] United Nations Environment Programme (UNEP). (2022). Global Status Report for Buildings and Construction. Retrieved from https://www.unep.org/resources/publication/2022-global-status-report-buildings-and-construction

[17] International Energy Agency (IEA). (2021). Net Zero by 2050: A roadmap for the global energy sector. Retrieved from https://www.iea.org/reports/net-zero-by-2050

[18] Compare Your Footprint. (2023). Difference between Scope 1, 2, and 3 emissions. Retrieved from https://www.compareyourfootprint.com/difference-scope-1-2-3-emissions/

[19] Carbon Equity. (2023). Decarbonizing cement: A blueprint to net zero. Retrieved from https://www.carbonequity.com/blog/decarbonizing-cement-a-blueprint-to-net-zero

[20] U.S. Energy Information Administration (EIA). (2019). Today in Energy: Global energy trends. Retrieved from https://www.eia.gov/todayinenergy/detail.php?id=41533