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Industry Decarbonization Roadmaps for Indonesia:

Opportunities and challenges to net-zero emissions

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Acronyms and Abbreviations

AFOLU	Agriculture, Forestry and Other Land Use
APKI	Indonesian Pulp and Paper Association
APP	Asia Pulp & Paper
APRIL	Asia Pacific Resources International Ltd
ASEAN	Association of Southeast Asian Nations
ASI	Indonesian Cement Association
BAPPENAS	Ministry of National Development Planning of Indonesia
BAT	best available technology
BECCS	bioenergy with carbon capture and storage
BEE	Bureau of Energy Efficiency
BF	blast furnace
BOF	basic oxygen furnace
BPS	Central Statistics Agency of Indonesia
CCS	carbon capture and storage
CCUS	carbon capture, utilization, and storage
CO_2	carbon dioxide
DRI	direct reduction of iron
EAF	electric arc furnace
EOR	enhanced oil recovery
FGDs	Focused Group Discussions
FIKI	Indonesian Chemical Industry Federation
FOLU	forestry and other land use
g	gram
GDP	gross domestic product
GHG	greenhouse gas
GJ	gigajoule
GoI	Government of Indonesia
Gt	gigatonnes
GW	gigawatt
H_2	hydrogen
HBI	hot briquetted iron
IEA	International Energy Agency
IESR	Institute for Essential Services Reform
IISIA	Indonesian Iron and Steel Industry Association
IPCC	Intergovernmental Panel on Climate Change
IPPU	Industrial process and product use
kg	kilogram
km	kilometer
kWh	kilowatt-hour
LBNL	Lawrence Berkeley National Laboratory

LCA	life cycle assessment
LEAP	Low Emissions Analysis Platform
MEA	monoethanolamine
MEMR	Ministry of Energy and Mineral Resources of Indonesia
MOE	molten oxide electrolysis
MOEF	Ministry of Environment and Forestry of Indonesia
MOI	Ministry of Industry of Indonesia
Mt	million tonnes
$MtCO_2e$	metric tons of carbon dioxide-equivalent
Mtoe	million tonnes of oil equivalent
MW	megawatt
N_2O	nitrous oxide
NDC	Nationally Determined Contributions
NZE	net-zero emissions
O&G	Oil and gas
OPC	Ordinary Portland Cement
PLN	Perusahaan Listrik Negara (State Electricity Company of Indonesia)
PPA	power purchase agreement
R&D	research and development
SCM	supplemental cementitious materials
SME	small and medium enterprise
SMR	steam methane reforming
SRI	smelting reduction of iron
t	ton
TRL	technology readiness level
TWh	terawatt-hour
USD	United States dollars
VFD	variable frequency drives

Executive Summary

It is technically feasible to achieve near-zero carbon dioxide (CO_2) emissions in Indonesia's industrial sector by 2060, the target year for carbon neutrality in Indonesia's updated Nationally Determined Contributions (NDCs). Achieving net-zero CO_2 emissions in Indonesia's industrial sector by 2050, as aspired in the government goals, will require extraordinary efforts and a much more accelerated pace of adoption of low-carbon technologies.

Achieving Indonesia's announced national economic development targets will require significant growth in the industrial sector, which provides the foundational materials and infrastructure for urbanization, improved living standards, and other industry development (renewables, batteries, electric vehicles) that is necessary for the country's energy transition.

Industrial capacity expansion is expected in several key industries in Indonesia, such as iron and steel, driven by domestic construction demand, as well as investment in and transfer of industrial production capacity from other Asian countries (e.g., China, Japan, and South Korea). As a result, the current industry development is not on track to achieve the Near Zero 2060 Scenario developed for this report.

A portfolio of technologies and measures is available for Indonesia to consider for industry decarbonization. Different strategies can play different roles in specific industries. Specifically:

- Iron and steel: Transitioning to scrap-electric arc furnace (EAF) (near term), followed by hydrogen (H_2)-direct reduction of iron (DRI)-EAF (mid to long term), while at the same time pursuing energy efficiency and material efficiency. There is a very limited role for carbon capture and storage (CCS).
- Cement: Increasing the use of supplemental cementitious materials (SCM), implementing material efficiency and energy efficiency measures (near term) and zero-carbon fuels (mid to long term). Conducting research and development (R&D) and pilots on CCS, and mitigating risks associated with investment cost of CCS and verifiability of CCS systems (mid to long term).
- Ammonia: Improving energy efficiency (near term), switching to zero-carbon (H_2, biomass) feedstocks (mid term), and implementing pilots on methane pyrolysis and CCS (long term).
- Pulp and paper: Improving energy efficiency, implementing material efficiency and recycling (near term), and switching from coal to other renewable sources in papermaking (mid term).
- Textiles: Fully electrifying spinning, weaving, and knitting processes (near term) and adopting industrial heat pumps and other renewable energy sources in wet processing (mid term).

National strategies on carbon-intensive materials (e.g., steel, and cement), green energy carriers (e.g., hydrogen and ammonia), and cross-cutting technologies (e.g., industrial heat pumps, and CCS) need to be developed. A coordinated approach on infrastructure development (pipelines, storage sites, power transmission, and distribution systems) and utilization is necessary.

Industry decarbonization also requires a rapidly decarbonizing power sector. Near zero CO_2 emissions in industry requires access to clean, low-cost electricity. Policies that support industry in connecting to renewable power or developing its own renewable electricity are very important.

Industry decarbonization brings with it the potential to develop new industries, grow local economies, reduce air pollution, and be more competitive in global trade. It is critical to involve all stakeholders in this process to minimize negative impacts to local communities and leverage this opportunity to reduce inequality.

Finally, a multifaceted policy approach is needed to encourage investment in industry decarbonization in Indonesia, including clear and credible emission targets at the sectoral level, a policy framework that encourages fuel switching and energy efficiency investment, a new market for material efficiency, and investment in research, development, innovation and demonstration projects. At the same time, it is necessary to prepare the workforce with the skills, knowledge, and capabilities necessary to enable the transition to low-carbon solutions and enable local communities to benefit from the transition.

Industry investment and policy decisions made today have important implications for 2050 and 2060. If Indonesia is going to meet its updated NDC goal of carbon neutrality by 2060 or sooner, industry development will need to be met by clean, low-carbon, and cost-effective technologies combined with policy strategies that create the right market conditions to speed and scale up adoption.

1. Introduction

1.1 Industry as the key driver in Indonesia rapid economic development

As the largest country in Southeast Asia and the fourth most populous nation globally, Indonesia is the tenth largest economy in the world in terms of purchasing power parity (World Bank 2022). Indonesia is experiencing rapid economic growth fueled by a young and growing labor force, rich and abundant natural resources, and rapid technological advancements. According to a report from Indonesia's Ministry of National Development Planning (BAPPENAS), the country's economy is expected to grow at an impressive rate of 5.7% annually from 2016 to 2045 (Kementerian PPN/Bappenas 2019). This potential growth trajectory not only positions Indonesia to break free from the middle-income trap[1] by 2036 but also sets the stage for it to potentially become the world's fourth-largest economy by 2050 (Daly and Gedminas, 2022).

One of the key sectors that drives Indonesia's economic development is the industrial sector. Figure 1 illustrates the contribution of various business fields to the country's gross domestic product (GDP) from 2018 to the second quarter (Q2) of 2023.

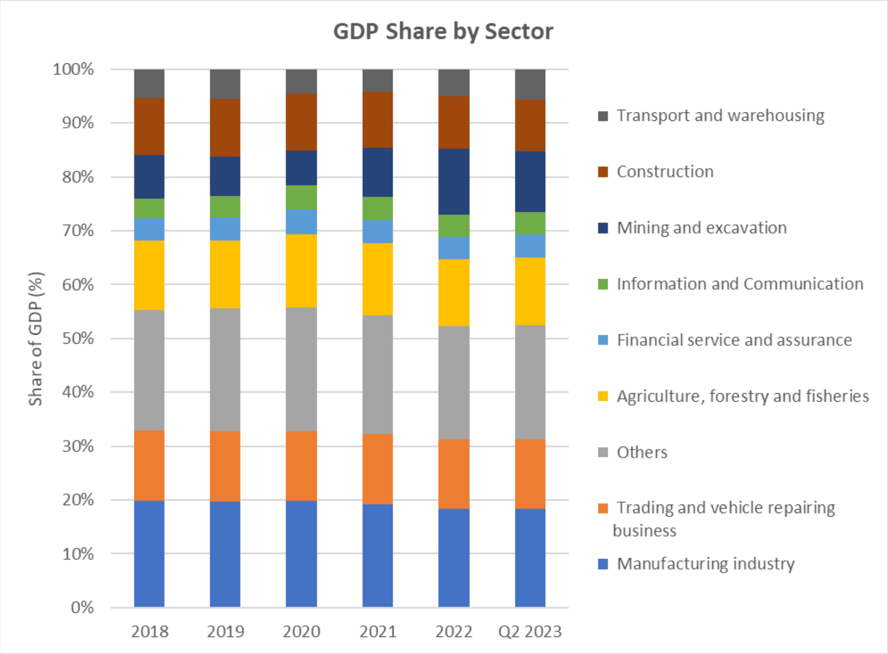

Figure 1. GDP share by sector in Indonesia (2018-Q2 2023)
Source: Statistic Indonesia 2023.

It is evident that the industrial sector, especially the manufacturing subsector, holds a prominent share in the country's economics portfolio despite the global COVID-19 pandemic. According to data from the

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[1] The middle-income trap captures a situation where a middle-income country can no longer compete internationally in standardized, labor-intensive goods because wages are relatively too high, but it also cannot compete in higher value-added activities on a broad enough scale because productivity is relatively too low. The result is slow growth, stagnant or falling wages, and a growing informal economy (Paus 2017).

Central Statistics Agency (BPS), this subsector, encompassing both oil and gas (O&G) and non-O&G industries, accounts for approximately 20% of the national GDP. This proportion is comparable to that of many industrialized economies (Oxford Business Group 2019). Furthermore, despite a temporary decline in its GDP contribution during the pandemic, Indonesia's manufacturing industries collectively continue to outperform other economic sectors, demonstrating their resilience and status as an economic powerhouse in the country.

In addition, the industrial sector in Indonesia plays a crucial role in job creation and commodity exports. Employment in the industrial sector has been increasing steadily. In 2020, the manufacturing industry provided employment to approximately 17.5 million individuals. This number saw a notable increase to 18.6 million in 2021 and further surged to about 19.1 million in 2022. Meanwhile, in terms of exported goods, the non-O&G manufacturing industry has emerged as a dominant contributor to Indonesia's export income. Over the past three years, Indonesia's non-O&G industry has seen a steady increase in its annual export revenue, reaching $131 billion USD in 2020, $177 billion USD in 2021, and a substantial $206 billion USD in 2022 (Ministry of Industry 2021) (Ministry of Industry 2023).

1.2 Indonesia's vulnerability to climate change threats and decarbonization opportunities from the industry sector

Despite experiencing exponential economic and development growth, Indonesia remains highly susceptible to climate change threats, including shifting weather patterns, severe and prolonged droughts, and increasingly frequent wildfires. Figure 2 presents data from the National Agency for Disaster Countermeasures (BNPB), reflecting many types of natural disasters that occurred in Indonesia between January and August 2023.

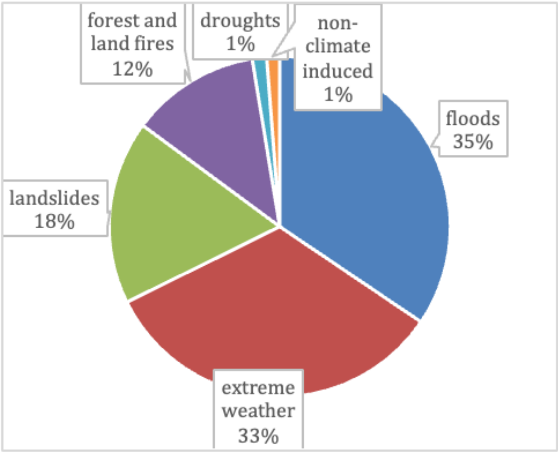

Figure 2.Indonesia natural disasters, January–August 2023

Source: BNPB 2023.

Of a total of 2,100 recorded cases, approximately 99% of them can be attributed to climate-induced disasters, such as floods, extreme weather events, droughts, forest and land fires, and landslides (Annur 2023). Non-climate-induced disasters, including earthquakes, volcanic eruptions, and coastal abrasion, make up the remainder. This situation is exacerbated by Indonesia's archipelagic nature and its heavy reliance on nature-based sectors like the maritime ecosystem. Currently, approximately one-third of Indonesia's invaluable coral reefs are in a deteriorated state, primarily due to the changing composition of seawater resulting from the ripple effect of climate change (InCorp 2022). Consequently, fisheries and other maritime products have reached unprecedented lows.

Given the importance of addressing climate change, devising a comprehensive decarbonization strategy is imperative. Recent data indicates that as of late 2022, the global average temperature had already risen by 1.2°C from pre-industrial levels. Consequently, the remaining carbon budget necessary to stay within the 1.5°C target is dwindling rapidly, and without decisive decarbonization measures, it is estimated that it will be exhausted by the end of 2028 (Lucas Chancel 2022). Surpassing this critical 1.5°C threshold, the consequences are dire, including heightened risk of crossing irreversible tipping points in the Earth's delicate systems, resulting in severe, lasting and irreversible damage (Rockstrom 2022).

Figure 3 shows that Indonesia's national CO_2 emissions reached approximately 600 million tonnes of carbon dioxide ($MtCO_2$) in 2021, a 5% increase from 2020. This is primarily attributed to the rapid economic development that Indonesia is currently undergoing. When emissions associated with electricity generation are aggregated, industrial sector's CO_2 emissions ranked the second highest, only after the power sector. It is important to note that industrial sector CO_2 emissions are even higher, when CO_2 emissions of electricity purchased by the industrial sector are included in the sector.

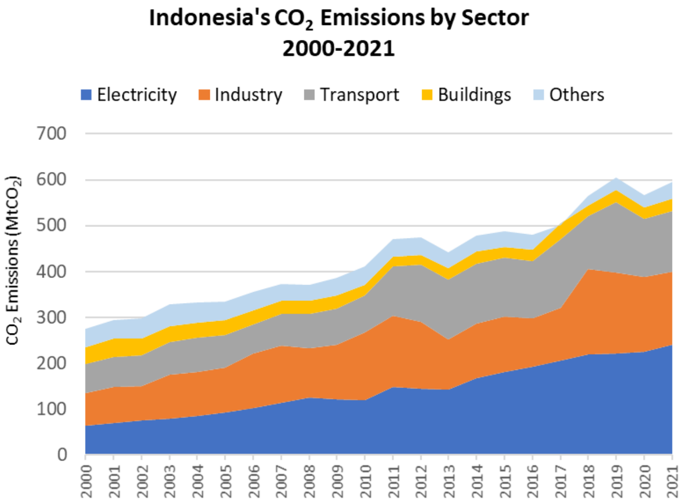

Figure 3. Indonesia's CO_2 emissions by sector (2000 to 2021)

Sources: IEA 2022a.

With a government projected annual economic growth rate of 5.7% from 2016 to 2045, it is expected that Indonesia's industrial final energy demand will surge to 250 million tonnes of oil equivalent (Mtoe) by 2050, accounting for roughly 55% of the nation's final energy demand by 2050. Consequently, unless current policies change, Indonesia's GHG emissions from the industrial sector are projected to more than double their current level (Ministry of Environment and Forestry 2021).

The majority of the industrial GHG emissions are from fossil fuel and electricity consumption (about 68% of total industrial GHG emissions), while the rest of the emissions are from industrial process and product use (IPPU), as well as waste (as shown in Figure 4). In 2016, Indonesia's Coordinating Ministry of Economic Affair (CEMA) estimated that eight industries contribute the highest to the national GHG emissions, including pulp and paper, cement, textiles, iron and steel, food and beverages, fertilizers, chemicals, and ceramic and glass (ranked from highest to the lowest emissions). The combination of eight industries emitted more than 147 $MtCO_{2e}$, or roughly 56% of total GHG emissions from industrial energy use in 2016. For some of these industries, emissions are largely attributed to natural gas or coal use. For example, in cement and the iron and steel industries, coal is the dominant driver of emissions, while the ammonia industry largely relies on natural gas inputs. The cement and iron and steel industries are also key sectors to mitigate IPPU emissions.

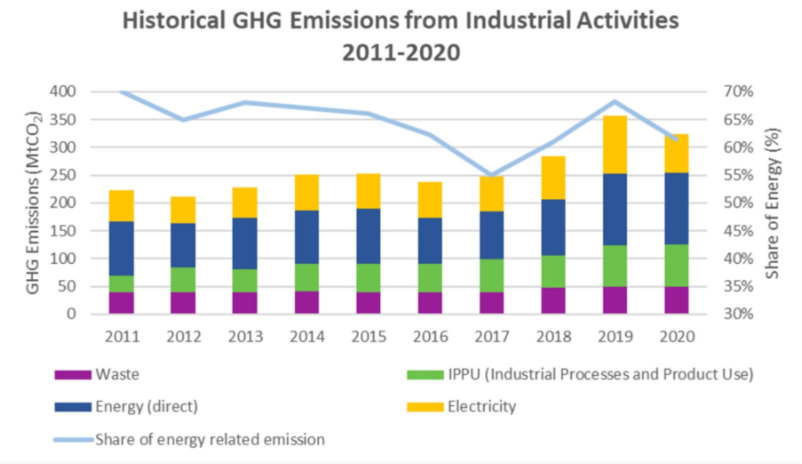

Figure 4. Industrial GHG emissions in Indonesia (2011-2020)
Source: IESR 2022.

1.3 A clearer and more ambitious emission reduction target is required to achieve net zero emissions in Indonesia by 2060 or earlier

Recognizing the paramount significance of decarbonization and its opportunities, the Government of Indonesia (GoI) has strengthened its climate goals through a series of strategic policies and regulations to address the urgent need for environmental sustainability. In its Enhanced Nationally Determined Contribution (NDC), Indonesia aims to achieve net zero emissions by 2060 or even earlier. This strategy encompasses both the Agriculture, Forestry and Other Land Use (AFOLU) and Non-AFOLU sectors, including the energy, waste, and IPPU sectors. Indonesia also has increased its ambition for emission reduction targets in the mid-term. The unconditional and conditional (with international support) goals have been augmented from 29% to 32% and from 41% to 43% by 2030, respectively, as stated in the Enhanced NDC (ENDC) 2022 (The Government of Indonesia 2022).

In actualizing the goals mandated in the aforementioned GoI official documents, the country aligns these efforts by increasing the renewable energy share in the Indonesia energy mix, as well as increasing the minimum energy end-use compliance following the new issuance of government regulation no. 33/2023. Based on President regulation no. 22/2022 about the General National Energy Plan (RUEN), Indonesia has the ambition to achieve new and renewable energy in the national energy mix by 23% in 2025 and at least 31% in 2050. However, until two years before the first target year (2025) is met, Indonesia's renewable energy capacity is only 12.6 gigawatt (GW), or about 14.9% of the national energy mix of 84.8 GW (Public Relation of New and Renewable Energy Directorate 2023). The renewable energy capacity consists of 6.7 GW from hydropower, 3.1 GW from bioenergy, 2.4 GW from geothermal power, 270 MW from solar, 154.3 MW from wind. Meanwhile, from government regulation no. 33/2023, it is expected that power generation companies, energy consumers from industry and transport sectors, as well as buildings to report their energy use and implementing energy efficiency and conservation measures, if they have a minimum annual energy consumption level of 6,000, 4,000 and 500 tonnes of coal equivalent (toe), respectively.

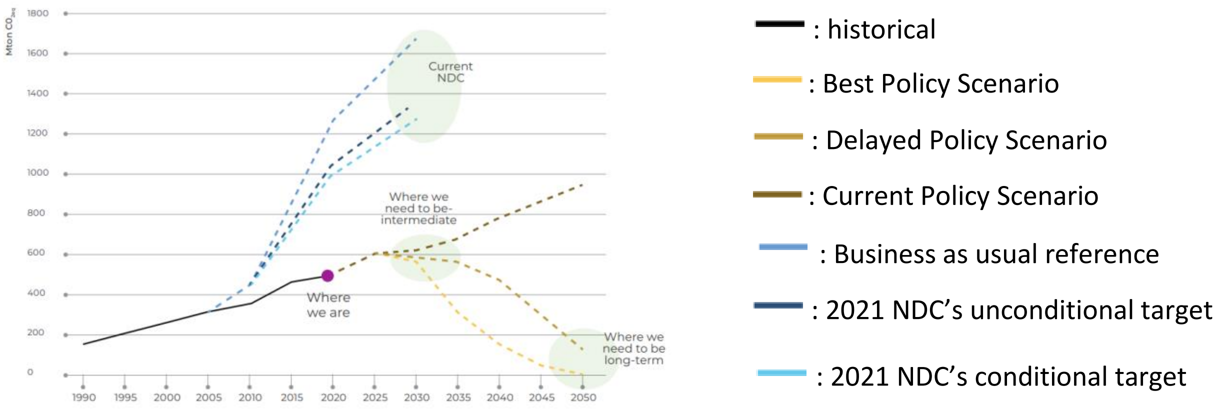

Figure 5. Emission projections in Indonesia following its 2021 NDC target

Sources: IESR et al., 2021.

Figure 5 illustrates the mismatch between Indonesia's national GHG emissions reduction goal, as per the Updated 2021 NDC, the current state of the energy system, and the trajectory required for achieving net-zero emissions by 2050. Despite aiming for unconditional and conditional emission reductions of 29% and 41% by 2030, respectively, the anticipated impact is modest, necessitating a significantly greater effort beyond 2030. Moreover, the same message is echoed by Climate Action Tracker. Their study found that the succeeding NDC target of Indonesia, Enhanced NDC 2022 with 32% and 43% emission reduction targets of without and with international support, is still deemed highly insufficient for reaching net-zero emissions by 2060 or earlier. Hence, to enhance the likelihood of achieving net-zero emissions, Indonesia should establish more ambitious climate targets for each end-use energy sector, ensuring actionable goals in implementation.

1.4 Policy landscape of the industrial sector in Indonesia

In Indonesia, cement, iron and steel, ammonia, pulp and paper, and textile industries are responsible for up to 70% or higher of industrial GHG emissions in the country in 2022 (Nugraha et al., 2018).

Several industries have begun to carry out their decarbonization efforts, for example:

- The cement industry is encouraged by the Global Cement and Concrete Association (GCCA), an international association whose members are undertaking many decarbonization efforts in Indonesia.
- The ammonia industry, driven by Indonesia's big ambition to become a low-carbon emission hub for ammonia, is projected to increase total capacity to 700 million tonnes per annum (MMTPA) by 2050 or 4 times the level in 2020. Today, there are planned developments of low carbon emissions ammonia-based projects in Indonesia by utilization of green hydrogen or CCS/CCUS.

In terms of policy development, Indonesia has made progress in establishing regulations and government programs to improve the energy efficiency, resource management, and decarbonization of the industrial sector. So far, there are 32 regulations have been made for cross-sector industries, specifically, four for cement industries, five for iron and steel industries, nine for pulp and paper industries, four for textile, and three for ammonia. Some of the following regulations are

- Active participation in the NDC with the last enhanced target update in 2022, creating a regulatory policy framework through Law No. 3 of 2014 concerning Industry;
- Government Regulation No.41 of 2015 concerning Industrial Resource Development;
- Government Regulation No. 14 of 2015 concerning the National Industrial Development Master Plan 2015 – 2035;
- Government Regulation 29 of 2018 concerning Industrial Empowerment;
- Government Regulation No. 33 of 2023 concerning energy conservation.

In addition, as part of the government's efforts to reduce industrial CO_2 emissions, the Ministry of Environment and Forestry (MOEF) established the Climate and Carbon Collaboration and Consultation House (RK2IK) in October 2023. The program’s objective is to receive consultation services on the Economic Value of Carbon as well as the implementation of the NDC, including industrial activities (PPID KLHK, 2023). The government is also formulating green industrial standards for each subsector industry; 35 have been launched up to today of the 503 priority standards planned by 2024 (Ministry of Industry, 2023b).

In the near future, it is expected that the Government of Indonesia will enhance the country’s NDC even further to a more ambitious level. It is anticipated that the development of carbon trading will be included as one of mitigation strategies in the next NDC. Currently, discussion on the development of carbon trading in the industry sector still undergoes and is led by the Green Industry Centre (PIH), a government agency under the Ministry of Industry (MOI).

1.5 Description, objectives and scope of Industry Decarbonization Roadmap

Building on the opportunity to increase the ambition for the industry sector and increase Indonesia’s technological and policy options to reach carbon neutrality targets by 2060 or sooner, this report lays out roadmaps to reach deep reductions in future energy and process-related CO_2 emission of the country's industry sector. This study did not conduct a detailed investment cost analysis for production processes in each of the industries, as the main purpose of the project was to lay the foundation of an industry decarbonization analysis of the five selected industries.

The decarbonization pathways provide Indonesian policymakers with essential tools that develop a knowledge base and synthesize key recommendations to support implementation of a portfolio of decarbonization technologies and measures in five priority industries:

- Iron and Steel
- Cement
- Ammonia
- Pulp and paper
- Textiles

The industry sector decarbonization roadmap provides the following:
(1) Bottom-up assessment of energy and emissions of key industries using public data sources and performance indicators, business-as-usual forecast of energy and emissions to 2060, based on methodology considering physical drivers and their limits.

(2) Scenario analysis to explore deep decarbonization measures that can contribute to Indonesia's 2060 carbon neutrality goal or sooner. Assessment of potential for each industry covering material efficiency and demand reduction, energy efficiency, innovative low-carbon technologies, electrification, low and zero-carbon fuels, and carbon capture, utilization, and storage.

(3) Policy recommendations for each industry identifying policy priorities and policy pathway for near-term implementation (by 2030) and mid- to long-term consideration (2030-2060). Recommendations are based on the deep decarbonization scenarios and a review of international policy experience.

2. Methodology and Scenario Setting

2.1 Methodology

This project utilized a bottom-up energy end-use accounting framework of Indonesia's energy and economic structure, built on Stockholm Environment Institute's Low Emissions Analysis Platform (LEAP) (Stockholm Environment Institute [SEI] 2022). Using the LEAP platform, the model employs both macroeconomic and non-linear, physical drivers to model integrated feedback within and across the buildings, industry, transportation, and energy transformation (primary energy supply including electricity) sectors.

This project focused on the industrial end-use sector, in particular on five industries: iron and steel, cement, ammonia, pulp and paper, and textile. Different from many other economic-driven modeling approaches, this analysis utilized non-linear, physical drivers such as population, demographics, infrastructure needs, and land area to drive the future growth of energy-consuming activities in the demand and production of industrial goods. Economic factors such as GDP growth rates were considered but not used as the primary driver of industrial activity. The use of physical drivers helps to capture saturation effects in building floorspaces, urban infrastructure development, fertilizer consumption, and equipment/product ownership and usage, which are important to a potential plateauing in energy demand. In addition, the use of physical drivers, in conjunction with economic drivers, provide unique insights into other end-use sectors, such as the buildings and transport sectors.

Specific industries (iron and steel, cement, ammonia, pulp and paper, and textile) were modeled individually. Each of these industries were modeled from the bottom up, i.e., considering production technologies, sizes of production facilities, primary and secondary production, energy inputs, raw material inputs, and energy intensity levels within each industry.

For calculating and reporting energy consumption and CO_2 emissions, the model uses the direct equivalent approach (consistent with the Intergovernmental Panel on Climate Change, IPCC) as the default for converting primary electricity; that is, renewable electricity and other non-fossil electricity (e.g., hydro, nuclear, geothermal) is converted based on its heat calorific value. For calculating energy-related carbon dioxide (CO_2) emissions, IPCC default CO_2 emission factors were used for specific fossil fuels (IPCC 2006).

Accelerated power sector decarbonization is a critical enabling factor for industry decarbonization in Indonesia. This project did not model power sector energy transition explicitly, as the analysis focused on the manufacturing processes. However, we relied on the IEA analysis for Indonesia's energy sector, which assumed that electricity generation in Indonesia will transition from its 80% unabated fossil fuel generation in 2021 to zero emissions by 2060. Specifically, the CO_2 emission intensity of power generation in Indonesia will decline from 760 grams (g) CO_2/kilowatt-hour (kWh) in 2021 to 580 gCO_2/kWh by 2030, before reaching net-zero by 2060 (IEA 2022a).

2.2 Stakeholder engagement

The project conducted extensive stakeholder engagement with government agencies and industry representatives in Indonesia. Appendix A provides a detailed mapping of all stakeholders for reference. Six Focused Group Discussions (FGDs) were held between the project team (Lawrence Berkeley National Laboratory [LBNL] and Institute for Essential Services Reform [IESR]) and Indonesia stakeholders from June 19 to June 22, 2023 (Table 1). During each discussion, the key assumptions, technologies and measures, and preliminary results of the decarbonization roadmaps were presented and consulted with the industry experts. Each industry presented their current status and conditions relevant to emissions reductions and provided suggestions and comments on the decarbonization roadmap analysis. In addition, policy questions were prepared and asked to both policymakers and industry representatives in Indonesia.

Table 1. Focused group discussions with stakeholders

Date	Topic	Stakeholders
June 19, 2023	Policies on industrial decarbonization	Ministry of Energy and Mineral Resources (MEMR)
June 20, 2023	FGD with government representatives	MEMR Ministry of Industry (MOI) Ministry of Environment and Forestry (MOEF)
June 20, 2023	FGD with cement industry representatives	MEMR MOI MOEF Indonesian Cement Association (ASI) PT Indocement Tunggal Perkasa Tbk
June 21, 2023	FGD with iron and steel industry representatives	MEMR MOI MOEF Indonesian Iron and Steel Industry Association (IISIA) UNPAGE Indonesia PT Krakatau Steel Tbk
June 21, 2023	FGD with pulp and paper industry representatives	MEMR MOI MOEF Indonesian Pulp and Paper Association (APKI) Asia Pacific Resources International Limited (APRIL)
June 22, 2023	FGD with ammonia industry representatives	MEMR MOI MOEF Association of Indonesian Fertilizer Producers (APPI) Indonesian Chemical Industry Federation (FIKI) PT Pupuk Indonesia

June 22, 2023	FGD with textile industry representatives	MEMR MOI MOEF PT Asia Pacific Rayon Pan Brothers

2.3 Scenario setting

In this analysis, we developed three scenarios to analyze energy and CO_2 emissions impacts of different decarbonization pathways in specific industries. Recognizing there are significant uncertainties in future technology developments, complexity of industrial processes, and heterogeneity among industrial sectors, we constructed the scenarios around three themes for each of the industries:

Reference: This "business as usual" scenario, considered slow adoption of low-carbon technologies and autonomous improvement in industrial production; no new policies were assumed in this scenario.

Near Zero 2060: The goal of this scenario was to achieve near-zero emissions in the modeled industries by 2060 to support the Indonesian government's 2060 carbon neutrality goal. Residual emissions were allowed and considered to be offset by removals and other mitigation measures in other sectors (outside of the modeled industry). This was the main scenario for this analysis.

Accelerated 2050: Approaching net-zero emissions by 2050. This scenario considered aggressive adoption of low-carbon technologies and reaching the maximum technical potential of the modeled technologies. It also reflects the language of achieving net-zero emissions by 2060 "or sooner" in Indonesia's updated NDC.

3. Achieving Near-Zero Emissions in the Indonesian Industry Sector

3.1 Iron and steel industry

3.1.1 Historical production and consumption

The iron and steel industry is the largest energy-consuming industry in Indonesia, accounting for more than 9% of industrial final energy consumption in Indonesia in 2021 (BPS 2022). Globally, Indonesia is the sixteenth largest crude steel-producing country in the world. It produced 14.3 million tonnes (Mt) of crude steel in 2021, or about 1% of the world's total production (worldsteel 2022). Crude steel production in Indonesia has been increasing sharply, driven by construction, infrastructure development, increasing population, and growing urbanization. From 2011 to 2021, Indonesia's crude steel production increased from almost 4 Mt/year to 14 Mt/year, growing on average 14% per year (Figure 6).

Figure 6. Indonesia steel production (2011–2021)
Source: worldsteel, various years.

Indonesia's apparent steel consumption was 57 kilograms (kg) per capita in 2021. This is significantly below the world average (233 kg/person) or the average level in Asia (306 kg/person). Compared to the European Union (EU-27) or the United States, Indonesia's per-capita steel consumption is significantly lower (see Figure 7). As seen from other countries' development trends and consumption patterns, we see a general correlation between material demand and economic growth. As the economy grows, measured by GDP per capita, more materials such as iron and steel, cement, and aluminum are consumed. Currently, Indonesia has a per-capita GDP level of less than $5,000 USD/person. It is expected that Indonesia may consume more materials as its income level rises.

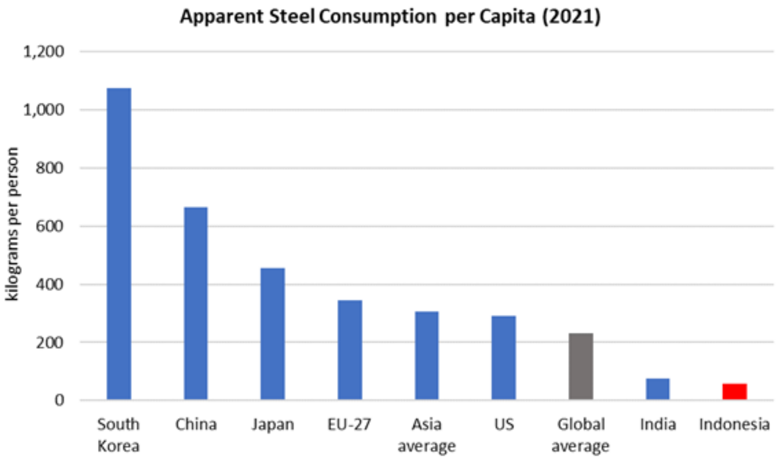

Figure 7. Apparent steel consumption per capita of selected countries (2021)
Source: worldsteel 2022.

3.1.2 Production forecast

At present, about 76% to 78% of Indonesia's steel demand is from construction, for activities such as infrastructure development and buildings. During the FGD meeting in June 2023, the Indonesia Iron and Steel Industry Association (IISIA) projected that construction will remain the key driver of Indonesia's steel demand, due to government announced economic growth goals and large-scale infrastructure development (e.g., building the new capital in Kalimantan).

Given the sensitivity of industrial production on energy and CO_2 emissions, we constructed two sub-scenarios of steel production for Indonesia. Under the "steady demand" assumption, it is assumed that per-capital steel demand almost doubles by 2060 from today's level, which is only half of today's world average per-capita steel demand. Net imports are fixed at the 2020–2021 level (the latest data available), given the challenges and uncertainties in forecasting international steel trade.

As shown in Figure 8, we projected that steel production in Indonesia increases from 13 Mt in 2020 to 29 Mt in the Near Zero 2060 Scenario under "steady demand." When considering the effects of material efficiency strategies (e.g., optimized design, improved production yields, material substitution and improved recycling; see Section 3.1.3.1 for details), steel production can be lowered to 22 Mt by 2050 and less than 25 Mt by 2060 in the Accelerated 2050 Scenario under "steady demand."

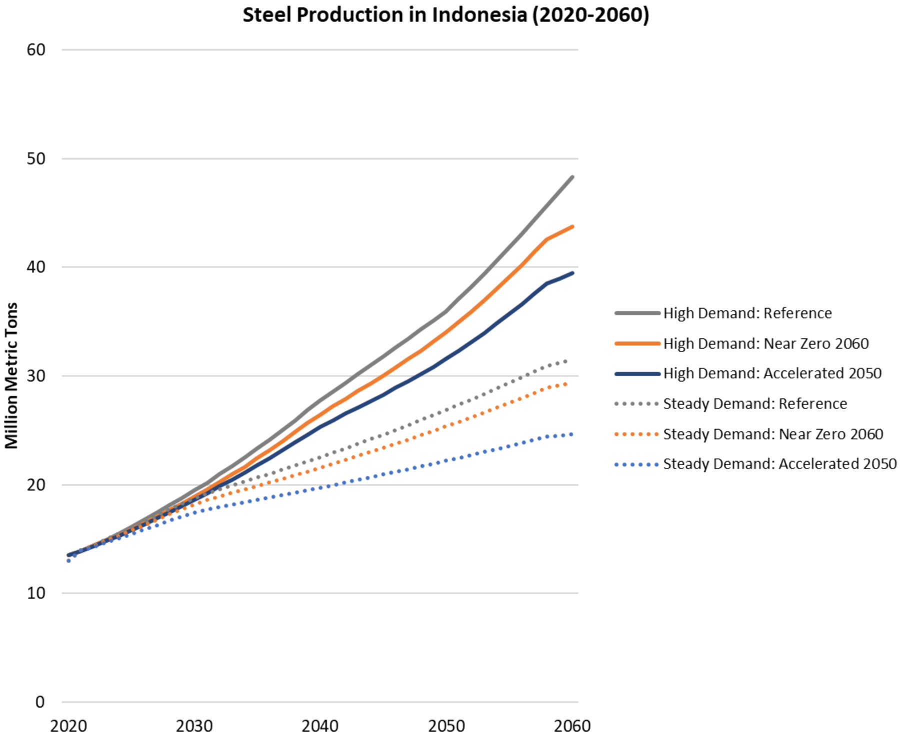

Figure 8. Steel production in Indonesia (2020–2060)

Source: LBNL analysis.

However, when taking a more aggressive forecast approach, we can see that it is also likely that steel production in Indonesia may increase much more significantly. Under the "high demand" assumption, per-capita steel consumption in Indonesia reaches today's global average by 2060. Net imports of steel products would account for 35% of total steel consumption by 2060, an increase from today's 10%. Under "high demand" assumptions, total domestic steel production in Indonesia rises from 13 Mt in 2020 to 44 Mt by 2060 in the Near Zero Scenario. Even with implementation of material efficiency strategies, steel production still increases to almost 32 Mt by 2050 and 40 Mt by 2060 in the Accelerated 2050 Scenario.

This analysis focused on how to decarbonize the Indonesian iron and steel industry under the "steady demand" assumptions, where steel production is projected to increase 130% by 2060 from the 2020 level. It should be noted that the challenge to decarbonize the sector will be significantly increased, if Indonesia's production trajectory follows the "high demand" assumptions.

3.1.3 Decarbonization strategies and technologies

The sections below discuss the production processes of the iron and steel sector, current CO_2 intensity of iron and steel production in Indonesia, and key strategies to achieve net-zero emissions in the iron and steel industry.

3.1.3.1 *Iron and steel manufacturing processes*

Conventionally, there are two main ways to produce steel (Figure 9). Primary steel making uses iron ore to produce iron and then make crude steel in blast furnaces (BF) and basic oxygen furnaces (BOF). Secondary steel making uses scrap steel (i.e., recycled steel) in electric arc furnaces (EAF). Other iron production methods exist, such as Direct Reduction Iron (DRI), Smelting Reduction Iron (SRI), Molten Oxide Electrolysis (MOE), aqueous solution-based electrowinning, and molten salt-based electrowinning.

Depending on which production method the plant uses, there are two types of steel mills: integrated mills and secondary mills. Integrated mills mainly adopt the primary steel making method, which requires preparing raw materials (sintering and pelletizing) and fuel (coking), producing molten iron in a BF, and then making crude steel in a BOF. Secondary mills have a shorter process, which only requires purchasing scrap steel and other raw materials to produce crude steel in an EAF. Outputs, such as sponge iron or hot briquetted iron (HBI) from the DRI process, can also be used in the EAF process to make steel.

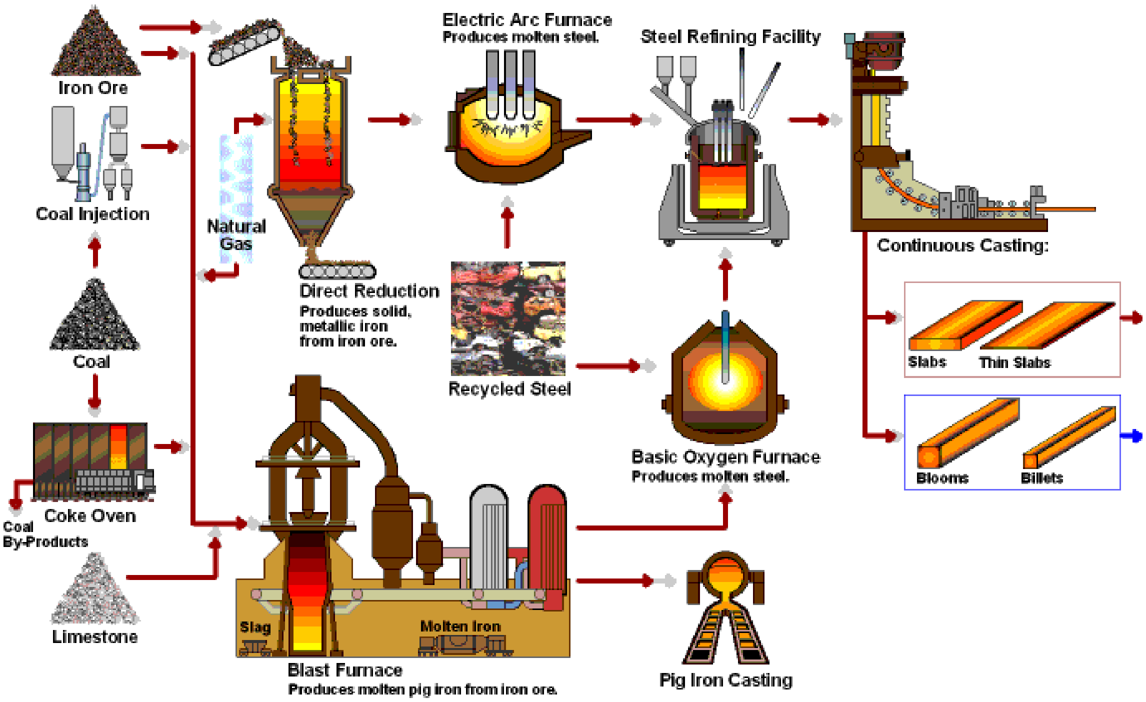

Figure 9. Iron and steel manufacturing processes

Source: AISI 2022.

The iron and steel manufacturing process involves multiple raw materials and processes, requires high temperature and chemical reactions, and has multiple sources of CO_2 emissions. A portfolio of strategies is required, ranging from material efficiency measures, energy efficiency technologies, using low or zero-carbon fuels, and implementing carbon capture and storage (CCS) (Table 2).

Table 2. Technologies and measures to decarbonize the iron and steel industry

Material Efficiency	Energy Efficiency	Fuel Switching	CCS
• Improved design and construction • Design for circular principles • Improved semi-manufacturing yields • Improved product manufacturing yields	• Improving thermal energy efficiency	• Increased use of EAF	• CCU technologies: carbon to methanol, carbon to chemical
• Extending product lifetime	• Improving electrical energy efficiency	• Onsite renewables	• Post-combustion CCS on BF
• Lightweight and higher strength materials • Alternative materials and construction	• Smart energy management	• Alternative reducing agent (hydrogen, biomass)	• CCS on DRI process
• Direct component reuse (without melting)	• Integrative design/system optimization	• Hydrogen DRI • Molten Oxide Electrolysis • Electrowinning aqueous • Electrowinning – molten salt	• CCS on smelting reduction process

Source: LBNL analysis.

In this analysis, we modeled the energy and CO_2 emissions impacts of each of these strategies in the iron and steel industry in Indonesia. The goal was to conduct a detailed bottom-up analysis of the technical potential and quantify the contributions of each of the decarbonization strategies under two different scenarios (Near Zero 2060 and Accelerated 2050).

3.1.3.1 Improving material efficiency

Material efficiency strategies, i.e., practices and technologies that deliver the same amount of services with fewer materials, can play an important role in reducing CO_2 emissions (Material Economics 2018; IEA 2019). Material efficiency strategies exist in every stage of the product, from product design to product use to and manufacturing to end-of-life.

Many material efficiency strategies are cost-effective and commercialized and can be implemented immediately. Material savings and emission reductions from these measures can be realized in the near term. Even so, savings from material efficiency measures are not often pursued due to lack of awareness, perceived risks, inertia of existing design, engineering, business practices, and challenges to intervene and coordinate among many stakeholders along the material/product supply chain.

It is important to model the saving potential of material efficiency strategies in our scenarios. For the iron and steel industry in Indonesia, we modeled eight material efficiency measures in all stages of a steel product:

1) improved design and improved construction, such as design optimization, use of prefabrication, post-tensioning techniques
2) improved semi-manufacturing yields, i.e., improving material efficiency in the process of turning crude steel into intermediate steel products (e.g., bars, coils, sheets)
3) improved product manufacturing yields, i.e., improving material efficiency in the process of turning intermediate steel products into final end-use products
4) extending building and vehicle lifetimes
5) the use of mass timber in low- to mid-rise buildings
6) the use of lightweight materials in vehicles
7) reduced use of vehicles through modal shifts, improvements in freight transport, reduced travel demand from urban form design, and increased teleworking
8) direct component reuse, without melting, i.e., reusing steel beams and other building/infrastructure components, reusing steel ship plates, and reusing pipelines

The modeled material efficiency measures and adoption rates are described for the Near Zero Scenario in Table 3 and for the Accelerated 2050 Scenario in Table 4. For each measure, we considered the maximum technical steel-saving potential, applicability of the technology (whether it is for all applications, or just for vehicles, buildings, or product steel, for example), and adoption rates[2] of the measure by a specific time frame under each scenario.

Our analysis showed that by implementing material efficiency measures at a moderate degree in the Near Zero Scenario, demand for steel – and hence steel production – could be reduced by 3% by 2030 and by 7% by 2060. This reflects a relatively conservative assumption that material efficiency strategies may face several implementation challenges, as mentioned earlier, especially in a growing economy with increasing demand for materials for construction, infrastructure, and buildings. In the Accelerated 2050 Scenario, our analysis showed that the suite of material efficiency measures could reduce domestic steel production by 4% by 2030, 12% by 2050 and 16% by 2060, leading to significant potential in terms of material and energy savings, as well as CO_2 emission reductions.

To achieve the untapped material efficiency potential, unprecedented efforts are needed to engage all stakeholders along the material and product supply chain to promote greater adoption of material efficiency measures. The Indonesian government can set up a regulatory framework and data collection system to set benchmarks and promote best practices (IEA 2019). Government agencies can provide incentives to award uptake of material efficiency and recycling. Life cycle assessment (LCA) can be required to assess product emissions, encompassing stages from design to end-of-life. Codes and standards can be shifted toward performance-based, rather than prescriptive-based ones. Awareness campaigns and training workshops can be developed to promote the practices of material efficiency.

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[2] Adoption rates of these measures are important assumptions. The assumptions were reviewed by our Indonesia research partners and reviewed at the iron and steel industry FGD, which was held in person in Jakarta, Indonesia, on June 21, 2023.

Table 3. Material efficiency measures and adoption rates in the Indonesian iron and steel industry: Near Zero 2060 Scenario

Phase	Measure	Savings Potential (%)	Saving	Applicability	References	2020 Level	Maximum Adoption Rates			
							2030 (%)	2040 (%)	2050 (%)	2060 (%)
Design	Improved design and construction	13	Steel	Buildings	Carruth, Allwood, and Moynihan 2011; Zhou et al. 2019	0	8	10	13	15
Production	Improving semi-manufacturing yields	7	Steel	All applications	Mission Possible Partnership 2021; Material Economics 2019	0	8	10	13	15
	Improving product manufacturing yields	13	Steel	Vehicles and product steel	Mission Possible Partnership 2021; Material Economics 2019	5	8	10	13	15
	Extending building and vehicle lifetime	30	Steel	All new buildings and vehicles	Hertwich et al. 2019	5	8	10	13	15
	Use of mass timber	40	Steel	Low to mid rises in new buildings	Dong et al. 2019; Guo et al. 2017	5	8	10	13	15
	Lightweight (vehicles)	11	Steel	Vehicles and product steel	Khanna et al. 2023	0	3	5	8	10
Use	Reduced use of vehicles	10	Steel	Vehicles	Khanna et al. 2023	0	3	5	8	10
Recycle	Direct component reuse (without melting)	15	Steel	Buildings and industrial steel use	Eberhardt, Birgisdóttir, and Birkved 2019	0	3	5	8	10

Table 4. Material efficiency measures and adoption rates in the Indonesian iron and steel industry: Accelerated 2050 Scenario

Phase	Measure	Savings Potential (%)	Saving	Applicability	References	2020 Level	Maximum Adoption Rates			
							2030 (%)	2040 (%)	2050 (%)	2060 (%)
Design	Improved design and construction	13	Steel	Buildings	Carruth, Allwood, and Moynihan 2011; Zhou et al. 2019	0	10	20	30	40
Production	Improving semi-manufacturing yields	7	Steel	All applications	Mission Possible Partnership 2021; Material Economics 2019	0	10	20	30	40
	Improving product manufacturing yields	13	Steel	Vehicles and product steel	Mission Possible Partnership 2021; Material Economics 2019	5	10	20	30	40
	Extending building and vehicle lifetime	30	Steel	All new buildings and vehicles	Hertwich et al. 2019	5	10	20	30	40
	Use of mass timber	40	Steel	Low-to-mid rises in new buildings	Dong et al. 2019; Guo et al. 2017	5	10	20	30	40
	Lightweight (vehicles)	11	Steel	Vehicles and product steel	Khanna et al. 2023	0	5	10	15	20
Use	Reduced use of vehicles	10	Steel	Vehicles	Khanna et al. 2023	0	5	10	15	20
Recycle	Direct component reuse (without melting)	15	Steel	Buildings and industrial steel use	Eberhardt, Birgisdóttir, and Birkved 2019	0	5	10	15	20

3.1.3.2 *Improving energy efficiency*

Steel production facilities in Indonesia are, on average, 18 years old, which is a relatively young production fleet, considering most steel facilities can last as long as 30 to 40 years, and much longer if proper relining and maintenance is performed. Indonesia is also adding new steel-producing capacities. As of 2019, 52% of the crude steel production capacity is fewer than 10 years old while 48% of the crude steel production capacity is 21 to 50 years old (Figure 10). At least 10 steel plants are active in the country.

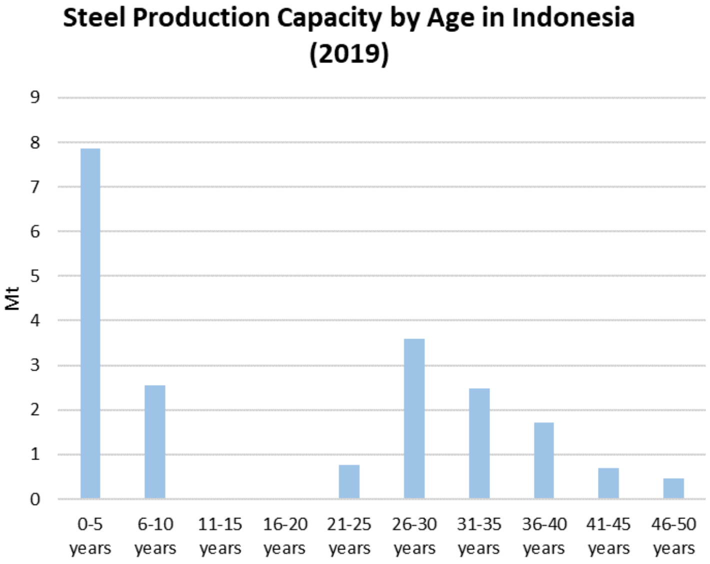

Figure 10. Steel production capacity by age in Indonesia

Source: Wang X. et al. 2019.

Table 5 shows our estimate of the energy intensity levels in the Indonesian iron and steel industry in 2020. It shows that on average the energy intensity for BF-BOF, scrap-based EAF, and DRI-EAF plants is: 20.4 gigajoule (GJ)/tonne (t) steel, 2.3 GJ/t steel, and 10.7 GJ/t steel, respectively. We estimated the steel rolling intensity was 2.1 GJ/t steel. The weighted average energy intensity for all crude steel production in 2020 was estimated to be 12.1 GJ/t steel.

Table 5. Energy intensity of iron and steel production in Indonesia (2020)

Process	**2020** (GJ/t steel)
Blast Furnace (BF)-Basic Oxygen Furnace (BOF)	20.4
Scrap-Electric Arc Furnace (EAF)	2.3
Direct Reduction of Iron - EAF	10.7
Steel Rolling	2.1
Weighted Average Energy Intensity	12.1

Source: LBNL analysis.

A number of commercialized and emerging technologies exist to improve energy efficiency in the iron and steel industry (Hasanbeigi, Lu, and Zhou 2023). Cost-effective, mature, energy-efficient technologies are available in all processes of the iron and steel industry, such as heat recovery measures and technologies, as well as smart energy management systems, using sensors, controls, modeling, and simulation (Worrell et al. 2010; IEA 2020a; He and Wang 2017).

When considering energy efficiency improvements in the framework of decarbonization and pursued together with net-zero goals, it is important to note that energy efficiency activities can deliver near term, cost-effective results, while also reducing the demand of low- or zero-carbon energy supplies (e.g., reducing the demand of renewable electricity). Even though the potential of decarbonization through energy efficiency improvement is limited in energy-intensive industries such as the iron and steel industry; while additional breakthrough technologies, fundamental process changes, or switching to zero-carbon fuels are necessary for the iron and steel industry to get to net-zero. It is important to recognize that energy efficiency measures can provide steady reductions in energy intensity over long periods of time.

In the Near Zero 2060 Scenario, we considered that the major steel production processes to improve their energy intensity to practical minimum energy intensity levels by 2060, reaching 12.3 GJ/t in BF-BOF, 1.3 GJ/t in scrap-based EAF, 9.8 GJ/t in DRI-EAF, and 1.8 GJ/t in steel rolling processes (US DOE 2015a), as illustrated in Figure 11. Energy efficiency improvement is driven by large-scale implementation of waste heat recovery and smart energy management systems in BF, BOF, EAF, and steel rolling processes. On average, energy intensity in the steelmaking processes improves by 1% per year, with the most significant improvement in the BF-BOF process (Figure 11).

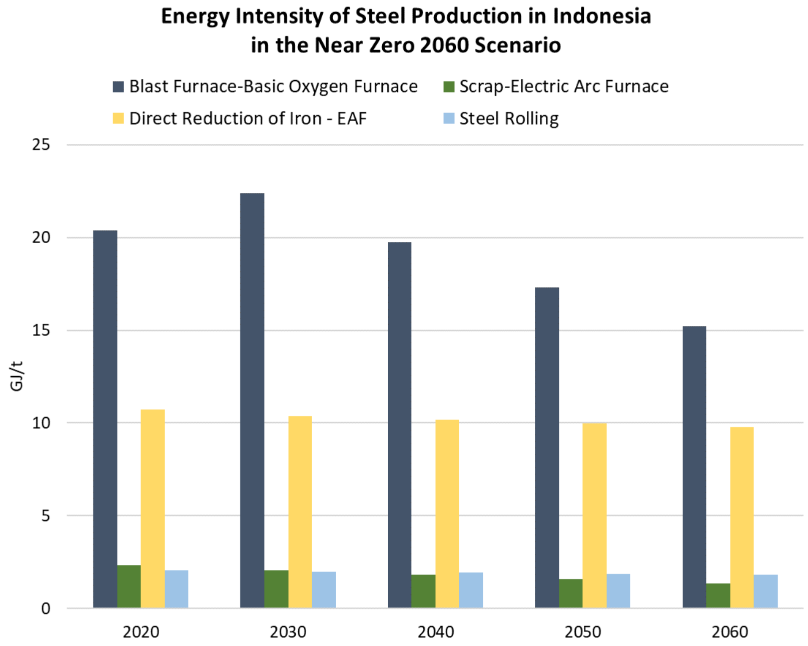

Figure 11. Energy intensity of steel production in Indonesia: Near Zero 2060 Scenario

Source: LBNL analysis.

The pace of energy intensity reduction is further accelerated in the Accelerated 2050 Scenario. Energy intensity levels in iron and steelmaking improve by 1.3% per year on average between 2020 and 2050, driven by improvements in the BF-BOF process. Iron and steel facilities achieve practical minimum energy intensity levels by 2050.

3.1.3.3 Switching to low- and zero-carbon fuels

Conventionally, ironmaking has relied significantly on fossil fuels such as coal, coke, and natural gas, due to the needs of higher reaction temperature, and the requirement of a feedstock to reduce iron oxide into molten iron. Ironmaking is the most energy and carbon intensive process in the iron and steelmaking process.

In recent years, several lower or zero-carbon fuels have been explored to replace the use of coal or coke in ironmaking, such as hydrogen injection in blast furnaces, use of biomass (charcoal), and solid wastes. For example, hydrogen injection in blast furnaces is being tested in Japan's COURSE 50, Super COURSE 50, and by Thyssenkrupp (thyssenkrupp 2021), Cleveland-Cliffs (Cleveland-Cliffs 2023), Tata Steel (Tata Steel 2023), Baowu Steel, and Shanxi Jinan Iron and Steel Group.

Current R&D shows that there are several challenges related to hydrogen injection, including the need to preheat hydrogen, less gas permeability in the blast furnace, and less contact with high-temperature heat, and therefore it may not fully replace coke use in blast furnaces (Yu, Hu, and Shen 2021). Research in this field indicates that a maximum of 30% replacement of fuels may be achieved by using hydrogen (Nippon Steel 2023). In this analysis, we assume that the hydrogen injected will be green hydrogen, which is produced via water electrolysis using renewable electricity.

Biomass injection into the blast furnace has also been tested. Studies showed that pulverized particles of charcoal from biomass can be injected through blast furnace tuyeres (Feliciano-Bruzual 2014) or through hydrothermal carbonization (K. Wang et al. 2022), and indicated that up to 15% of charcoal can be injected. Biomass resources are renewable, and if managed sustainably, are also carbon neutral. However, the use of biomass in the ironmaking process is also constrained by limited access to resources, the need to reduce the lignin and cellulose in biomass, and the need to reduce alkali metal elements in biomass.

In addition, the use of solid wastes (plastic wastes) have been explored as alternatives to coke (Worrell et al. 2010; Babich et al. 2016; Devasahayam, Bhaskar Raju, and Mustansar Hussain 2019). Studies suggest that up to 30% of coke could be replaced by solid wastes (Babich et al. 2016). Solid wastes have the advantages of lower sulfur and alkali contents, but the chlorine content in wastes may lead to dioxin formation, which requires efficient flue gas control (Worrell et al. 2010). It should also be emphasized that solid wastes (such as plastics) are not carbon neutral by any measure, and their usage and emissions should be measured, reported, and included in the emission reporting.

To achieve near zero emissions by 2060 in Indonesia, the iron and steel industry needs to significantly diversify and decarbonize its energy inputs in blast furnaces (Figure 12). In the Near Zero 2060 Scenario, the share of coal and coke declines from 80% of total fuel inputs to 20% by 2060, green hydrogen increasingly plays a more prominent role, with its share increasing to 8% by 2030 and 30% by 2060, and biomass and solid wastes will each represent 15% by 2060. The share of natural gas is expected to stay about the same in 2060 as it was in 2020 in this scenario.

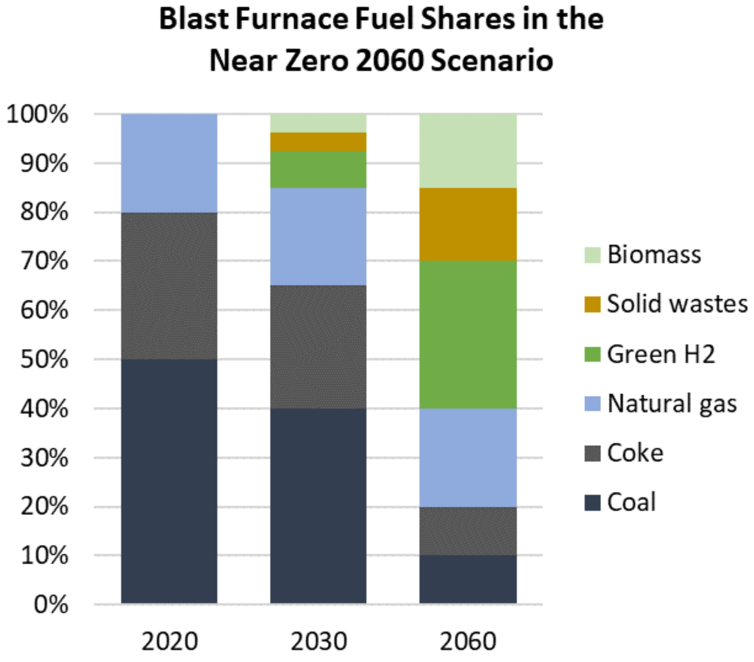

Figure 12. Fuel switching in blast furnace: Near Zero 2060 Scenario

Source: LBNL analysis.

In addition to the change of fuels in blast furnaces, use of low/zero fuels will increase significantly in the EAF and steel rolling processes, with an increased use of electricity and decreased share of natural gas or other fossil fuel consumption.

3.1.3.4 Low-carbon steelmaking technologies

The iron and steel industry, globally and in Indonesia, is expected to undergo transformative changes in order to be on track with the Paris Agreement goals and Indonesia's NDC goals. In addition to traditional BF-BOF and scrap-based EAF, innovative iron and steelmaking technologies are becoming more mature and emerging. These include DRI, SRI, MOE, aqueous solution-based electrowinning, and molten salt-based electrowinning. While electrolysis of iron ore (MOE-, aqueous-, or molten salt-based) are attractive alternatives to DRI, as they offer a potentially lower cost option and higher utilization of lower grade iron ores, these technologies are still in the emerging and developmental stages, with small-scale pilots. Given the limited information on the feasibility and scalability of these technologies, it is challenging to assess the technology adoption of these technologies in Indonesia's iron and steel industry.

Scrap-based EAF production is a mature steelmaking technology. Based on data updated through March 2023, EAFs accounted for 36% of the total existing steel production capacity in Indonesia.

However, the share of EAFs declines significantly to 11% if including announced and under-construction steelmaking projects, most of which are BF-BOF (Global Energy Monitor 2023). In terms of total production, about 45% of the steel produced in Indonesia in 2020 was from scrap-EAF while BF-BOF and DRI-EAF accounted for 38% and 17% in 2020, respectively.

Scrap-EAF production requires only one-sixth of the energy inputs and emits one-fourth of the CO_2 emissions, when compared to unabated BF-BOF process (US EIA 2014). In the Near Zero 2060 Scenario, it is expected that the production share of scrap-based EAF will increase from 45% in 2020 to 70% by 2060 (Figure 13). Unabated BF-BOF will be phased out by 2060, while natural-gas-based DRI and green hydrogen-based DRI will contribute 10% and 20% of the total crude steel production, respectively, by 2060.

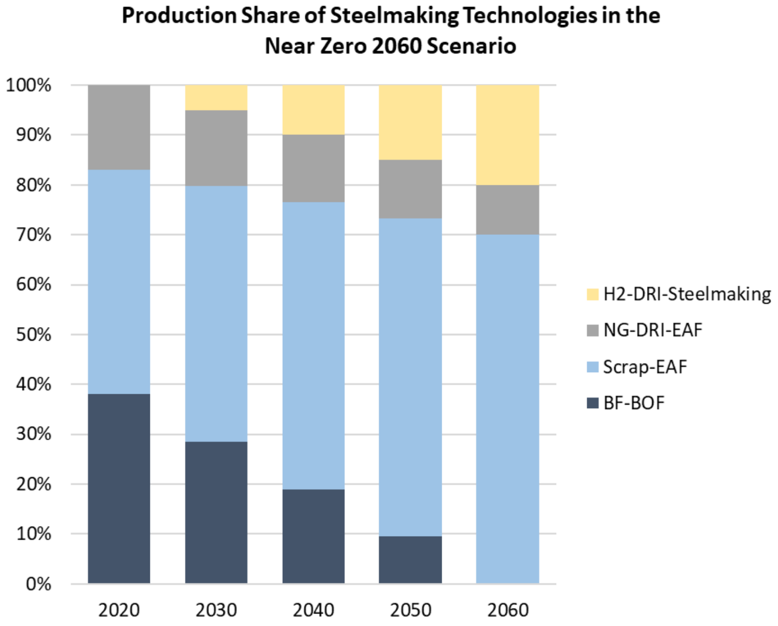

Figure 13. Production shares of steelmaking technologies in Indonesia in the Near Zero 2060 Scenario

Source: LBNL analysis.

Specific material demand for EAFs varies depending on the type of equipment as well as the type and quality of the charging materials. Remus et al. (2013) reported on average 1,039–1,232 kg of scrap and 0–53 kg of pig iron is required to produce one metric ton of steel in EAF based on the EU experience (Remus et al. 2013). To estimate the potential amount of scrap that may be needed to support the transition to scrap-based EAF in Indonesia, we assumed that scrap-based EAF production will rely on 100% scrap. However, we do recognize that in practice DRI and/or hot briquetted iron (HBI) from the green H_2-DRI process can also be mixed together with scrap to produce steel in EAF facilities. Based on the total production forecast ("steady demand" scenario), the share of scrap-EAF, and scrap intensity in EAFs, we estimated that the total scrap required will be approximately 11 Mt by 2030 and increase to 23 Mt by 2060 (Figure 14).

While the increase in scrap demand for Indonesia is not small, we expect the additional scrap need (12 Mt by 2060) can be met by regional scrap resources, driven by peak steel demand and increased scrap availability in China. A global steel study showed that by 2050, a total of 100 Mt of scrap is expected to be available in Southeast Asia, with more than 600 Mt of scrap is available from China alone (Mission Possible Partnership 2022a).

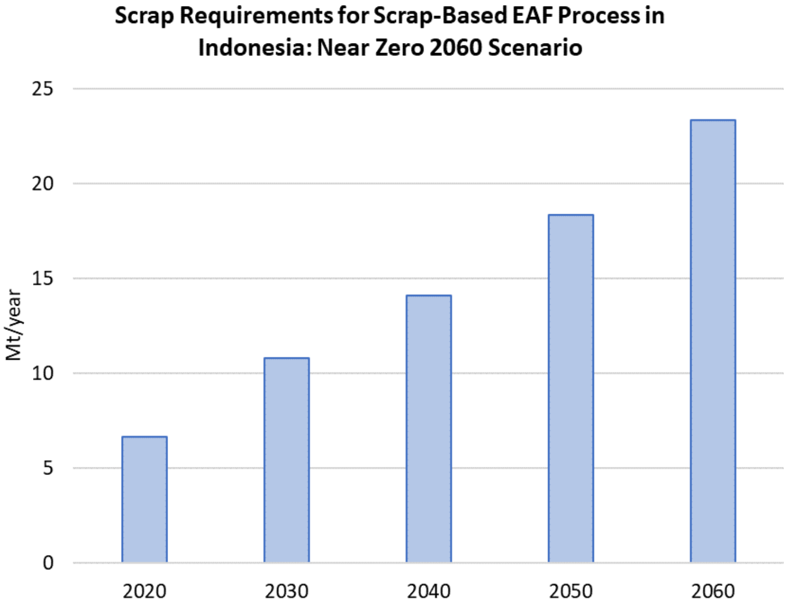

Figure 14. Scrap demand for Indonesia: Near Zero 2060 Scenario

Source: LBNL analysis.

This analysis considered both the natural gas- and green hydrogen-based DRI-EAF steelmaking processes. Natural gas-based DRI technology has been commercialized and has been implemented in facilities. Green hydrogen-based technology has been piloted at the industrial scale. A list of green hydrogen projects (updated through April 2023) in steel companies around the world is presented in Appendix B. The projects include both green hydrogen production and green hydrogen-based DRI.

For the Near Zero 2060 Scenario, we estimated that Indonesia's iron and steel industry will require 47,000 tonnes of green hydrogen by 2030 and that would increase to 300,000 tonnes by 2060 (Figure 15, left). Renewable or other zero-carbon (e.g., hydro power, geothermal) electricity generation is critical. Indonesia's iron and steel industry would require 2.4 terawatt-hours (TWh) of zero-carbon power generation by 2030 and 15 TWh by 2060 (Figure 15, right). In comparison, Indonesia produced a total of 65 TWh zero-carbon electricity in 2022 (Ritchie, Roser, and Rosado 2022). While the demand for zero-carbon electricity from Indonesia's iron and steel industry will be significant, the increased demand may be achievable by 2060.

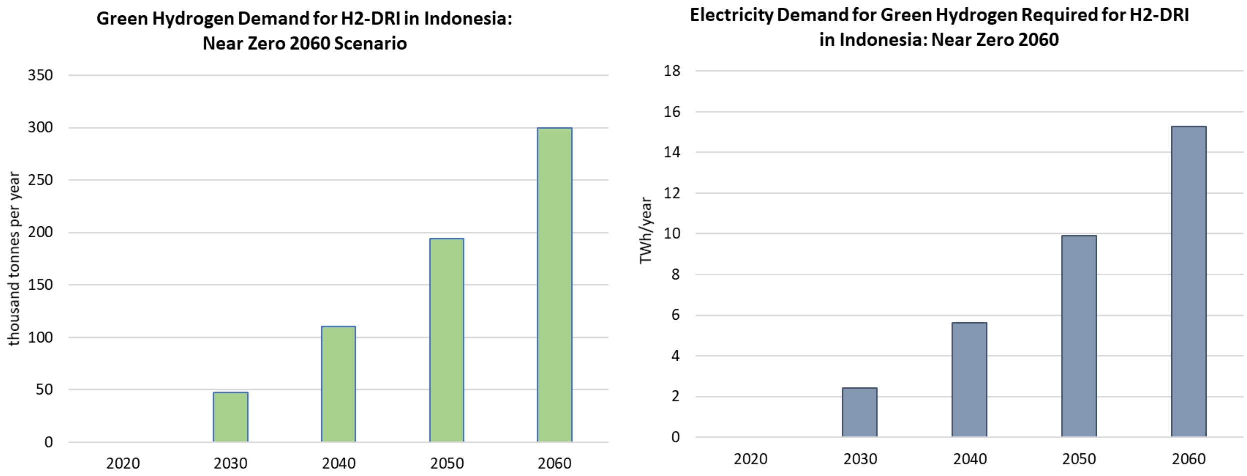

Figure 15. Green hydrogen (left) and associated zero-carbon electricity demand (right) for the iron and steel industry in Indonesia: Near Zero 2060 Scenario

Source: LBNL analysis.

At the global level, studies show that low-carbon and innovative steelmaking technologies currently have a cost premium. As shown in Figure 16, IEA data indicated that the 2020 levelized cost of green hydrogen-based DRI-EAF technology was 39%–89% more expensive than a conventional BF-BOF process. Natural gas-based DRI-EAF was 11%–29% more expensive at the global level. However, the cost difference between BF-BOF and H_2-DRI technologies is expected to decline (IEA 2023a).

Specific cost analysis of the Indonesian iron and steel industry is needed to understand the cost differences and uncertainties across iron and steel production technologies. In addition to cost sensitivity to energy prices, other barriers should also be considered in the iron and steel technology transition, such as technology manufacturing and engineering capacity (e.g., DRI technologies), access to raw materials (e.g., iron ore and higher quality scrap), and feedstocks (e.g., green hydrogen), as well as engineering knowledge and capacity.

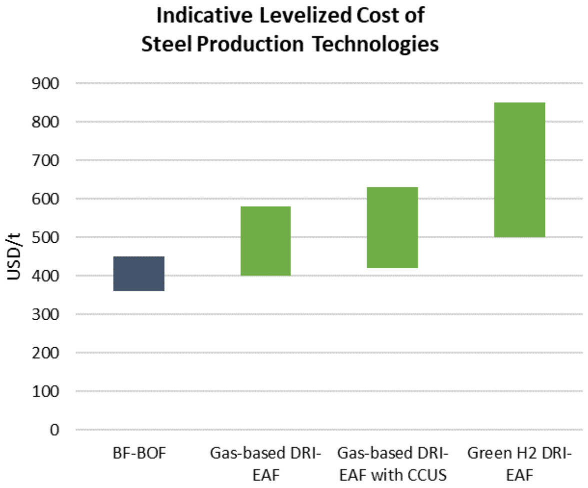

Figure 16. Indicative levelized cost of steel production technologies

Source: IEA 2020a.

3.1.3.5 CCS considerations for the iron and steel industry

As the Indonesian iron and steel industry transitions from a carbon-intensive BF-BOF process to low-carbon scrap-EAF and H_2-DRI processes that rely on electricity and non-carbon feedstocks, respectively, direct fossil-fuel related CO_2 emissions will be reduced significantly. As a result, it is possible that the role for CCS is quite limited.

This analysis considered the adoption of CCS systems on BF and natural gas-based DRI processes. Currently, blast furnaces are responsible for 60%–70% of total CO_2 emissions in the primary steelmaking (BF-BOF) processes. Blast furnaces are targeted also due to relatively higher CO_2 concentrations (20%–25%) in the flue gases.

In the Near Zero 2060 Scenario, we considered 4% CCS adoption by 2030 and 15% by 2060. The adoption rate of CCS is increased to 8% by 2030 and 25% by 2050 under the Accelerated 2050 Scenario. In addition, the analysis also considered the energy impacts of CCS systems.

3.1.4 Decarbonization pathways

3.1.4.1 Near Zero 2060 Scenario

Our analysis found that it is technically possible to reduce CO_2 emissions of Indonesian iron and steel industry to near zero by 2060, while still increasing total crude steel production to about 30 Mt by 2060. The iron and steel industry provides not only foundational material for urbanization and improved living standards in the country, but also supports the development of new industries (e.g., renewables, power sector expansion, batteries, and electric vehicles) that are critical to the energy transition.

In the Near Zero 2060 Scenario, total CO_2 emissions from the iron and steel industry will decline from 16 $MtCO_2$ in 2020 to 2 $MtCO_2$ by 2060. The analysis showed that low-carbon iron and steelmaking technologies such as the scrap-based EAF and H_2-DRI-EAF routes, as well as a rapid decarbonization of the power sector, are the most critical, mitigating a total of 16 $MtCO_2$ of emissions by 2060, as shown in Figure 17. Energy efficiency improvements have the potential to reduce emissions by 2 $MtCO_2$, while material efficiency and fuel switching each account for 1 $MtCO_2$ emission mitigation potential. The use of CCS in the iron and steel industry contributes about 3 $MtCO_2$ emissions by 2060.

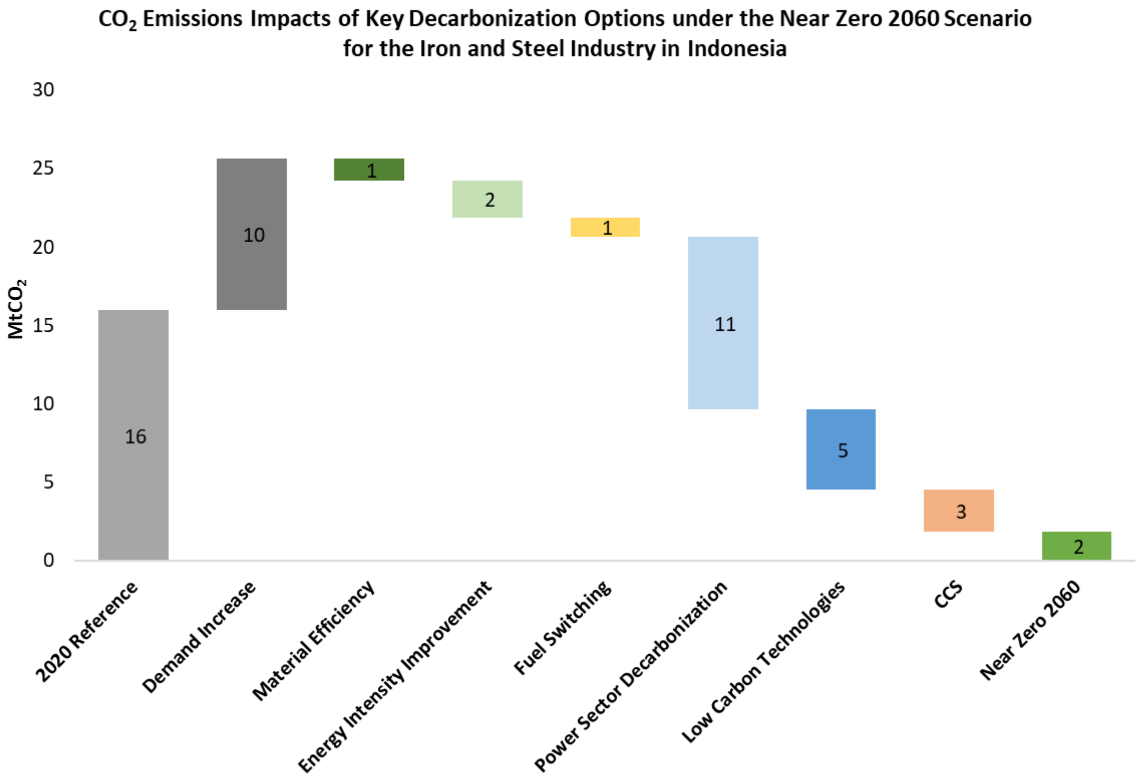

Figure 17. CO_2 emissions impacts of key decarbonization options for the iron and steel industry in Indonesia: Near Zero 2060 Scenario

Source: LBNL analysis.

In the near term by 2030, the results show that a diversified approach is required to reduce CO_2 emissions in the iron and steel sector (Figure 18, left). The use of scrap-EAF production process needs to be accelerated, while building or restarting traditional BF-BOF production capacity should be discouraged. Energy efficiency and fuel switching in all iron and steelmaking processes should be strengthened. Material efficiency strategies from product design, manufacturing, use, and end-of-life can deliver tangible results.

In the mid to long term, from 2030 to 2060, low-carbon technologies (scrap-EAF and DRI-EAF) supported by a decarbonized power sector are responsible for a total of 61% of total CO_2 emissions reduction (Figure 18, right). Collectively, improving material and energy efficiency could result in an approximately 20% emission reduction. Fuel switching and CCS technologies play a less important role.

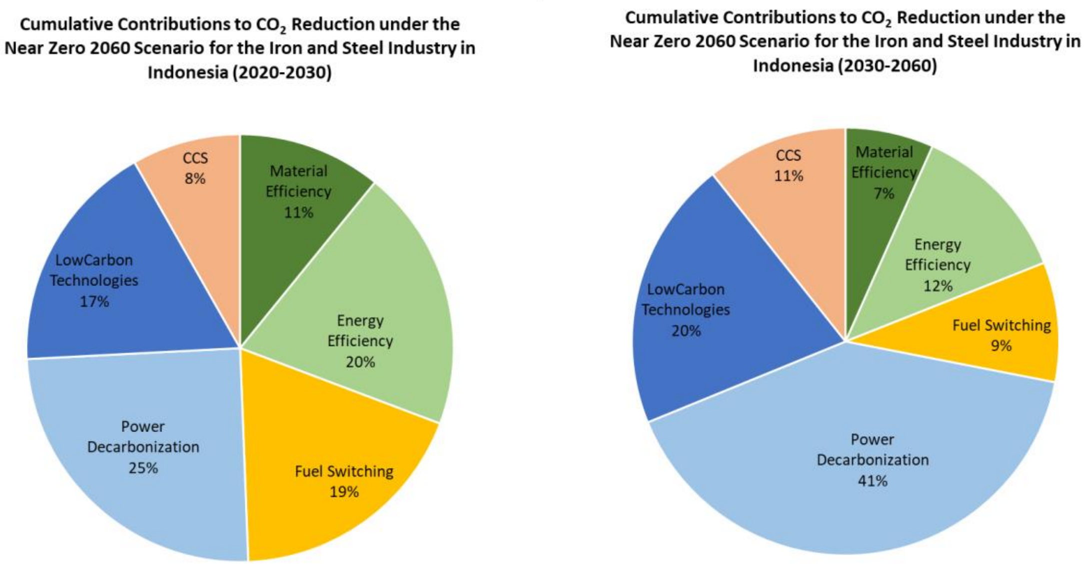

Figure 18. Cumulative contributions of key strategies of iron and steel sector decarbonization: Near Zero 2060 Scenario, 2020-2030 and 2030-2060

Source: LBNL analysis.

3.1.4.2 Accelerated 2050 Scenario

The Accelerated 2050 Scenario showed that the Indonesian iron and steel industry can reduce its CO_2 emissions to almost zero by 2050 (Figure 19). This scenario highlighted the roles of low-carbon iron and steelmaking technologies, as well as the potential of material efficiency and fuel switching (e.g., use of biomass, hydrogen, and other alternative fuels).

From 2020 to 2050, low-carbon technologies and power sector decarbonization are responsible for 45% of the total emission reductions (10 $MtCO_2$), collectively. Material efficiency, fuel switching, and energy efficiency represent 15% (3 $MtCO_2$), 13% (3 $MtCO_2$), and 12% (2 $MtCO_2$) of the total CO_2 reductions. The scale of CO_2 reduction through CCS is the same as in the Near Zero 2060 Scenario. Power sector decarbonization has a smaller contribution in the Accelerated 2050 Scenario, due to the assumption that power generation will not be fully decarbonized by 2060 (the same assumption used for the Near Zero 2060 Scenario).

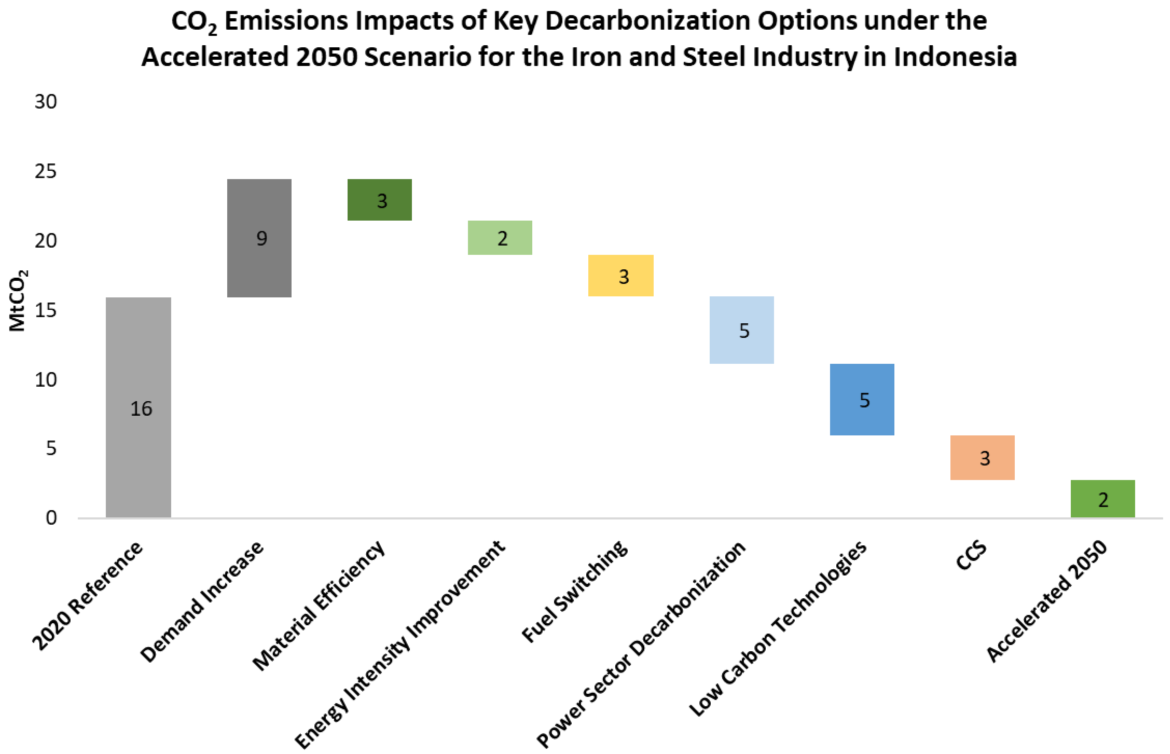

Figure 19. CO$_2$ emissions impacts of key decarbonization options for the iron and steel industry in Indonesia: Accelerated 2050 Scenario

Source: LBNL analysis.

3.2 Cement industry

3.2.1 Historical production and consumption

Cement and concrete are foundational materials that are essential for our society. They are used extensively for construction, buildings, roads, pavements, bridges, airports, and other infrastructure systems. Globally, cement production is one of the most energy and carbon-intensive sectors. Cement production alone accounted for 7% of global CO_2 emissions (GCCA 2021), which is about 3.5 gigatonnes (Gt) of CO_2 emissions per year.

Indonesia is the seventh largest cement-producing country in the world, accounting for about 2% of global cement production in 2022 (USGS 2023a). Domestic cement production in Indonesia has grown from 39 Mt in 2010 to 65 Mt in 2023, increasing on average 4% per year, as shown in Figure 20. The Indonesia Cement Association (ASI) estimated that cement industry energy and process-related CO_2 emissions accounted for 5.2% of Indonesia's total CO_2 emissions (excluding emissions from Forestry and Other Land Use [FOLU]).

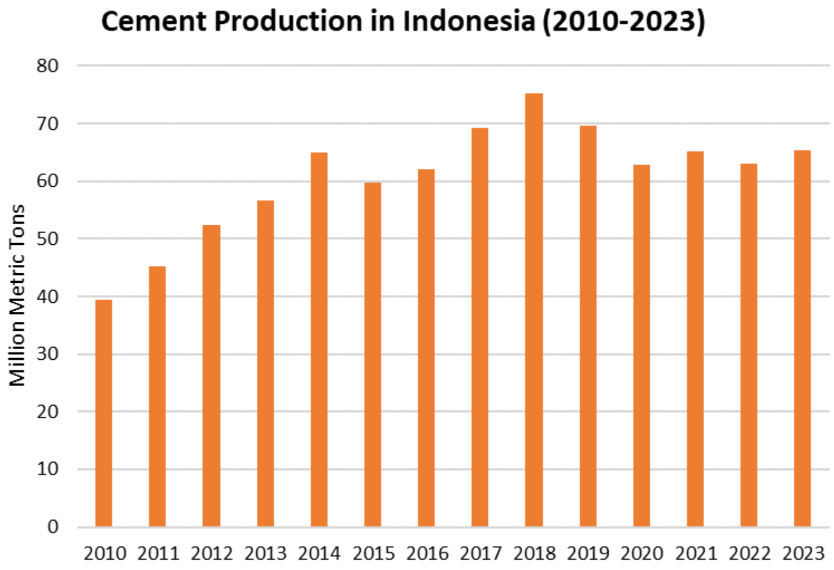

Figure 20. Cement production in Indonesia (2010–2023)

Source: USGS, various years.

Indonesia's cement sector is dominated by two cement-producing companies: Semen Indonesia (SIG) and Indocement. Combined, these two companies accounted for about 70%–75% of total cement production in Indonesia (Subiyanto 2020). Other smaller companies produce about 25%–30% of Indonesia's total cement production. A breakdown of cement production by companies in Indonesia as of 2021 is shown in Figure 21.

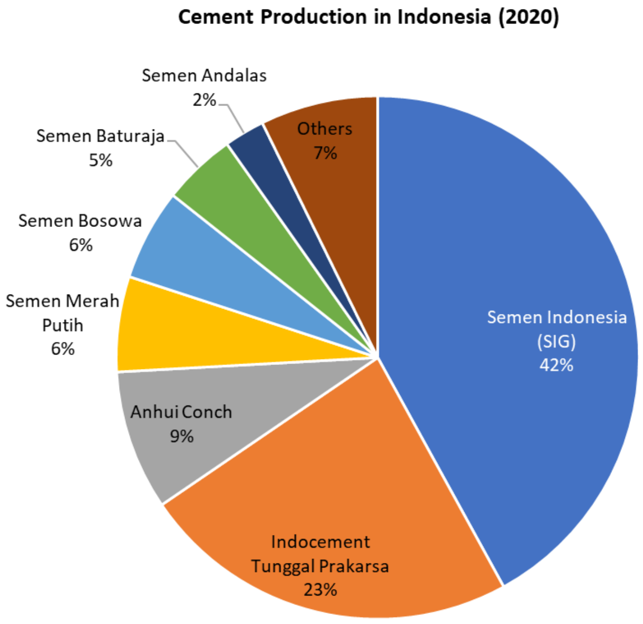

Figure 21. Cement production by companies in Indonesia (2020)
Source: Subiyanto, 2020; and Indonesia Cement Association (ASI).

It is interesting to note that Indonesian cement production capacity is significantly higher than the total production, indicating a relatively low utilization rate. From 2016 to 2019, the overall cement production utilization rate has been about 65%. In 2021, the utilization rate further declined to 54%, potentially due to the impact of COVID-19.

3.2.2 Production forecast

Multiple methods of production forecasting exist, such as relying on historical growth rates, announced and planned production capacity expansion, and economic growth rates as a proxy for physical demand. For this analysis, we used the bottom-up approach to analyze the demand for cement by end-use application. This approach considers Indonesia's population growth, urbanization rate, and current infrastructure development.

It is expected that the total population in Indonesia will continue to grow, increasing from 271 million in 2020 to 291 million by 2030 and 319 million by 2060 (Figure 22), based on the United Nations Population Division's medium scenario projection (UN 2022). In the 2060s, Indonesia's total population begins to plateau and slowly declines to a little less than 300 million by 2100.

Figure 22. Indonesia population: historical and projections (1970–2100)
Source: UN 2022.

The urbanization rate in Indonesia has increased significantly over the years. The percentage of the urban population has grown from 15% in 1960 to 57% by 2021 (Figure 23). Compared to other nearby Asian countries, Indonesia's urbanization rate is average; slightly higher than urbanization rates in Thailand (50%) and Philippines (48%), which have similar GDP per capita levels[3] to the Indonesians. It is expected that Indonesia will reach an urbanization rate of 70% by 2045 (Roberts, Sander, and Tiwari 2019).

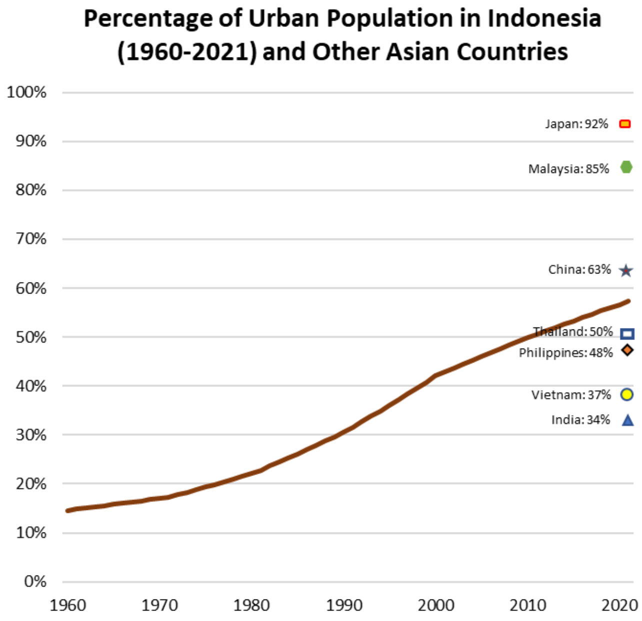

Figure 23. Urbanization rate in Indonesia and other selected Asian countries
Source: World Bank 2023a.

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[3] 2022 GDP per income levels (current USD): Indonesia: $4,788 USD/capita; Philippines: $3,499 USD/capita; Vietnam: $4,164 USD/capita; Thailand: $6,908 USD/capita. Source: World Bank, 2023.

Compared to other nearby Asian countries or countries with similar income levels, we found that Indonesia is still in the early stages of infrastructure and urban development. For example, railway length per million people in Indonesia for 2017 was less than 7 kilometers (km)/million people, which is only 30% of the level in Vietnam (Figure 24, left). Main road lengths per million people in Indonesia for 2015 was estimated to be 110 km/million people, only one-sixth of the level in Thailand (Figure 24, right).

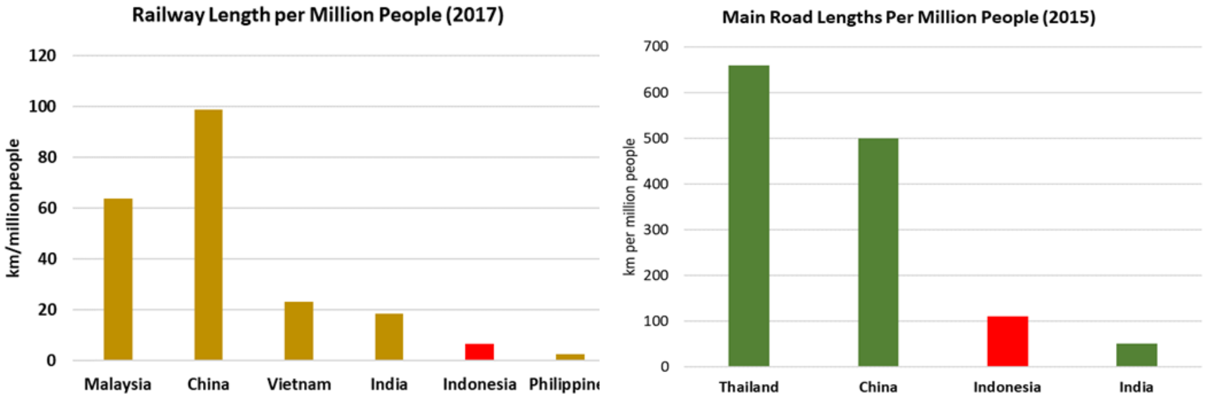

Figure 24. Average railway lengths and road lengths per million people in Indonesia and selected Asian countries

Source: Roberts, Sander, and Tiwari 2019.

Most of Indonesia's cement demand is driven by construction of buildings and infrastructure systems, such as roads, highways, and railways. By 2060, we expect that Indonesia's cement production will increase to 105 Mt in the Reference Scenario. This is an increase of 59% from today's level. In the Near Zero 2060 Scenario, cement production in Indonesia grows, but due to large-scale adoption of material efficiency strategies to reduce cement demand (see details in Section 4.2.3.2 on improving material efficiency), total cement production increases to 89 Mt by 2060. The Accelerated 2050 Scenario adopts material efficiency even more aggresively, and cement production in Indonesia increases to 82 Mt by 2050 (83 Mt by 206), as shown in Figure 25.

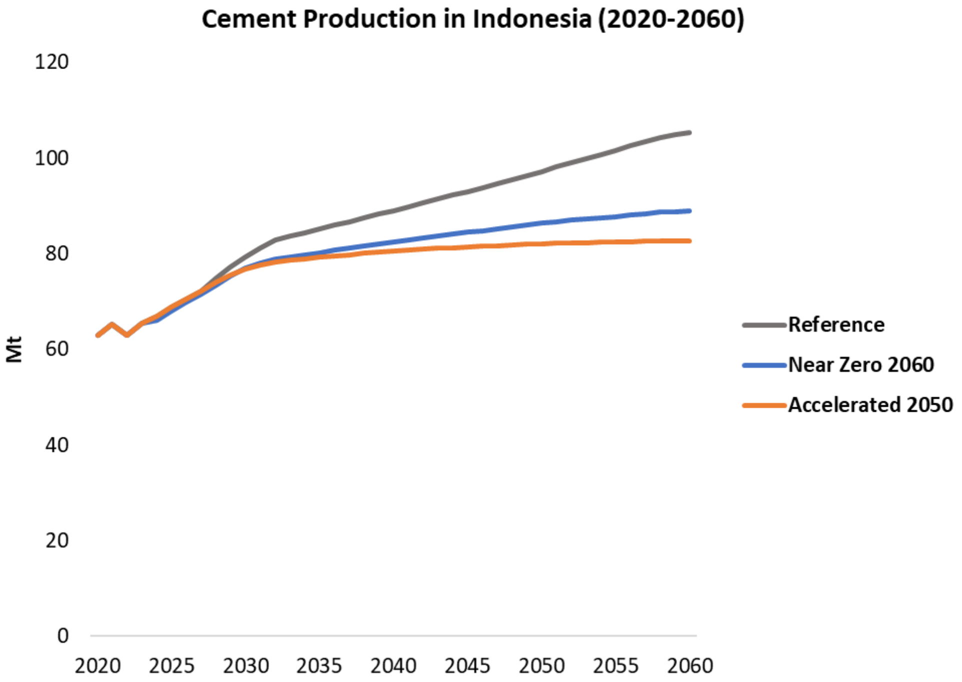

Figure 25. Cement production forecast in Indonesia under three scenarios (2022–2060)

Source: LBNL analysis.

3.2.3 Decarbonization strategies and technologies

The sections below discuss the cement manufacturing production process, challenges to decarbonize the cement industry, and the key strategies to achieve net-zero emissions in the cement industry in Indonesia.

3.2.3.1 Cement manufacturing processes

Cement is a non-metallic substance with hydraulic binding properties. It is a fine power and can be mixed with water to form a paste, which hardens due to formation of cement mineral hydrates (Worrell, Kermeli, and Galitsky 2013). Mixing cement with mineral aggregates and water forms concrete, which is a key and common building material.

Cement is extensively used in buildings, the transportation sector, industry, and energy supply systems. In addition, cement is used to build industrial facilities, power plants, distribution for power, heat, gas, and water, as well as other urban and rural infrastructure. In Indonesia, the majority of the cement is used in buildings and infrastructure systems.

The process of cement manufacturing dates back to the Romans or even earlier. However, the modern cement manufacturing process started in the early nineteenth century when an established process was developed. This manufacturing process involves quarrying and crushing of calcareous rocks (usually limestone), grinding the calcareous material with other raw materials—such as shale, clay, slate, blast furnace slag, silica sand, and iron ore—and heating the raw materials at controlled high temperatures in a kiln to produce clinker. After being discharged from the kiln, clinker (usually gray and in the size of marbles) is then cooled by ambient air. In the final stage of the process, cooled clinker is grounded and mixed with gypsum and limestone in cement grinding facilities. The general manufacturing process flow is depicted in Figure 26.

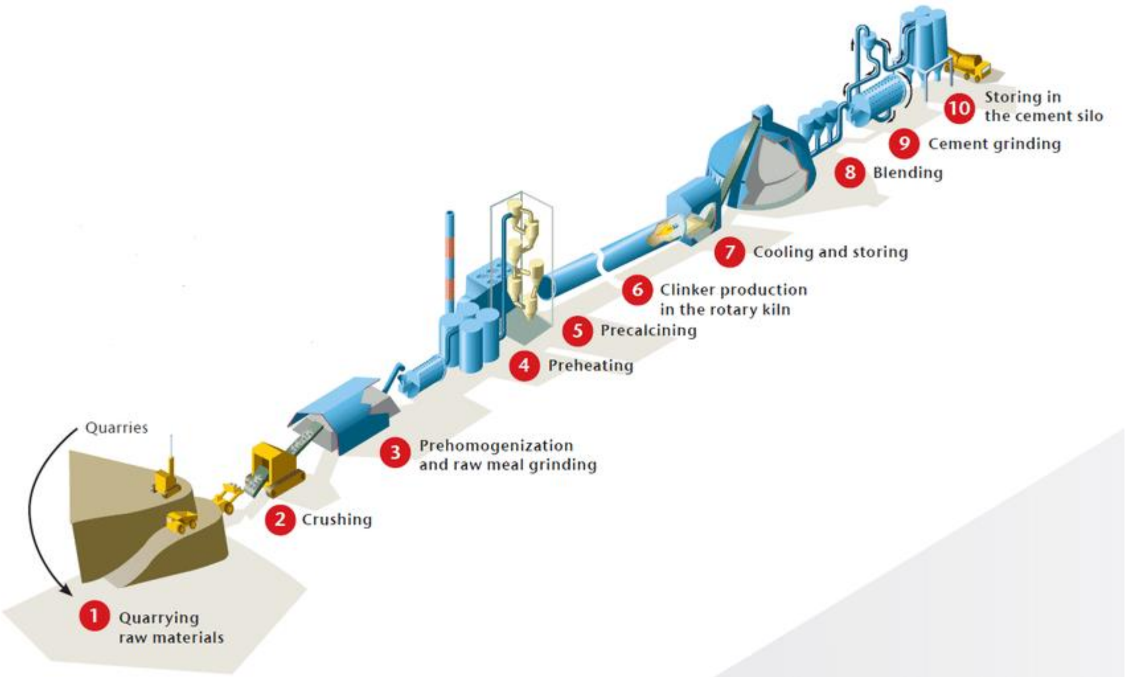

Figure 26. Cement manufacturing process

Source: IEA 2009.

The cement industry is one of the key energy-consuming and carbon-intensive manufacturing sectors in Indonesia. Due to the high process temperature for calcination (1,450°C), almost all the cement facilities require fossil fuels (with a few relying on wastes as fuels completely). The industry in Indonesia currently relies significantly on coal as the main fuel, accounting more than 90% of total thermal energy use. In addition, "process emissions," i.e., the emissions associated with the raw materials and chemical reactions in the process, are quite high in conventional cement manufacturing, accounting for about 50%–60% of total CO_2 emissions.

Energy and process-related CO_2 emission from the cement industry accounted for 5.2% of total CO_2 emissions in Indonesia, excluding emissions from FOLU, as reported by the Indonesian Cement Association (Raharjo 2023). To achieve Indonesia's Enhanced NDC targets, it is critical to identify the technologies and pathways to decarbonize the cement industry. Given the challenges to decarbonize the industry, Indonesia needs a portfolio approach that combines decarbonization measures from both the supply (production) side and the demand (consumption) side of the industry. The measures include improving material efficiency, improving energy efficiency, increasing the use of SCM and adopting alternative cement products, switching to low or zero-carbon fuels, and implementing carbon capture, utilization, and storage (CCUS) systems (Table 6).

Table 6. Technologies and measures to decarbonize the cement industry

Material Efficiency	Energy Efficiency	Clinker Substitution and Alternative Cement	Fuel Switching	CCUS
• Improved building design • Optimizing cement content in concrete	• Improving thermal energy efficiency	• Use of SCM: coal fly ash, BF slag	• Alternative fuels: industrial wastes, municipal solid wastes, agricultural byproducts	• Post-combustion CO_2 capturing technologies
• Increased use of precast components and post-tensioning of floor slabs • Extending product lifetime	• Improving electrical energy efficiency	• Use of SCM: calcined clay, end-of-life binder	• Onsite renewables	• Oxyfuel combustion CO_2 capturing or calcium looping
• Alternative materials (e.g., mass timber) • Additive manufacturing	• Smart energy management	• Use of SCM: other by products (e.g., silica fume, bauxite residue, agricultural byproduct ashes)	• Hydrogen blending	• Integrated calcium looping with the calcination process
• Recycling construction wastes • Recycling concrete into recycled concrete aggregates	• Integrative design/system optimization	• Alternative cement chemistry	• Concentrated solar	• CO_2 mineralization (CO_2 mixing and curing)

Source: LBNL analysis.

Notes: SCM = supplemental cementitious materials; CCUS = carbon capture, utilization, and storage.

In this analysis, we modeled the energy and CO_2 impacts of each of these strategies in the cement industry in Indonesia. The goal was to conduct a detailed bottom-up analysis on the technical potential and quantify the contributions of each of the decarbonization strategies under two different scenarios (Near Zero 2060 and Accelerated 2050).

3.2.3.2 Improving material efficiency

Conventionally, many technological and policy efforts have been focused on improvements in the production of cement in order to conserve energy, reduce air pollution, and mitigate CO_2 emissions. These efforts have achieved significant results. Today, more and more emerging economies, such as

Indonesia, have some of the latest and mature cement production technologies. Practices to improve energy efficiency has been developed and spread to engineers, plant managers, and technicians.

As the cement industry transitions to achieve net-zero emissions, however, it is critical to shift the traditional mindset from only focusing on the supply-side to emission reduction through the product value-chain. This means expanding from technologies used to reduce CO_2 emissions in clinker production or reducing clinker content in cement to material efficiency technologies and measures (see Section 3.1.3.1 for an introduction on material efficiency).

For the cement industry in Indonesia, we modeled eight material efficiency measures in the design, production, use, and end-of-life stages of a cement product:

1) Improved building design through design optimization
2) Optimizing cement content in concrete
3) Increased use of precast components and post-tensioning of floor slabs
4) Extending building lifetime
5) Use of mass timber
6) Additive manufacturing
7) Reducing construction wastes
8) Recycling concrete into recycled concrete aggregates

The modeled material efficiency measures and adoption rates are described for the Near Zero Scenario in Table 7 and for the Accelerated 2050 Scenario in Table 8. For each measure we considered the maximum technical cement-saving potential, applicability of the technology, and adoption rates of the measure by a specific time frame under each scenario, as shown in Table 7 and Table 8. The assumptions of adoption rates were shared and presented to the cement industry FGD, which was held in person in Jakarta, Indonesia, on June 20, 2023.

Table 7. Material efficiency measures and adoption rates in the Indonesian cement industry: Near Zero 2060 Scenario

Phase	Measure	Savings Potential (%)	Saving	Applicability	References	2020 Level	Maximum Feasible Penetration			
							2030 (%)	2040 (%)	2050 (%)	2060 (%)
Design	Improved building design	10	cement	New buildings + industrial construction	Cao et al. 2021; Shanks et al. 2019	0	10	20	35	50
Production	Optimizing cement content in concrete	8	cement	All applications	Shanks et al. 2019; Eberhardt, Birgisdóttir, and Birkved 2019	0	10	20	35	50
Use	Increased use of precast components and post-tensioning of floor slabs	10	cement	Low- to mid-rises in new buildings in urban residential and commercial (85% of new buildings)	Shanks et al. 2019	5	15	25	35	50
	Extending building lifetime	25	cement	All new buildings	Sandberg et al. 2016; Aktas and Bilec 2012; Monteiro, Miller, and Horvath 2017	5	15	25	35	50
	Use of mass timber	40	cement	Low- to mid-rises in new buildings	Dong et al. 2019; Guo et al. 2017	0	1	3	5	10
	Additive manufacturing	15	cement	New residential single family homes (rural residential)	Habert et al. 2020	0	3	5	8	10
Recycle	Reducing construction wastes	2	cement	All applications (excluding buildings)	Cao et al. 2021; Huang et al. 2013	0	5	7	12	15
	Recycle concrete into recycled concrete aggregates	2	cement	Roads and urban paved area	Cao et al. 2021; Di Maria, Eyckmans, and Van Acker 2018	0	5	7	12	15

Table 8. Material efficiency measures and adoption rates in the Indonesian cement industry: Accelerated 2050 Scenario

Phase	Measure	Savings Potential (%)	Saving	Applicability	References	2020 Level	Maximum Feasible Penetration			
							2030 (%)	2040 (%)	2050 (%)	2060 (%)
Design	Improved building design	10	cement	New buildings + industrial construction	Cao et al. 2021; Shanks et al. 2019	0	15	25	45	60
Production	Optimizing cement content in concrete	8	cement	All applications	Shanks et al. 2019; Eberhardt, Birgisdóttir, and Birkved 2019	0	10	25	45	60
Use	Increased use of precast components and post-tensioning of floor slabs	10	cement	Low- to mid-rises in new buildings in urban res. and commercial (85% of new buildings)	Shanks et al. 2019	5	15	30	50	70
	Extending building lifetime	25	cement	All new buildings	Sandberg et al. 2016; Aktas and Bilec 2012; Monteiro, Miller, and Horvath 2017	5	15	30	50	70
	Use of mass timber	40	cement	Low- to mid-rises in new buildings	Dong et al. 2019; Guo et al. 2017	0	3	8	15	25
	Additive manufacturing	15	cement	New residential single family homes (rural residential)	Habert et al. 2020	0	5	10	15	20
Recycle	Reducing construction wastes	2	cement	All applications (excluding buildings)	Cao et al. 2021; Huang et al. 2013	0	5	10	15	20
	Recycle concrete into recycled concrete aggregates	2	cement	Roads and urban paved area	Cao et al. 2021; Di Maria, Eyckmans, and Van Acker 2018	0	5	10	15	20

By adopting material efficiency strategies through the value chain of cement products, cement demand could be reduced by 4% by 2030 and by 16% by 2060 in the Near Zero 2060 Scenario. Our assumptions are moderate, but not overly ambitious, as adopting these measures at a large scale could face many challenges, such as lack of awareness and lack of capacity, but most importantly, coordination among all the key stakeholders along the supply chain.

In the Accelerated 2050 Scenario, material efficiency strategies, especially in the design, production, and use phase are amplified with urgency. The results show cement demand could be reduced by 5% by 2030 and 16% by 2050.

3.2.3.3 Improving energy efficiency

The level of energy efficiency in a cement plant is driven by multiple factors, such as the age the of facility, adoption of technologies, utilization rate of the capacity, and energy management practices of the facility. Cement plants in Indonesia are relatively new, with an average age of 17 (weighted average by production capacity). Among them, about 42% of the production capacity is less than 10 years old (Figure 27).

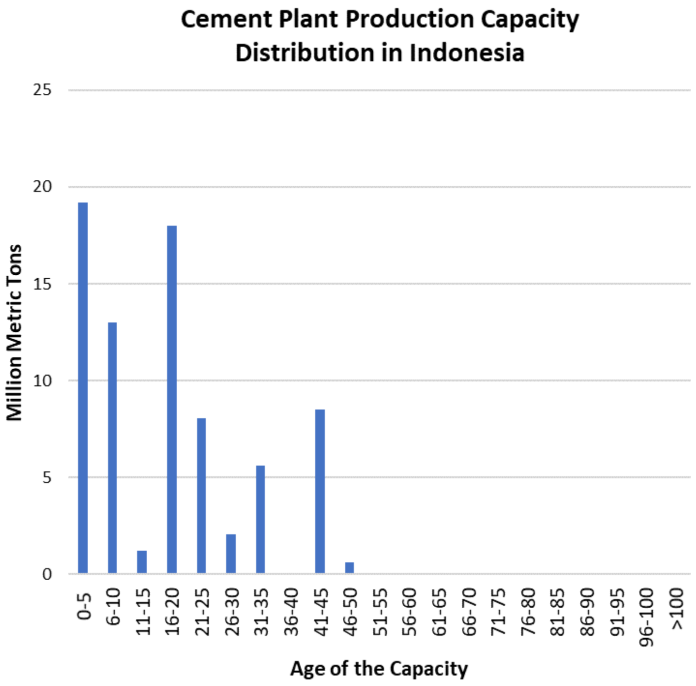

Figure 27. Cement plant production capacity distribution in Indonesia

Sources: GID 2019; Liu et al. 2021.

The theoretical minimum thermal energy required for clinker production, including raw material drying and the calcination of raw materials at a temperature of 1,450°C, is 1.85 to 2.8 GJ/t clinker (IEA 2018). The current best available technology (BAT) for a six-stage preheater and precalciner kiln is in the range of 2.9 to 3.3 GJ/t clinker. For electrical energy demand, the current BAT level is in the range of 90 to 100 kWh/tonne cement (European Cement Research Academy 2022).

Given that the majority of the cement plants in Indonesia were built in the last 20 years, we expect that the technological level in these facilities is at least an average performance level. Working with IESR (our local partner) and talking to the Indonesian Cement Association, we assumed that most of the operating capacity in the cement industry is using rotary kilns, but with limited waste heat recovery. The average rotary kiln thermal energy intensity in Indonesia is estimated to be 3.6 GJ/t clinker in 2020, and the clinker-to-cement ratio is reported to be about 0.71 by 2020.[4] The electrical energy intensity is estimated to be 125 kWh/t cement.

Many commercialized energy-efficiency measures are readily available (see an example list of measures in Appendix C). These energy-efficiency measures and technologies can be adopted to improve the existing energy intensity levels to BAT levels, and potentially they could approach practical minimum levels. Technologies such as waste heat to power generation, preheaters and precalciners, and efficient finish grinding can improve thermal and electrical energy intensity.

Improving energy efficiency can deliver near term and cost-effective results while also tuning the production system to be more efficient and supporting decarbonization technologies better (e.g., hydrogen blending or CCS systems). Even so, the potential for energy efficiency is limited given the relatively new facilities and dominance of coal use in the industry, as well as the fact that 60% of total CO_2 emissions are associated with limestone (the key raw material input). Decarbonization of the cement industry will require adoption of material efficiency strategies to reduce demand, using zero-/low-carbon fuels, exploring new supplemental cementitious materials, and piloting breakthrough technologies.

In the Near Zero 2060 Scenario, we expect that the thermal energy intensity of clinker production improves to 2.84 GJ/t clinker (practical minimum level) while electrical energy intensity declines to 75 kWh/t cement by 2060. In the Accelerated 2050 Scenario, thermal and electrical energy intensity improves to 2.86 GJ/t clinker and 75 kWh/t cement by 2050, respectively (Table 9). These energy intensity values do not include potential energy requirement increases from adopting CCUS systems on site.

Table 9. Thermal and electrical energy intensity of cement production in Indonesia

Energy Intensity*	Reference (2020)	Near Zero 2060 (2060)	Accelerated 2050 (2050)
Thermal Energy Intensity (GJ/t clinker)	3.6	2.84	2.86
Electrical Energy Intensity (kWh/t cement)	125	75	75

Source: LBNL analysis.

*Note: This does not include the energy requirements for implementing CCS units.

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[4] From the FGD meeting with Indonesia Cement Association (ASI).

3.2.3.4 Increased use of supplemental cementitious materials

In Indonesia and the world on average, Ordinary Portland Cement (OPC) makes up of the most common type of cement product. Portland cement can be blended with other additives to have different properties. Reducing clinker content, i.e., by increasing the use of SCMs can reduce the energy needed and the fuel and process CO_2 emissions associated with clinker production, making it one of the most effective measures to reduce CO_2 intensity in the cement industry.

There are many different types of SCM (Shah et al. 2022), including the following:

- coal fly ash, a byproduct of coal-fired power generation
- blast furnace slag, a byproduct of pig iron production
- silica fume, a byproduct of a silicon and ferrosilicon alloy
- natural pozzolan, which may be limited by local resource conditions
- calcined clay, which is metakaolin that has been heated to 700°C–850°C
- bauxite residue, a byproduct from alumina production
- agricultural byproduct ashes
- forestry byproduct ashes
- end-of-life binder

Cement plants currently use coal fly ash and blast furnace slag, which are readily available given the development of coal-fired power generation and ironmaking. However, limited supply is a key challenge to increase the scale of SCM in cement production. For example, the amount of slag available worldwide is about 5%–10% of the amount of cement production (Scrivener et al. 2018). Fly ash availability is about 30% of cement production, but the quality of fly ash is variable, and only one-third is used for blending in cement (Snellings 2016). As the Indonesia power sector decarbonizes and ironmaking shifts away from the blast furnace, the availability of coal fly ash and slag may decline in the future.

On the other hand, studies show that calcined clay, especially calcined clay in combination with limestone (LC^3 technology) can reduce half of the clinker content and cut CO_2 emissions up to 40%, compared to OPC (Scrivener et al. 2018; Scrivener, John, and Gartner 2016). This technology, with a technology readiness level (TRL)[5] of 9 has been adopted in cement plants in a several countries, such as India, Cuba, Brazil, the United States, and European Countries (IEA 2023b).

The cement industry in Indonesia needs to continue scale up the use of SCMs to reduce the clinker-to-cement ratio. In our analysis, we expect that the clinker-to-cement ratio in Indonesia will decrease from 0.71 in 2020 to 0.5 by 2060 in the Near Zero 2060 Scenario; and decrease to 0.5 by 2050 and stays at

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[5] The technology readiness level (TRL) provides a framework to assess and compare the maturity of a technology. It is now being widely used by research institutes and technology developers to set research priorities and design research & development programs. TRL levels ranges from concepts stage (TRLs 1-3) to prototype (TRLs 4-6) to demonstration (TRLs 7-8) to early adoption (TRLs 9-10) to mature (TRL 11).

this level through 2060 in the Accelerated 2050 Scenario.

3.2.3.5 Use of low-carbon fuels

We estimated that about 6%–8% of the total fuel consumption in Indonesia's cement industry was from fuels other than coal, including biomass (agricultural byproducts, fuel oil, pet coke, and wastes). The rest and the majority of the fuel inputs are coal. In more developed countries (e.g., in EU countries), the share of wastes and biomass used for cement production is significantly higher.

There are many types of alternative fuels such as paint residue, solvent, used tires, municipal solid waste, sewage sludge, and biomass (waste wood, sawdust, and other agricultural byproducts) that can be used in cement kilns to replace coal, fuel oil, or pet coke.

However, there are technical challenges related to using various alternative fuels. Issues such as the low calorific value and high moisture content of some alternative fuels, potential for high concentration of chlorine and other trace substances, requirements to pretreat certain alternative fuels to ensure uniform composition and optimum combustion, and the need to minimize the content of potentially problematic substances. In addition to technical challenges, supply chain challenges also exist. Waste collection, sorting, and management systems need to be established to ensure the availability and supply of waste materials. Co-processing of wastes may face challenges in terms of social acceptance.

A significant challenge of large-scale adoption of alternative fuels to achieve net-zero emissions is that many of the alternative fuels (excluding biogenic fuels) are not zero-carbon fuels. This is an important distinction from using zero-carbon fuels, and proper documentation and reporting of the emissions from the non-biogenic fuels are necessary. In our analysis, CO_2 emissions from solid wastes (excluding biogenic fuels) are included.

Our analysis also considered use of zero-carbon fuels, including green hydrogen (Heidelberg Materials 2021) and renewable heat, such as concentrated solar (CEMEX 2022). Both of these measures are being piloted. Electrolysis of limestone has been studied and explored in laboratories; this can reduce fuel-related CO_2 emissions if renewable electricity is used (Ellis et al. 2019). However, at present, electrolysis has yet to be piloted. Thus, we did not include the potential of electrolysis of limestone in the fuel switching analysis.

In the Near Zero 2060 Scenario, the share of coal in rotary kilns is reduced significantly by increased use of solid wastes and biomass in the near term (by 2030). After 2030, green hydrogen and renewable heat also are adopted. Specifically, the shares of solid wastes and biomass increase from about 3% in 2020[6] to 18% by 2030 and further increase to 60% by 2060. The share of green hydrogen increases to 15% by 2060 (Figure 28).

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[6] From the FGD meeting with Indonesia Cement Association (ASI).

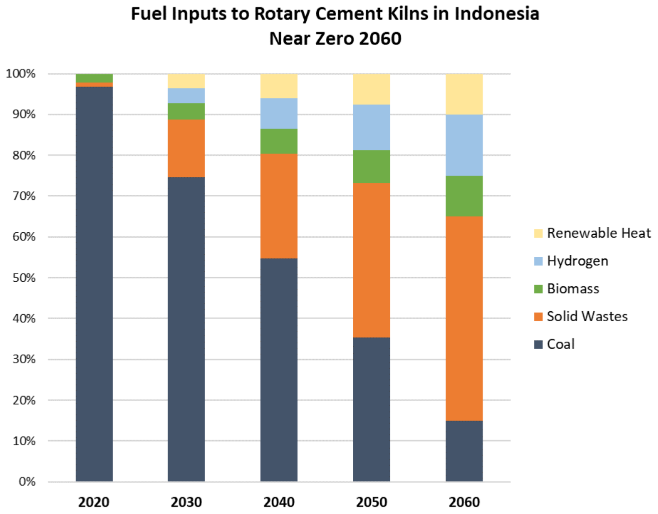

Figure 28. Fuel shares of rotary kilns in the Indonesian cement industry: Near Zero 2060 Scenario

Source: LBNL analysis.

In the Accelerated 2050 Scenario, the adoption of alternative fuels and zero-carbon fuels is more ambitious. The shares of solid wastes and biomass increase to 60% by 2050, while green hydrogen accounts for 20% of total fuel inputs by 2050.

3.2.3.6 CCS

More than 60% of the total CO_2 emissions from the cement industry are process-related, i.e., from limestone calcination. A number of carbon capture technologies have been investigated over the last 15 years, with various TRLs and capturing yields (Table 10).

Table 10. Carbon Capture Technologies in the Cement Industry

Carbon Capture Technology Groups	Carbon Capture Technologies	Technology Readiness Level (TRL)	Capturing Yields* (%)
Post Combustion	Post-combustion + Amine (monoethanolamine, or MEA)-absorption	8–9	95
	Post-combustion + membranes	4–5	78
	Cryogenic and adsorption	5–6	90
	CO_2 mineralization (in mixing and curing)	9	N/A
Integrated	Oxyfuel + MEA	6	95
	Oxyfuel-combustion calcium looping (tail-end)	7–8	95
	Integrating calcium looping with the calcination process	6–7	95
	Indirect combustion + Direct CO_2 capturing	6–7	55

Sources: European Cement Research Academy 2022; IEA 2023b.

* Capturing yields vary by specific system design and conditions.

Notes: MEA = monoethanolamine.

Currently, chemical absorption (using amine) post-combustion capturing has the highest technological readiness level, with a TRL of 8 or 9 (European Cement Research Academy 2022). The technology has been applied extensively in other industrial processes (e.g., ammonia production) and fossil power plants. For cement plants, it can capture CO_2 emissions from both the fuel combustion and the limestone calcination processes. The capturing yield can reach up to 95%.

It is important to note there are energy requirements associated with carbon capture. For post-combustion amine-based carbon capture, thermal and electrical energy is required, at about 1.0 to 3.5 GJ/t clinker and 50 to 90 kWh/t clinker, respectively, to heat and regenerate the sorbent (ECRA and CSI 2017; Plaza, Martínez, and Rubiera 2020).

In our analysis, CCS adoption rate in Indonesia's cement industry will increase from 0% to 2% of total production by 2030 and 50% by 2060 in the Near Zero 2060 Scenario. CCS adoption is more aggressive in the Accelerated 2050 Scenario, reaching to 5% by 2030 and 60% by 2050. The Near Zero 2060 Scenario indicates that the Indonesian cement industry needs to capture and store about 1 $MtCO_2$/year by 2030, 10 $MtCO_2$/year by 2040, and almost 30 $MtCO_2$/year by 2060 (Figure 29).

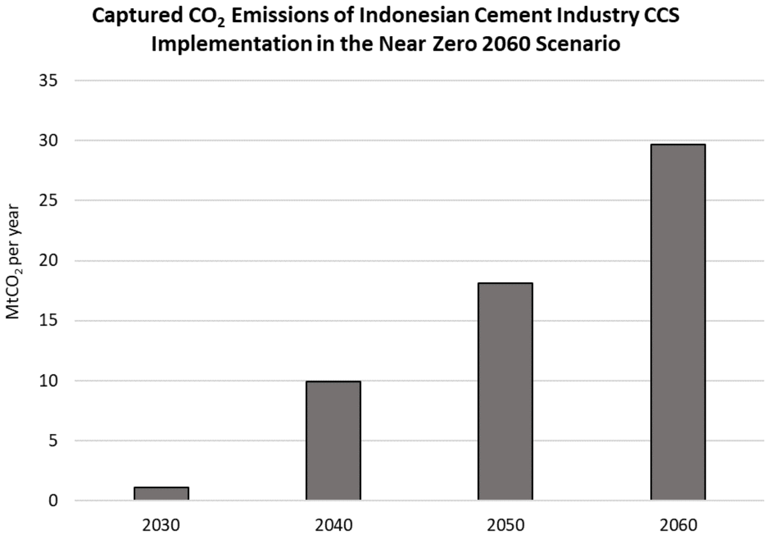

Figure 29. Amount of cement industry CO_2 emissions per year that needs to be captured and stored: Near Zero 2060 Scenario

Source: LBNL analysis.

In terms of theoretical storage capacity, the IEA estimated that Indonesia has a total of 8.4 $GtCO_2$ of storage capacity (IEA 2021a), indicating significant technical capacity available as compared to the storage needed for the cement industry. The storage capacity is mostly located in South Sumatra Basin, Java Basin, Tarakan Basin, and Central Sumatra Basin (Figure 30). However, due to Indonesia's geological conditions (i.e., its location within the Ring of Fire) it has frequent earthquakes and volcanic eruptions. Therefore, identifying and selecting a proper CCS storage site is crucial. Robust testing and validation, and ongoing measurement, monitoring, and reporting is a critical before, during, and after the operations (IEA 2021a).

Figure 30. CCS Storage potential in Southeast Asia and Australia
Source: IEA 2021a.

A major barrier to CCS implementation is high cost, e.g., costs required for site selection, capital cost of the system, and additional cost for CO_2 compression, transportation, and storage. On average (globally), CCS systems in cement production would increase the levelized cost significantly, in the range of 50%–400% (Figure 31). Specific costs vary depending on the type of technology, cost of energy, location, transport distance, and geological storage conditions.

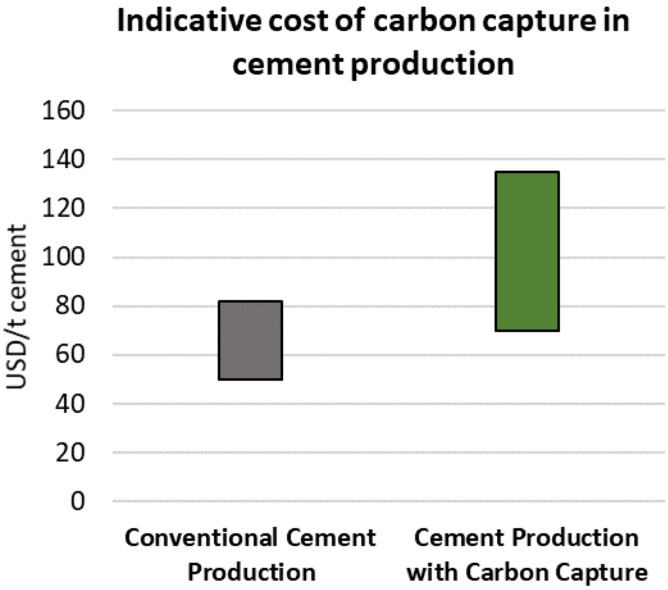

Figure 31. Indicative levelized cost of conventional cement production and cement production with carbon capture technologies
Source: IEA 2021a.

3.2.4 Decarbonization pathways

3.2.4.1 Near Zero 2060 Scenario

Even with total cement production increasing 41% by 2060 from its 2020 level, our analysis found that under the Near Zero 2060 Scenario Indonesia's cement industry can significantly reduce its CO_2 emissions and achieve near-zero emissions by 2060.

Specifically, total CO_2 emissions, including both fuel and process-related emissions, will decline from 44 $MtCO_2$ in 2020 to 17 $MtCO_2$ by 2060 (Figure 32). The largest contributor of CO_2 emissions reductions is CCUS technologies, accounting for 16 $MtCO_2$ emissions reduction per year by 2060. However, as discussed in the section above, adopting CCS faces several technical and regulatory challenges, as well as significant high implementation costs.

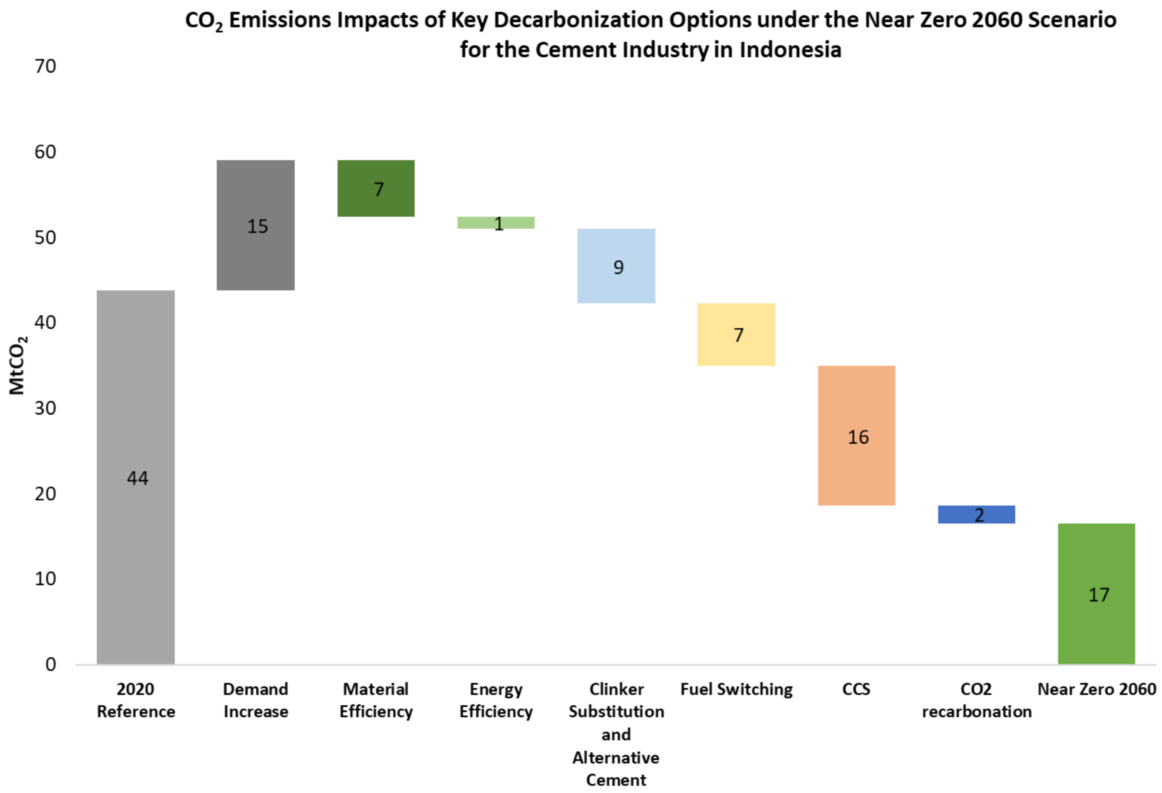

Figure 32. CO_2 emissions impacts of key decarbonization options for the cement industry in Indonesia: Near Zero 2060 Scenario

Source: LBNL analysis.

More importantly, in the near term by 2030, the most high-impact strategy to reduce CO_2 emissions in the cement industry in Indonesia is to increase the adoption of SCMs, reduce the clinker-to-cement ratio, and moderately adopt alternative cement products. These measures are the most effective, low-cost, and near term actions that can achieve significant results, representing 30% of total emission reductions from 2020 to 2030 (Figure 33, left). Reducing the clinker-to-cement ratio needs to be supported by scientific, ample testing, validating, and reporting on the various SCMs and their impacts on the performance of cement products. It also requires timely updates in existing codes and standards of cement-based products.

Fuel switching (i.e., switching to use alternative fuels and zero-carbon fuels) and energy efficiency improvement also contribute 27% and 16%, respectively, of the total accumulative CO_2 emissions reductions by 2030. Various material efficiency measures (from design, production, use, to end-of-life) collectively account for 18% of total CO_2 emissions reduction by 2030.

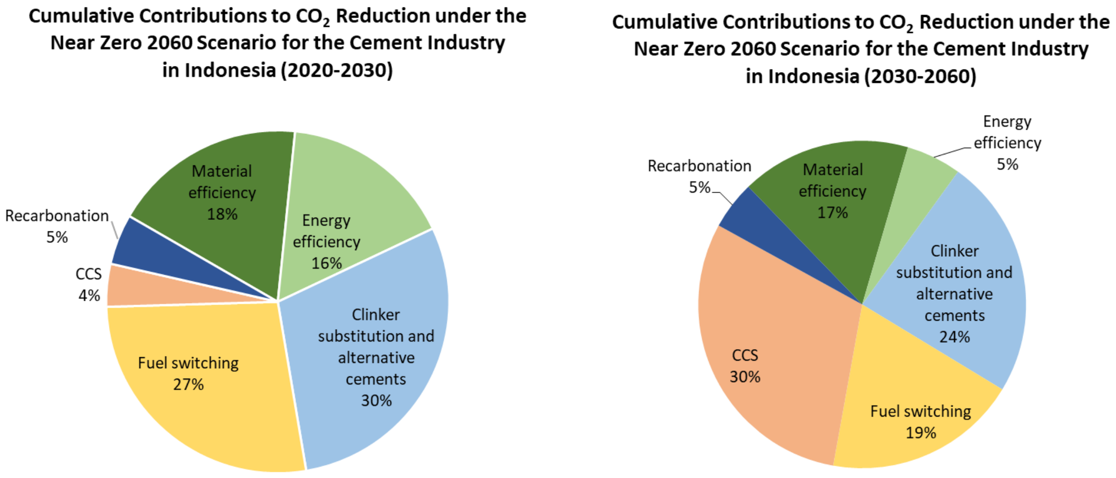

Figure 33. Cumulative contributions of key strategies of cement industry decarbonization: Near Zero 2060 Scenario, 2020-2030 and 2030-2060

Source: LBNL analysis.

In the mid to long term, from 2030 to 2060, while the role of energy efficiency will be limited, clinker substation and alternative cement continues to play an important role, contributing to 24% of total emissions during this period. Further emission reductions are achieved through fuel switching (19%), material efficiency (17%), and CCS (30%) (see Figure 33, right).

3.2.4.2 Accelerated 2050 Scenario

The Accelerated 2050 Scenario showed that the total CO_2 emissions of the Indonesian cement industry could be further reduced and at an earlier year. As shown in Figure 34, total CO_2 emissions will decline from 44 $MtCO_2$ in 2020 to 11 $MtCO_2$ by 2050. This further reduction, compared to the results in the Near Zero 2060 Scenario, is a result of aggressive adoption and scale up of material efficiency strategies to reduce demand, improving energy efficiency to approach practical minimum energy intensity, increased adoption of alternative cements, and aggressive adoption of CCS technologies.

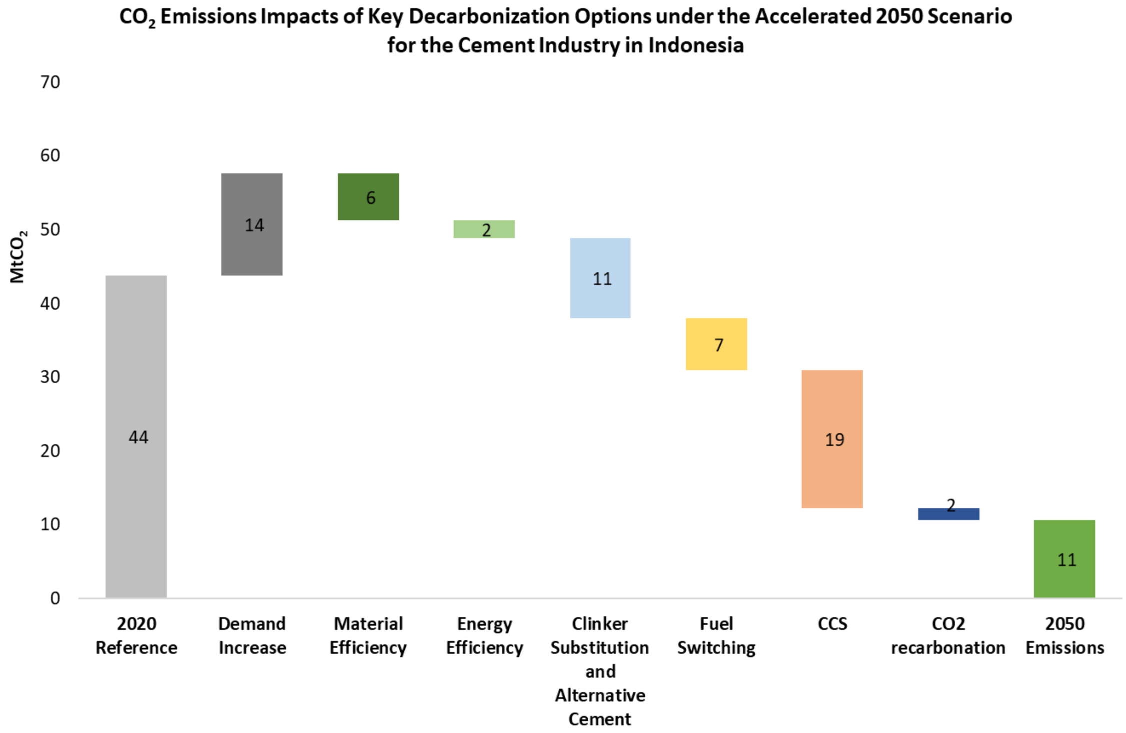

Figure 34. CO_2 emissions impacts of key decarbonization options for the cement industry in Indonesia: Accelerated 2050 Scenario

Source: LBNL analysis.

Comparing the 2050 CO_2 emissions in the Accelerated 2050 and Reference Scenarios, we found that CCS plays the biggest role, accounting for a 19 $MtCO_2$ reduction in 2050, or 40% of the total emission reductions in 2050. Clinker substitution and alternative cements has the potential to reduce 11 $MtCO_2$ in 2050, or 23% of the total CO_2 emission reductions. Fuel switching and material efficiency represent 15% and 14% of 2050 CO_2 emissions reductions, respectively.

3.3 Ammonia industry

3.3.1 Historical production and consumption

Ammonia (NH_3) is used as a feedstock input to produce both straight nitrogen-based fertilizers and compound fertilizers. It also can be used to produce industrial products such as explosives, plastics, synthetic fibers, and other chemical products. Ammonia is a critical building block for the agricultural industry and food security, and it is a potential energy carrier in the future.

Indonesia is the fifth largest ammonia producer in the world, as shown in Figure 35, accounting for 5% of total ammonia production globally (USGS 2023b). In 2020, Indonesia produced about 9.5 Mt of ammonia, with a net export of 3.5 Mt (IEA 2021b). About 72% to 74% of ammonia is used to produce fertilizers in Indonesia. This is similar to other countries, where the level is 88% in the US, 86% in China, and 70% globally (USGS 2023b; World Economic Forum 2022a).

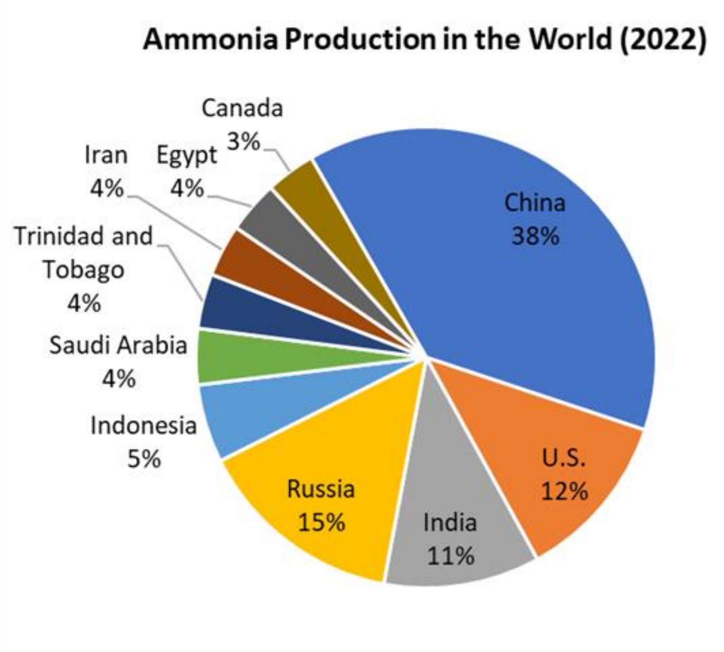

Figure 35. Ammonia production in the world (2022)
Source: USGS 2023b.

Fertilizer consumption varies significantly by country, depending on a combination of factors, such as whether the country is a major exporter of agricultural products, the level of industrialized farming, fertilizer prices, availability of other alternative fertilizers, types of crops, types of soil, climate conditions, and others.

Historically, Indonesia’s fertilizer consumption has been increasing significantly. From 1970 to 2020, fertilizer consumption per hectare increased from 12 kg/hectare to 164 kg/hectare. Per capita fertilizer consumption during this period also increased notably, from 2 kg/capita to 16 kg/capita (Figure 36).

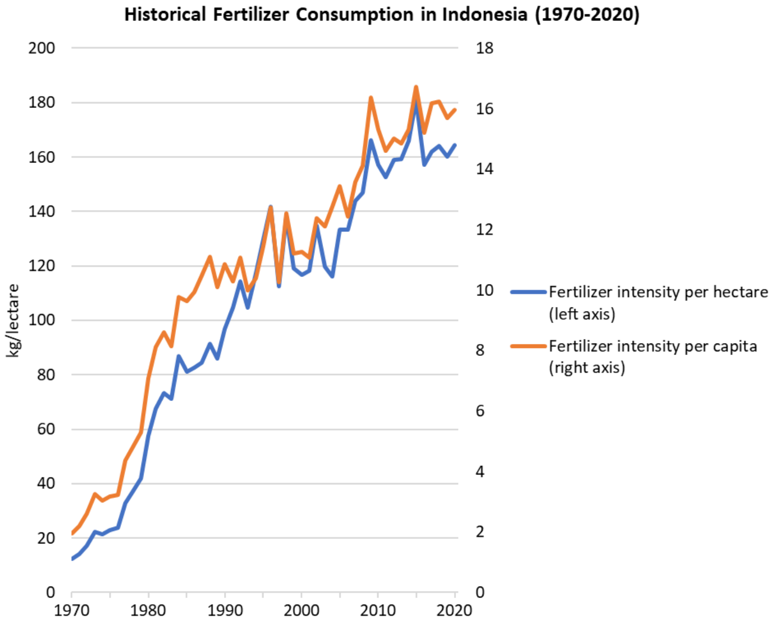

Figure 36. Historical fertilizer consumption in Indonesia (1970–2020)

Sources: Calculated based on IFA 2023; UN 2022; World Bank 2023b.

As of today, Indonesia's fertilizer consumption per capita is about 87% of the world average, which is 18 kg/capita (Figure 37). Indonesia's fertilizer consumption is about the same as the level in India, but it is much lower than the level in China (which uses fertilizer intensively to boost production) and Brazil and the US (both of which are major agricultural product exporters).

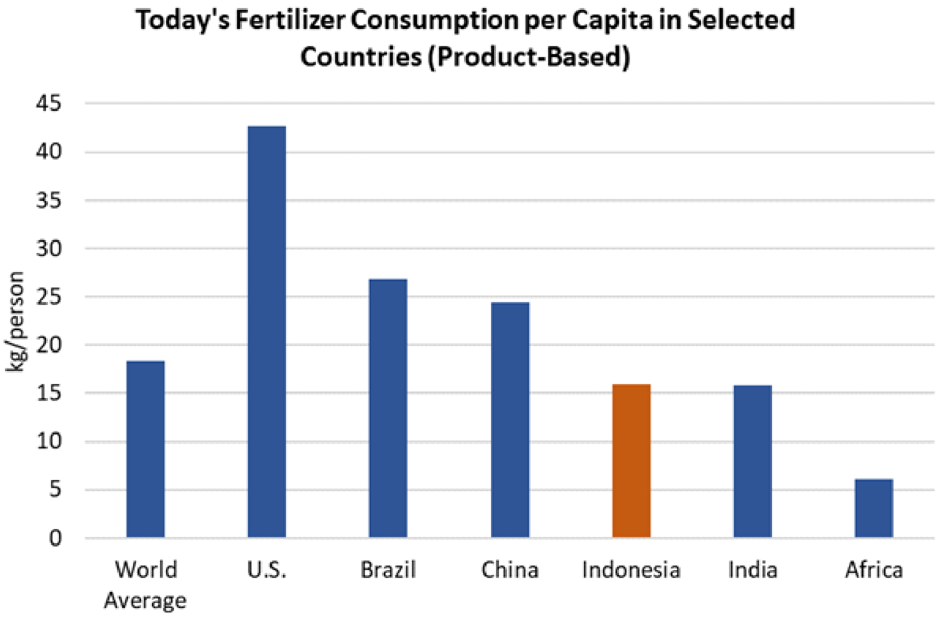

Figure 37. Fertilizer consumption per capita in selected countries

3.3.2 Production forecast

In this analysis, we modeled Indonesia's ammonia production through both domestic demand (on fertilizers and non-fertilizers) and net exports. Due to the uncertainties in international trade over a long period of time (40 years), we assumed net exports to be fixed at the 2020 level.

Domestic demand was estimated based on Indonesia's population growth, arable land availability, and fertilizer use intensity. We continue to assume that about 72% of domestic ammonia production is used for fertilizers through 2060, while recognizing the potential but uncertainties in using and producing ammonia as an energy carrier (for shipping, power generation, and other uses) in the future.

In the Reference Scenario, total ammonia production increases from 9.5 Mt in 2020 to 10.3 Mt by 2030 and continues to increase to 11.5 Mt by 2060, reaching today's world average of fertilizer consumption per capita level (Figure 38).

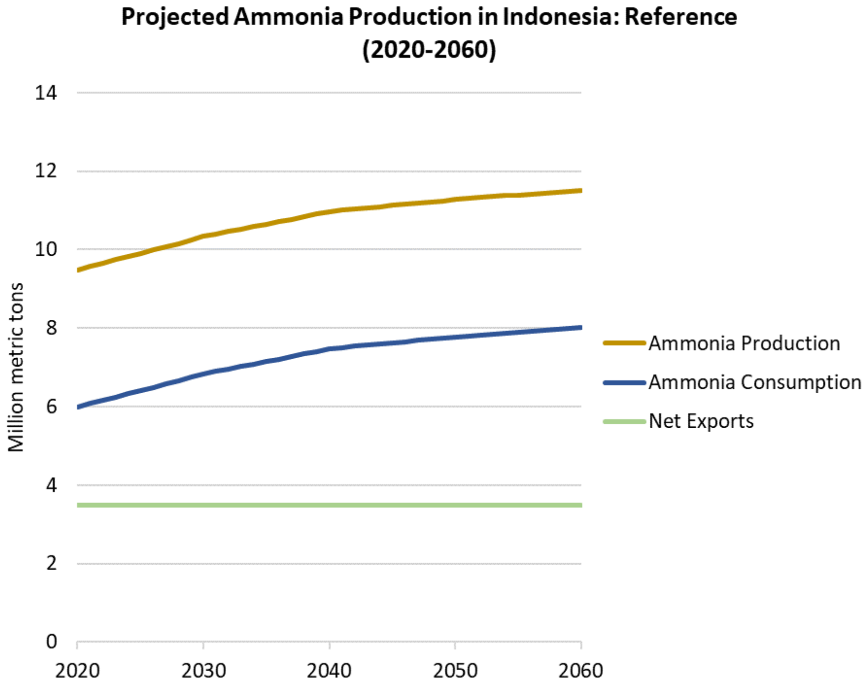

Figure 38. Ammonia production and consumption in Indonesia (2020–2060): Reference Scenario

Source: LBNL analysis.

In the Near Zero 2060 and Accelerated 2050 Scenarios, Indonesia's ammonia production increases at a slightly lower rate, reaching 11 Mt by 2060 and 10.8 Mt by 2050, respectively. This decrease in production level is driven by material efficiency strategies, such as an increased uptake efficiency of fertilizers, reduced food wastes, a switch to organic fertilizers, and increased plastic recycling (see Section 3.3.3.2 for more details).

3.3.3 Decarbonization strategies and technologies

3.3.3.1 Ammonia manufacturing processes

Ammonia can be produced from coal, natural gas, biomass, hydrogen, or methane pyrolysis. Today, the predominant method of ammonia production is steam methane reforming (SMR), which produces hydrogen from natural gas and then reacts the hydrogen with nitrogen from air in the Haber-Bosch Process to produce ammonia. Globally, this approach accounts for 72% of the total ammonia produced worldwide (IRENA 2022). About 26% of the global ammonia is produced via coal gasification, mostly in China. About 1% of ammonia is produced from oil products, while electrolysis-based ammonia production currently accounts for less than 1%. In Indonesia, the majority of ammonia is produced via the steam methane reforming route (IEA 2021b). We estimate this share reached to 90% by 2020.

After natural gas desulfurization, five steps are needed to produce synthetic ammonia (Figure 39), including (1) catalytic steam reforming in primary and secondary reformers, (2) water shift reaction, (3) CO_2 separation and removal, (4) methanation, and (5) ammonia synthesis.

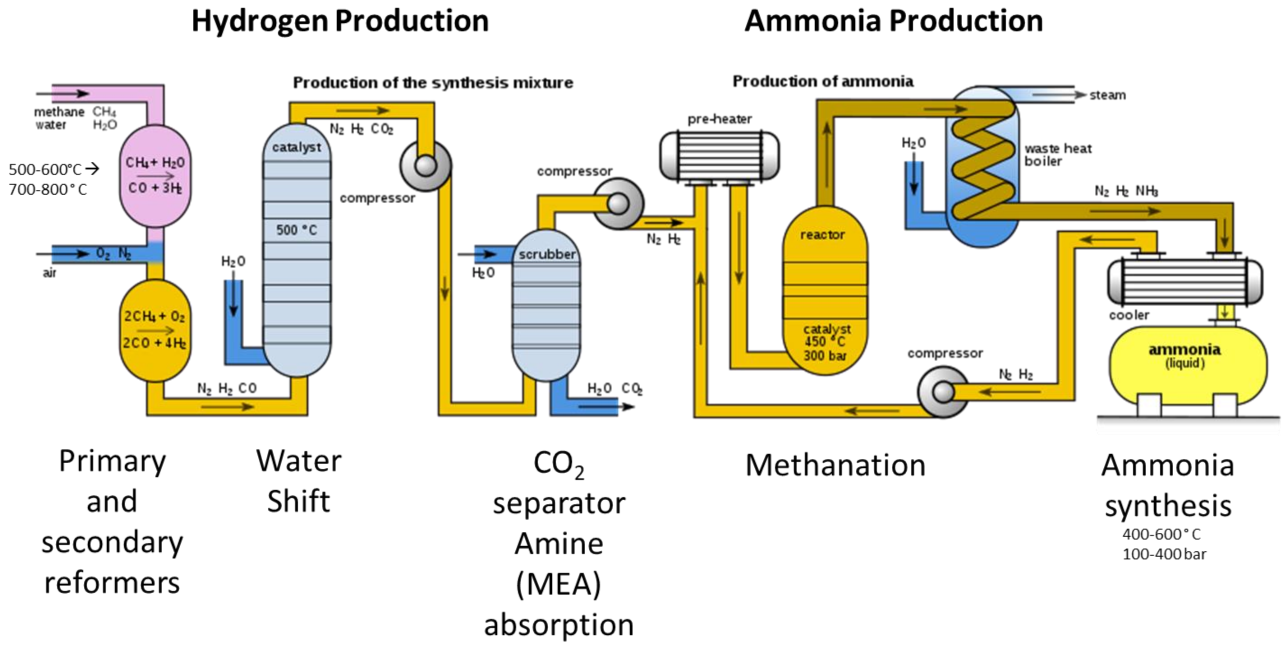

Figure 39. Ammonia production process

Ammonia production is an energy and carbon-intensive process. Most production uses natural gas or coal as feedstocks to obtain hydrogen. In addition, regardless of the hydrogen production process, the ammonia synthesis (Haber-Bosch Process) requires high temperature (400°C–600°C) and high pressure (100–400 bar) to drive the reaction in the presence of the catalyst. Globally in 2020, ammonia production accounted for 2% of the total final energy use worldwide, or 1.3% of CO_2 emissions from the energy systems (World Economic Forum 2022a).

The largest source of CO_2 emissions in ammonia production is from hydrogen production, accounting for more than half of the total CO_2 emissions (Boerner 2019). Depending on the feedstocks used and plant efficiency, ammonia production's Scope 1 CO_2 emissions (onsite fossil-related) are in the range of 1.6 to 4 tCO_2/t ammonia. Scope 2 CO_2 emissions (associated with purchased electricity) are estimated to be 0.22 tCO_2/t ammonia (Mission Possible Partnership 2022a). The upstream and downstream of the ammonia value chain also emits a significant amount of Scope 3 greenhouse gas (GHG) emissions[7]. This includes methane emissions from natural gas flaring, venting, and leaking during the extraction and transportation process. It also includes nitrous oxide (N_2O) emissions from the use of nitrogen-based fertilizers, as well as CO_2 emissions from the application of urea-based fertilizers. The CO_2 emissions released during the use phase of urea-based fertilizers were captured from fossil fuels used during the production phase of ammonia, but then released from the use phase of the fertilizer.

In this analysis, we included Scope 1 and Scope 2 emissions, as well as the consideration of CO_2 emissions released during the application of urea-based fertilizers. Methane emissions from the upstream of the value chain, CO_2 emissions from the transportation and distribution of fertilizers, and the N_2O emissions from the application of nitrogen-based fertilizers were not included in this analysis.

The ammonia production process currently relies on fossil fuels, high temperature, and high pressure. A portfolio of decarbonization solutions is needed, including improving material efficiency, reducing demand of synthetic ammonia, improving the production facility's energy efficiency, innovative technologies to produce green ammonia, and CCS (Table 11).

Table 11. Technologies and measures to decarbonize the ammonia industry

Material Efficiency	Energy Efficiency	Green Ammonia	CCS
• Increase uptake efficiency of fertilizers • Reduce leakage to water and air	• Improve thermal energy efficiency • Improve electrical energy efficiency	• Green hydrogen-based ammonia production	• Natural gas-based ammonia production with CCS
• Reduce food wastes	• Smart energy management	• Biomass-based ammonia production	• Coal-based ammonia production with CCS
• Increase plastic recycling	• Integrative design/system optimization	• Methane pyrolysis	• Biomass gasification with CCS *(not modeled)*

Source: LBNL analysis.

In this analysis, we modeled the energy and CO_2 impacts of each of these strategies (except for biomass gasification with CCS) in the ammonia industry in Indonesia. We excluded biomass gasification with CCS due to its expected small share of adoption by 2060 and the higher cost of implementation. The goal of

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[7] Scope 1 emissions include direct emissions from owned or controlled sources of the reporting entity. Scope 2 emissions include indirect emissions from purchased or acquired electricity, steam, heat and cooling of the reporting entity. Scope 3 emissions include indirect emissions from value chain activities. See: WRI Greenhouse Gas Protocol: https://www.wri.org/initiatives/greenhouse-gas-protocol

the analysis was to conduct a detailed bottom-up analysis on the technical potential and quantify the contributions of each of the decarbonization strategies under two different scenarios (Near Zero 2060 and Accelerated 2050).

3.3.3.2 Improving material efficiency

Reducing the amount of ammonia that would be needed—or increasing the utilization of ammonia through material efficiency strategies, circular business models, and material substitution—can play an important role in helping the Indonesian ammonia industry achieve net-zero emissions.

This analysis focused on three material efficiency measures for ammonia-based products:

- Increasing uptake efficiency of fertilizers and reducing leakage to water and air
- Reducing food wastes
- Increasing plastic recycling

Fertilizer uptake efficiency can be improved by controlling soil conditions, timing application to weather conditions, increasing the precision of the application, using more frequent and varied applications, and ensuring sufficient availability of other nutrients (Material Economics 2019). CO_2 emissions from urea application may be reduced by using additives in the fertilizer to minimize volatilization of urea. In addition, improved plastic recycling may also have the potential to reduce demand on ammonia as about 26-28% of ammonia produced in Indonesia is used for non-fertilizer applications, such as plastics and synthetic fibers.

It can be very challenging to incorporate all these material efficiency measures into agricultural, business, and retail practices. Some of these measures (e.g., increase uptake efficiency, plastic recycling technologies) require capital investment, while others (e.g., reduce food wastes and increase plastic recycling) require both technological improvements and coordination across the value chains (farmers, food manufacturers, retailers, and consumers).

In this analysis, we explored the adoption and impacts of material efficiency in reducing ammonia demand through the Near Zero 2060 Scenario (Table 12) and Accelerated 2050 Scenario (Table 13). For each measure we considered the maximum technical ammonia-saving potential, affected percentages of ammonia production, and adoption rates of the measure by a specific time frame under each scenario. The adoption rates assumptions were shared and presented to the ammonia industry FGD, which was held in person in Jakarta, Indonesia, on June 22, 2023.

Table 12. Material efficiency measures and adoption rates in the Indonesian ammonia industry: Near Zero 2060 Scenario

Measures	Ammonia Saving Potential (%)	References	Adoption Rate 2030 (%)	Adoption Rate 2060 (%)	Applicability in Ammonia Production (%)
Increase uptake efficiency of fertilizers and reduce leakage to water and air, by - controlling conditions - improving application timing - increasing application precision	20	IEA 2021b	10	40	72
Reduce food wastes	10	Material Economics 2019	3	12	72
Increase plastic recycling	5	Material Economics 2019	15	30	28

Table 13. Material efficiency measures and adoption rates in the Indonesian ammonia industry: Accelerated 2050 Scenario

Measures	Ammonia Saving Potential (%)	References	Adoption Rate 2030 (%)	Adoption Rate 2060 (%)	Applicability in Ammonia Production (%)
Increase uptake efficiency of fertilizers and reduce leakage to water and air, by - controlling conditions - improving application timing - increasing application precision	20	IEA 2021b	15	35	72
Reduction of food wastes	10	Material Economics 2019	5	15	72
Increase plastic recycling	5	Material Economics 2019	20	40	28

The results show that total ammonia production in Indonesia could be reduced by about 2% by 2030 and 7% by 2060 in the Near Zero 2060 Scenario. Through more ambitious demand reduction and material efficiency strategies, ammonia production could be reduced by about 3% by 2030 and 12% by 2060 in the Accelerated 2050 Scenario.

3.3.3.3 Improving energy efficiency

Globally, the world average energy intensity of ammonia production is about 46 GJ/t on a gross basis, i.e., not considering heat integration and waste heat recovery during the production process. On a net basis, by considering heat integration and waste heat recovery, the world average of ammonia production is 41 GJ/t in 2020 (IEA 2021b), as shown in Table 14. We estimated that the average energy intensity of ammonia production in Indonesia is 37 GJ/t on a net basis. During the FGD discussions, industry representatives commented that there is still room for energy efficiency improvements in Indonesia's ammonia production facilities.

Based on these findings and feedback from the industry, in the Reference Scenario, we assumed no significant improvement in ammonia production energy efficiency, given that most (>90%) of Indonesia's ammonia production is already produced from natural gas using steam methane reforming and the Haber-Bosch Process. In the Near Zero 2060 Scenario, the goal is to improve the energy efficiency of the natural gas-based ammonia production route to today's BAT level by 2060, i.e., 28 GJ/t on a net basis. In the Accelerated 2050 Scenario, the pace of energy efficiency improvement is faster, reaching the BAT level by 2050.

Table 14. Ammonia energy intensity: World averages, BAT values, theoretical minimums, and the Indonesia average

Ammonia energy intensity	Value (GJ/t)	Year	Basis
World average	46	2020	Gross basis
World average	41	2020	Net basis
Natural Gas (BAT)	32	Not applicable	Gross basis
Natural Gas (BAT)	28	Not applicable	Net basis
Natural Gas (theoretical minimum)	20.9	Not applicable	Gross basis
Natural Gas (theoretical minimum)	18.6	Not applicable	Net basis
Indonesia average	37	2020	Net basis

Sources: IEA 2021b and LBNL analysis.

It should be noted that while improving energy efficiency delivers immediate and near term energy and CO_2 savings, there are practical and theoretical limits to reducing energy intensity (e.g., 18.6 GJ/t for natural gas-based ammonia production on a net basis). To achieve net-zero emissions in the ammonia industry, technology innovation and large-scale adoption of a cleaner production process is required.

3.3.3.4 Innovative technologies: Green ammonia

As noted in previous sections, today's ammonia production in Indonesia fully relies on fossil fuels. To achieve the country's economic development and NDC goals, it is critical to identify alternatives to fossil-based ammonia production routes.

In this analysis, we considered several alternatives, collectively called "green ammonia" production process, i.e., producing ammonia through a synthesis process (via Haber-Bosch) and producing ammonia directly, as shown in Table 15. In this analysis, we modeled the following three technologies, due to their relatively high TRL levels:

- ***Electrolytic ammonia production*****:** Hydrogen is produced through electrolyzers. In this analysis, we only considered green hydrogen production based on zero-carbon electricity. Nitrogen is provided through an air separation unit, and then ammonia is produced through the Haber-Bosch Process. Both air separation and the stand-alone Haber-Bosch processes are powered by zero-carbon electricity. See Appendix D (Table D-1) for a list of ongoing and announced green ammonia projects based on green hydrogen in the world.

- **Biomass gasification ammonia production:** This is similar to coal-gasification for ammonia production, but it uses biomass as the feedstock. After air separation to produce oxygen, biomass is heated in the presence of oxygen and water to produce syngas.[8] After cleaning the syngas, the production goes through water shift conversion, CO_2 removal, methanation, and ammonia synthesis.
- ***Methane pyrolysis*:** Hydrogen is obtained by employing electrical plasma to split hydrogen and carbon atoms in methane. This process does not emit CO_2 emissions but produces solid carbon. In this analysis, we assumed the solid carbon produced would not be combusted.

Other technologies, such as low-temperature electrochemical ammonia production, the molten salt (moderate temperature) electrochemical process, solid-state (high temperature) electrochemical ammonia production, lithium-mediated ammonia synthesis, photocatalytic ammonia production, non-thermal plasma production, using metallocomplexes to stimulate nitrogen fixation, and bio-digestion process are been investigated. However, due to technical barriers such as durability, efficiency, and high temperature/energy requirements, as well as economic barriers such as high capital costs, these technologies have much lower TRLs, with no industrial-scale pilots or demonstration projects. Thus, this analysis did not model these other ammonia production technologies.

Table 15. Green ammonia production technologies and TRLs

Green Ammonia Production Routes	Technologies	TRL
Ammonia synthesis	Electrolytic ammonia production	8 (industrial pilots)
	Biomass gasification ammonia production	5 (large prototype)
Direct ammonia production	Methane pyrolysis	7 (precommercial demonstration)
	Electrochemical process	1–3 (concept stage)
	Photochemical process	1–3 (concept stage)
	Plasmatic synthesis	1–3 (concept stage)
	Metallocomplexes	1–3 (concept stage)
	Bio-chemical (biomass digestion) process	1–3 (concept stage)

Sources: IEA 2021b; Olabi et al. 2023; Mitchell Crow 2023; Sánchez, Martín, and Vega 2019; Mission Possible Partnership 2022a; Smith, K. Hill, and Torrente-Murciano 2020.

In the Near Zero 2060 Scenario, the share of electrolytic ammonia production in Indonesia increases from essentially zero in 2020 to 15% by 2030 and 60% by 2060. In addition, the share of other green ammonia production routes (biomass gasification and methane pyrolysis) accounts for 4% by 2030 and 14% by 2060. The Accelerated 2050 Scenario adopts green ammonia even faster and at a larger scale,

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[8] Different configurations exist, such as indirect gasification, direct gasification with oxygen and steam, and direct gasification with air (or enriched air) and steam (see: Sánchez, Martín, and Vega 2019).

increasing the share of all three green ammonia production to 20% by 2030 and 60% by 2050, as shown in Figure 40.

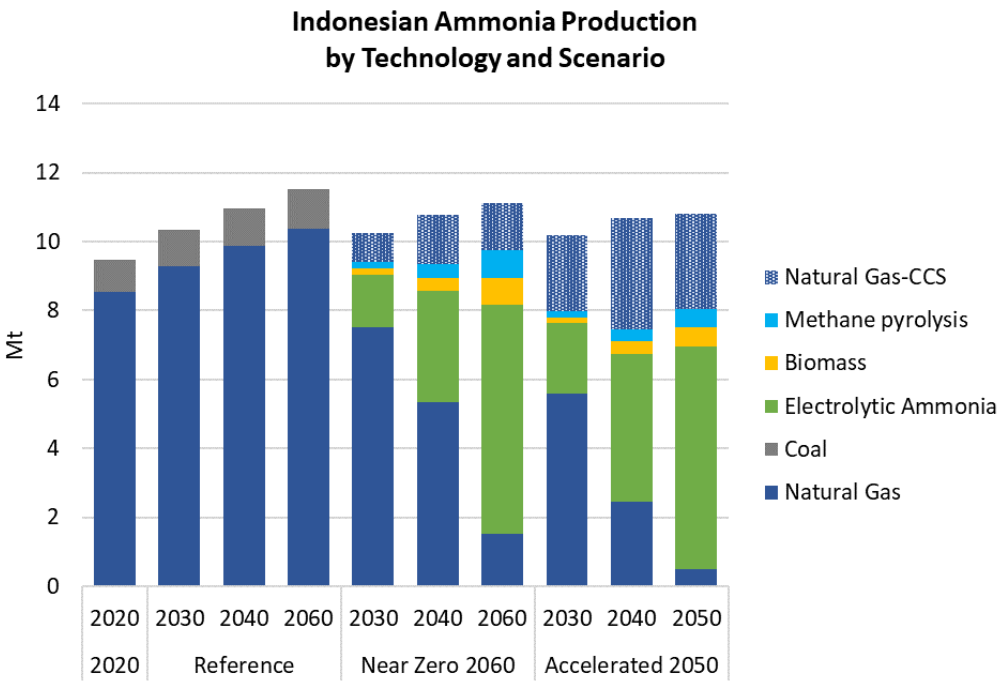

Figure 40. Ammonia production in Indonesia by technology and by scenario

Source: LBNL analysis.

3.3.3.5 Use of low-carbon fuels and grid decarbonization

In terms of switching to other low-carbon fuels and feedstocks, this analysis assumed that Indonesia's ammonia industry would phase out coal use by 2030 in both the Near Zero 2060 and Accelerated 2050 Scenarios.

As Indonesia's ammonia production transitions from fossil-based to green ammonia, demand for green hydrogen and zero-carbon electricity will increase significantly. Thus, it is critical to decarbonize Indonesia's power sector. While this analysis did not explicitly model power sector capacity expansion and decarbonization, it is assumed Indonesia's grid emission factor will decrease from 760 gCO_2/kWh in 2021 to 580 gCO_2/kWh by 2030, before reaching net-zero by 2060, as modeled by the IEA analysis (IEA 2022a).

3.3.3.6 CCS

In addition to green ammonia technologies (Table 16), in this analysis we considered natural gas ammonia production with CCS (blue ammonia), which has a TRL level of 9 (commercial operation in relevant conditions). Many of the current operating and announced blue ammonia projects are capturing CO_2 emissions from natural gas. These are used for (1) enhanced oil recovery (EOR) traditionally, and (2) now gradually with CO_2 utilization and storage (see Appendix B for a list of blue ammonia projects).

In the Near Zero 2060 Scenario, we assumed CCS adoption in unmitigated fossil-ammonia production would increase from 0% in 2020 to 12.5% by 2030 and reach 50% by 2060, while the share of unabated fossil-ammonia decreases significantly (Figure 36). CO_2 capturing yields improve from 80% today to 95% by 2060. In the Accelerated 2050 Scenario, the CCS adoption rate in unabated fossil-ammonia increases sharply to 28% by 2030, given the industry's extensive experience in CO_2 capturing. The share of CCS adoption increases to 85% of total fossil-based ammonia production in Indonesia by 2050.

3.3.4 Decarbonization pathways

3.3.4.1 Near Zero 2060 Scenario

The ammonia industry in Indonesia has the potential and pathways to reduce its CO_2 emissions (both Scope 1 and Scope 2 emissions) to near zero by 2060. As shown in the Near Zero 2060 Scenario, it is technically feasible to achieve CO_2 emissions reduction even though domestic ammonia production increases by 20% by 2060 from the 2020 level.

Specifically, as shown in Figure 41, total CO_2 emissions (Scope 1 and 2) can be reduced from 26 $MtCO_2$ in 2020 to 4 $MtCO_2$ by 2060. The largest contributer to these CO_2 emission reductions is electrolytic ammonia technology, i.e., producing ammonia by using green hydrogen produced from electrolysis. By 2060, electrolytic ammonia will be responsible for 12 $MtCO_2$/year emissions reduction, as compared to the Reference Scenario.

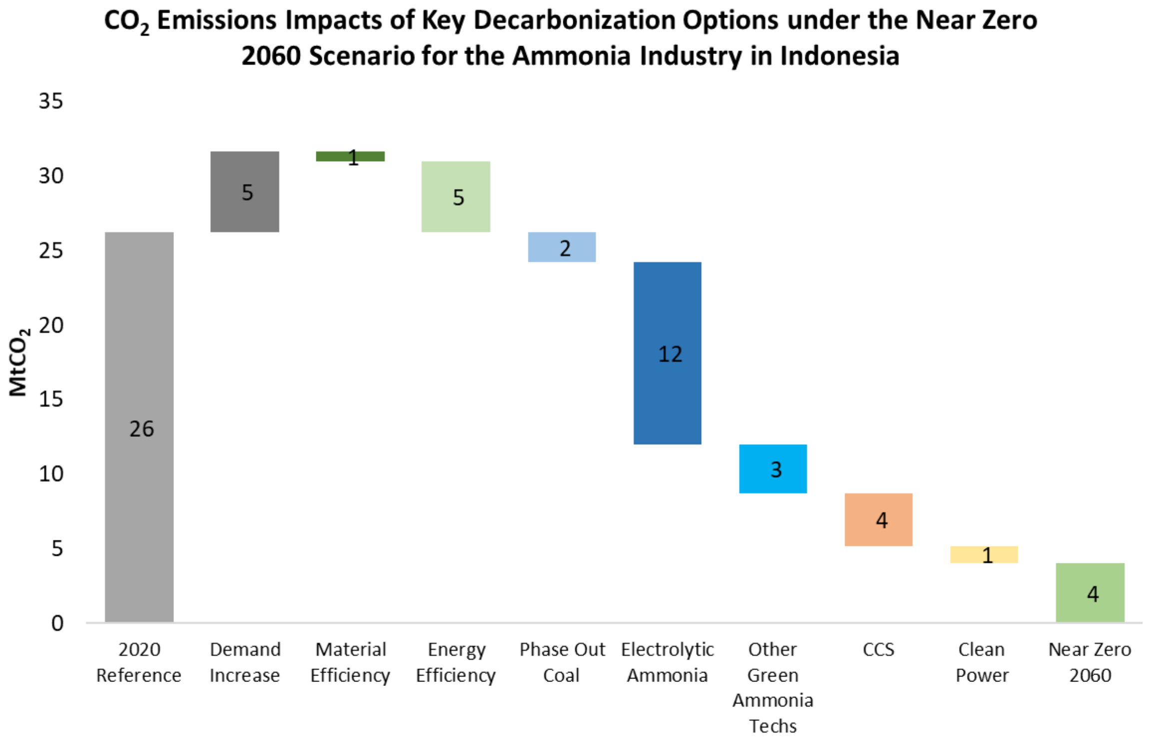

Figure 41. CO_2 emissions impacts of key decarbonization options for the ammonia industry in Indonesia: Near Zero 2060 Scenario

Source: LBNL analysis.

Energy efficiency improvement contributes the second largest CO_2 emission reduction (5 $MtCO_2$/year in 2060), and such savings can be realized in the near term in Indonesia's ammonia industry. In addition, phasing out coal and switching to other feedstocks will also bring near term CO_2 reduction results.

Other green ammonia technologies, such as biomass gasification and methane pyrolysis, can play a role in the mid to long term, as the technologies become more mature. In this analysis, we assumed that the biomass used will be sourced and managed sustainably.

Our analysis showed that in the near term, the Indonesian ammonia industry should completely phase out coal (if not already done) and significantly improve energy efficiency in existing facilities. Both strategies represent 31% of the total accumulative emission reductions from 2020 to 2030 (Figure 42, left). In the mid to long term, green ammonia technology is the key. Electrolytic ammonia, biomass gasification, and methane pyrolysis will contribute to almost 60% of the total emission reductions from 2030 to 2060 (Figure 42, right).

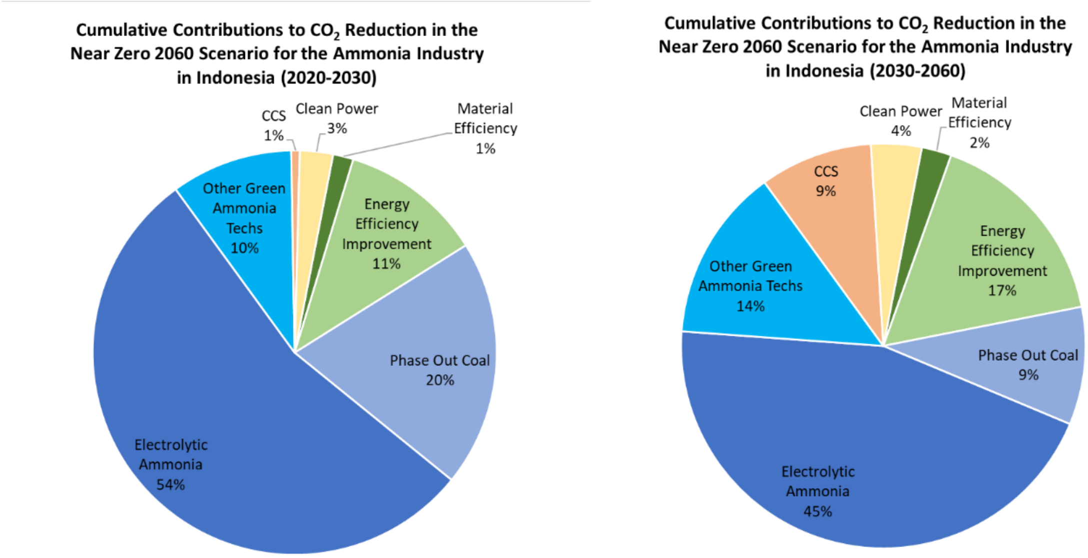

Figure 42. Cumulative contributions of key strategies of ammonia industry decarbonization: Near Zero 2060 Scenario, 2020-2030 and 2030-2060

Source: LBNL analysis.

3.3.4.2 Accelerated 2050 Scenario

The Accelerated 2050 Scenario showed that total CO_2 emissions from Indonesia's ammonia industry can be reduced to near zero by 2050. Total emissions can be reduced from 26 $MtCO_2$ in 2020 to 2 $MtCO_2$ in 2050, a reduction of 92% (Figure 43). Compared to the Near Zero 2060 Scenario, this scenario increased technology adoption ambitions in both green ammonia technology, as well as natural gas-based ammonia production with CCS (i.e., blue ammonia).

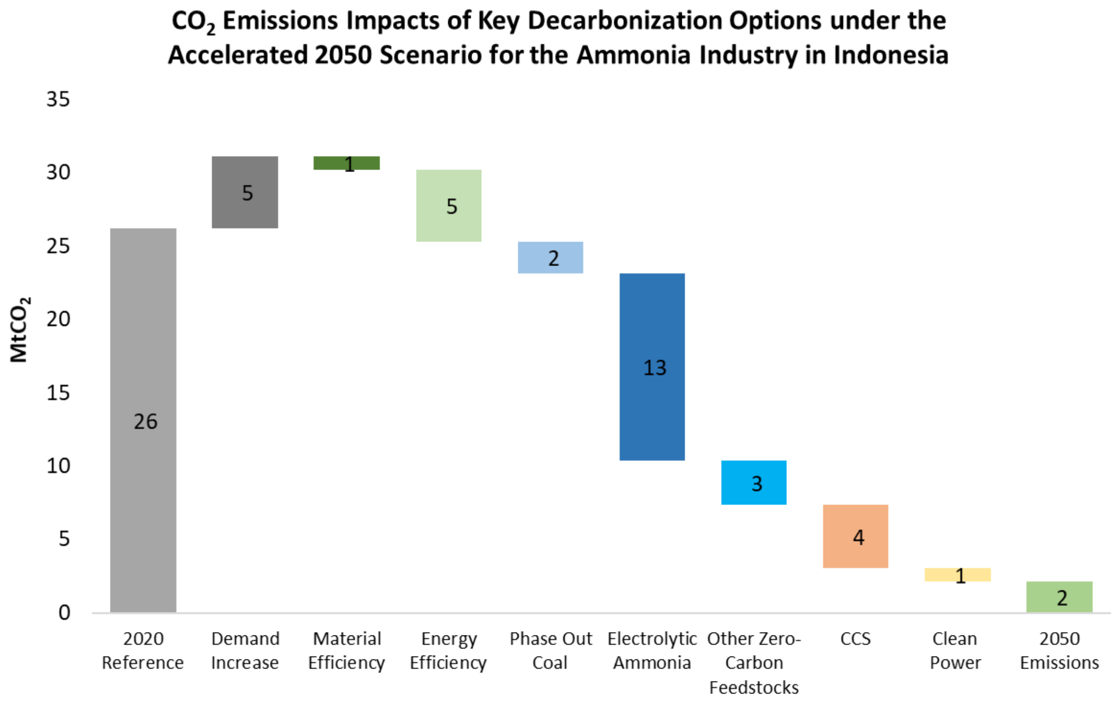

Figure 43. CO$_2$ emissions impacts of key decarbonization options for the ammonia industry in Indonesia: Accelerated 2050 Scenario

Source: LBNL analysis.

Specifically, electrolytic ammonia contributes the most CO$_2$ reduction potential by 2050, assuming green hydrogen and clean electricity is used for the production process, or 46% of total emission reduction potential. Biomass gasification and methane pyrolysis contribute another 11% of the total emission reduction potential by 2050. In the near term, energy efficiency improvement and phasing out coal represent 16% and 11% of the total emission reductions by 2050, respectively. To reach near zero emissions by 2050, the adoption of natural gas-based ammonia production with CCS systems was increased in the Accelerated 2050 Scenario. By 2050, CCS contributes to 10% of total emission reductions.

To support the decarbonization of the ammonia industry, the Indonesian government needs to develop a national strategy for the production, transportation, storage, and applications of green hydrogen. The national strategy on hydrogen should consider production sites, permitting processes, accessibility to renewable electricity, and prioritization of industry to use green hydrogen. Access to zero-carbon and low-cost electricity is important to incentivize the ammonia industry to transition to adopt electrolysis or other green ammonia production technologies. Last but not the least, to support the CCS implementation, Indonesia needs to focus on infrastructure development as well as coordination across industries (e.g., oil and gas extraction, other chemical industries, and the ammonia industry) for developing, accessing, and utilizing the infrastructure (e.g., pipelines, storage capacity, etc.).

3.4 Pulp and paper industry

3.4.1 Historical production and consumption

Indonesia is a main pulp and paper producer globally, accounting for 5% of the world's wood pulp production in 2020 (FAO 2023a). The pulp and paper industry consumed 6.7% of Indonesia's manufacturing energy use in 2020 (Park 2021). It also plays an important role in the Indonesian economy, directly employing about 160,000 workers and indirectly affecting 1.2 million jobs.[9] By 2020, the pulp and paper industry accounted for about 0.7% of the national GDP, or almost 4% of non-oil and gas processing GDP in Indonesia (Fitriana 2023 and FGD discussion).

Indonesia's total pulp production has been increasing rapidly, at 6% per year on average from 2015 to 2021 (Figure 44). Chemical wood pulp is the dominate production process, accounting for 85% of total pulp production in 2021. Mechanical and semi-chemical wood pulping represented 3% of total production (FAO 2023b). Most of the pulp produced is used to produce paper. Pulp production for paper increased from 7.1 Mt in 2015 to almost 9 Mt in 2021 (Figure 44).

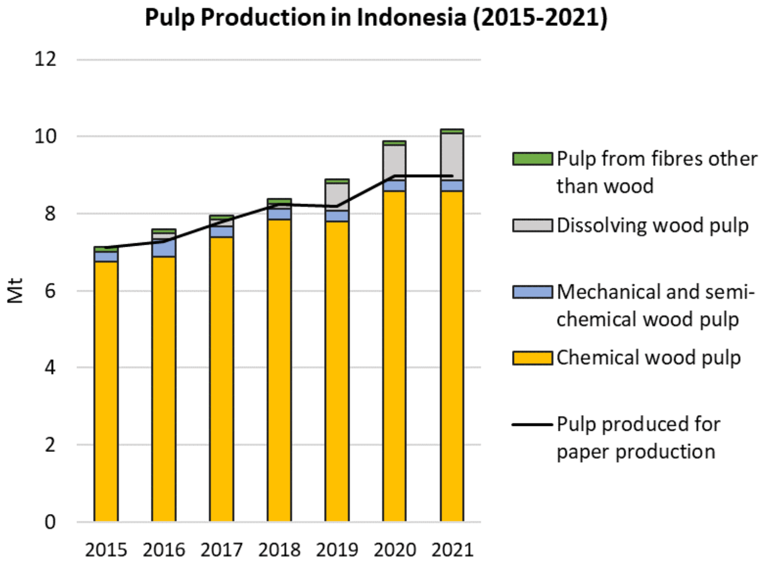

Figure 44. Total pulp production in Indonesia (2015–2021)

Source: FAO 2023b.

Indonesia's total paper production increased slower than its pulp production, growing from 10.6 Mt in 2015 to about 12 Mt by 2020, increasing on average 3% per year (FAO 2023b). About 43% of total paper production consists of graphic papers, i.e., newsprint and printing and writing papers (Figure 45). Another 48% of total paper production is packaging paper and paper board, including case materials, carton boards, and wrapping papers. Sanitation papers, industrial papers, and other paper types accounted for 9% of Indonesia's total paper production.

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[9] Based on conversation with representatives from Ministry of Industry during the FGD discussion in June 2023.

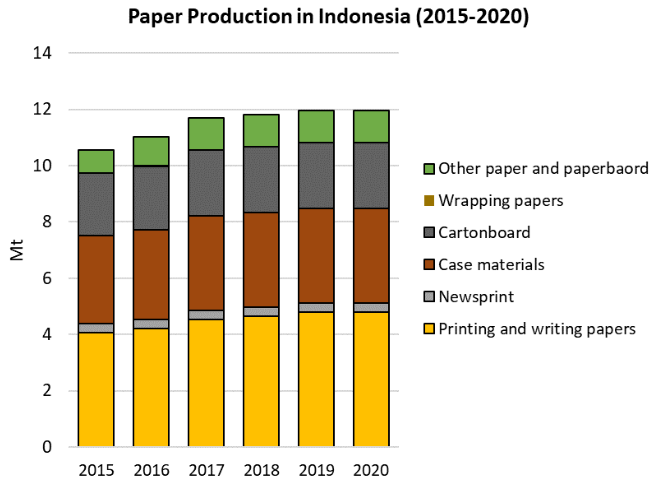

Figure 45. Paper production in Indonesia (2015–2020)
Source: FAO 2023b.

Indonesia exports a significant share of pulp and paper products. From 2015 to 2020, the share of pulp net exports averaged 40% of the total production. During the same period, the share of paper product net exports averaged 34% of the total domestic production (FAO 2023b).

Given the high levels of pulp and paper exports, Indonesia's domestic paper consumption has stayed relatively flat, increasing only slightly, from 4.6 Mt in 2015 to 4.9 Mt by 2020. On a per capita basis, Indonesia's paper consumption has declined over the years, due to population growth, from 27 kg/capita to less than 25 kg/capita by 2020. This per-capita paper consumption level is quite low, less than 50% of the world average (55 kg/capita). Indonesians' paper consumption is only 32%–35% of other Asian countries (Singapore and China) and significantly lower compared to the per-capita consumption in Western Europe and North America (Figure 46).

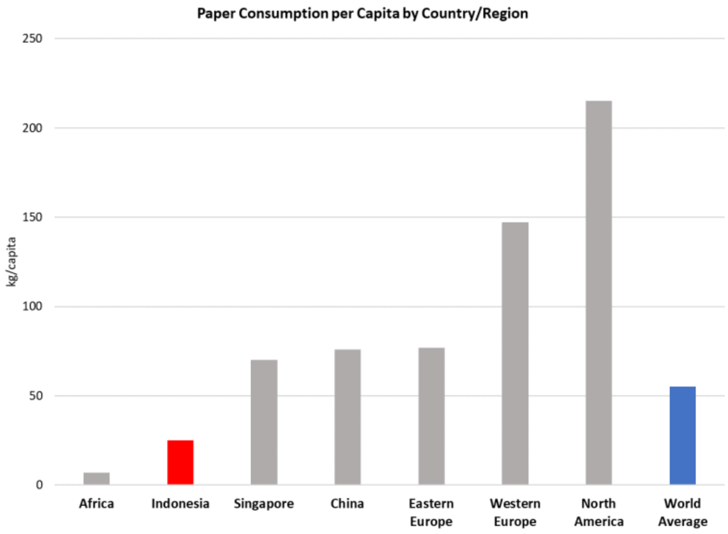

Figure 46. Paper consumption per capita in Indonesia and selected countries and regions

3.4.2 Production forecast

It is expected that Indonesia's pulp and paper production will continue to increase, driven by improved living standards domestically and export demand. By 2035, domestic paper demand is projected increase to 35 kg/capita, the average Association of Southeast Asian Nations (ASEAN) country level. By 2060, per-capita paper consumption will increase to 76 kg/capita (today's average level in China) under the Reference Scenario. In the Near Zero 2060 Scenario, per-capita consumption will increase to 70 kg/capita (today's average level in Singapore). The Accelerated 2050 Scenario assumes average paper consumption in Indonesia increases to today's global average by 2050.

In addition to domestic demand, export demand plays an important role in Indonesia's pulp and paper industry. Given uncertaintities in modeling long term trade activities, we assumed the net export amount is fixed at 4 Mt, which was the average level beween 2018 and 2021.

As shown in Figure 47, total paper production in Indonesia is expected to increase to almost 29 Mt by 2060 in the Reference Scenario and 26 Mt by 2060 in the Near Zero 2060 Scenario.

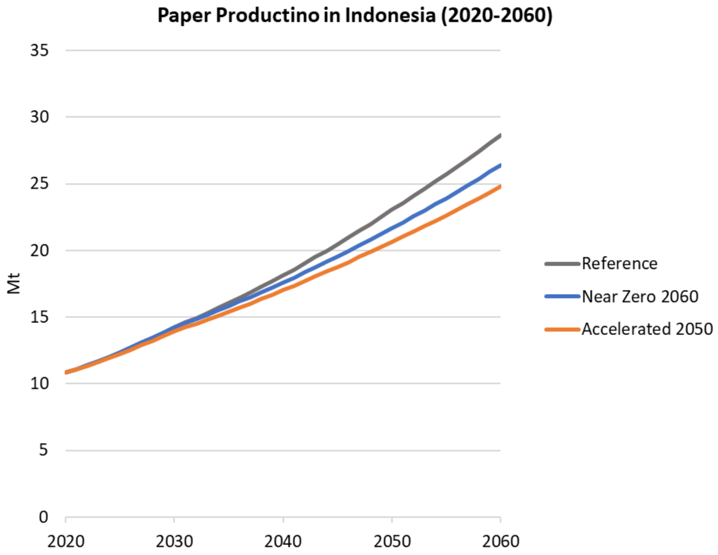

Figure 47. Paper production in Indonesia (2020–2060)

Source: LBNL analysis.

Three main types of paper products are produced in Indonesia, including graphic papers (newsprint, printing and writing papers), packaging (corrugated paper and Kraft paper), and domestic and sanitary papers (e.g., toilet paper, paper towels, diapers). In this analysis, we expected that the share of graphic papers may decline over time, driven by use of multimedia and digitalization. But the shares of packaging papers and domestic and sanitary papers are likely to increase (Figure 48), driven by improved living standards.

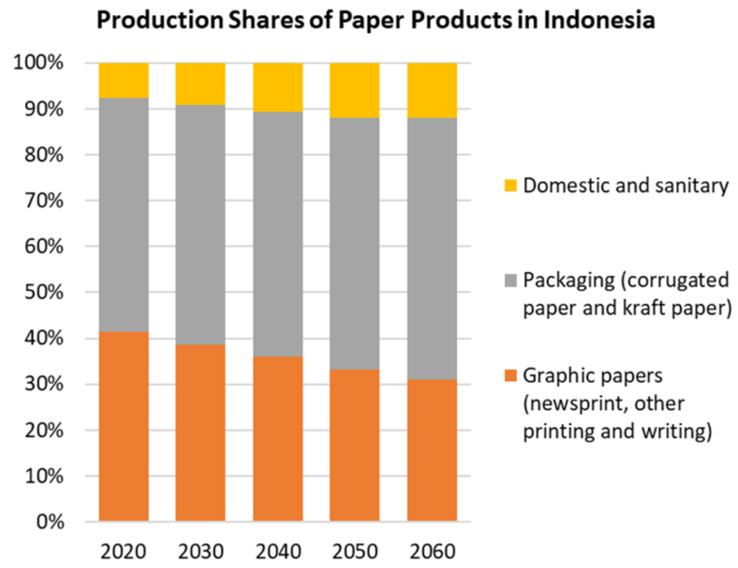

Figure 48. Production shares of paper production in Indonesia
Source: LBNL analysis.

3.4.3 Decarbonization strategies and technologies

3.4.3.1 Pulp and paper manufacturing processes

Pulp and papermaking processes are complex and highly integrated (Bajpai 2015). Figure 49 shows a simplified process flow from wood preparation to pulping, chemical recovery, washing and screening, and bleaching to papermaking.

In an integrated pulp and paper mill, the process starts with wood debarking, chipping, screening, and cleaning. Virgin pulp can be produced by either chemically separating the cellulous with lignin or doing so mechanically.

In a Kraft chemical pulping process, which is the dominant one used today, cleaned chips are cooked in a pressure cooker (digester) with chemicals. Steam with specific pressures is used in the digester. The cooking liquor (black liquor) contains lignin and is utilized in a recovery boiler to produce steam and recover the chemicals used in the digestion process. Bark from the wood preparation stage is also used as fuel in a bark boiler to produce steam. In the cogeneration facility, steam and electricity are produced and used in both the pulping and papermaking processes. The cooked pulp discharged from the digester then is washed, screened, and cleaned before it is chemically bleached. Bleached and unbleached pulp is then mixed with water to form a slurry (with 1% fiber content). The slurry is cleaned and screened before it goes through the paper machines to be formed, pressed, dried, and treated to become paper products.

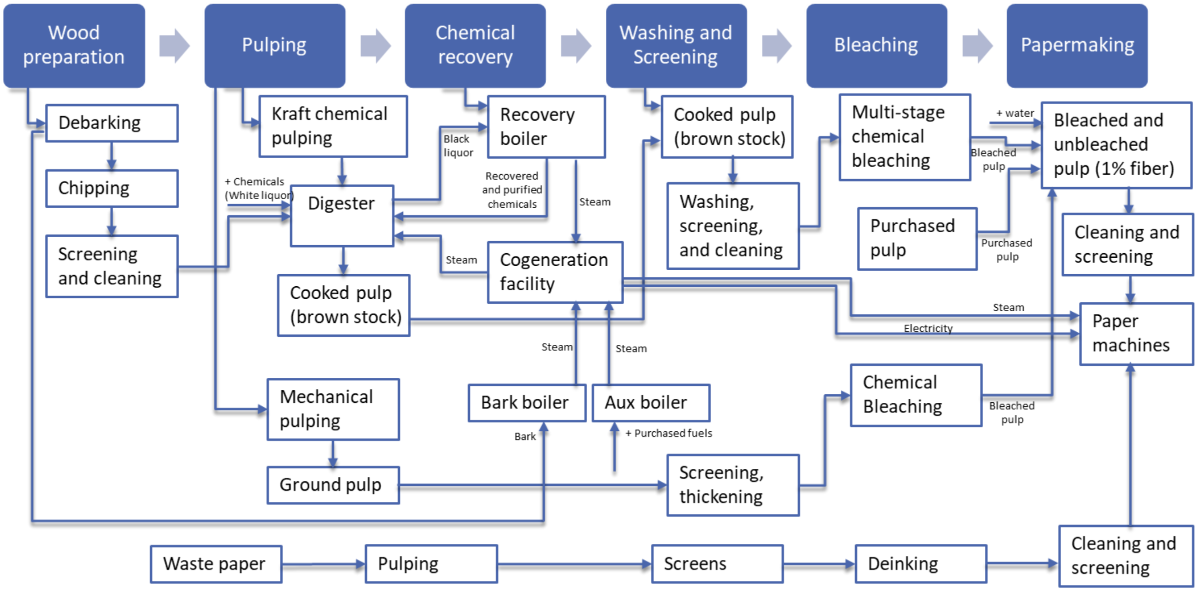

Figure 49. Simplified pulp and papermaking process
Source: LBNL analysis.

In a stand-alone paper mill, where pulp is not produced onsite but purchased, the purchased pulp will go through a pulper, be cleaned and screened, and then be fed into the paper machines. When recycled paper is used, collected waste paper goes through a similar pulping process, washing, and screening. Chemicals are used to remove the ink on waste paper, before it is cleaned and screened for the papermaking process.

In terms of energy use and CO_2 emissions, the pulping process accounts for the majority of energy use in the pulp and paper industry. The more dominant Kraft chemical pulping process emits significantly more CO_2 emissions than the mechanical pulping process (Onarheim et al. 2017).

3.4.3.2 Improving energy efficiency

Several factors play a role in the overall pulp and paper energy intensity. These include production capacity, the manufacturing process, whether to use recycled papers, whether it is an integrated or stand-alone process, any installation of cogeneration of electricity and heat, and the types of paper products produced.

In Indonesia, the pulping industry is dominated by five large integrated companies (including six pulp mills), most notably Asia Pulp & Paper (APP), Asia Pacific Resources International Ltd (APRIL), and Marubeni. APP and APRIL are the two biggest pulp and paper companies, and were responsible for 95% of Indonesia's pulp export during 2015-2019 (Trase insights 2021). Indonesia has 95 papermaking producers in the papermaking industry.

The vast majority of the virgin pulp produced in Indonesia is from the chemical pulping process, with an estimated share of 95% by 2020. In terms of recycled fibers, about 10% of the total pulp (for paper making) came from recycled materials in Indonesia.

Based on APP's sustainability reports (APP 2023) and international sources from the US (US DOE 2015b), EU (Worrell et al. 1994; Laurijssen et al. 2010; Cepi 2023; Suhr et al. 2015), Japan (Ministry of Economy, Trade and Industry of Japan 2022), China (Kong et al. 2020), and global studies (Kong, Hasanbeigi, and Price 2016; Park 2021), we estimated that the average heating and electricity demand of virgin pulp making in Indonesia is 16.5 GJ/t and 631 kWh/t, respectively. Compared to pulpmaking using virgin pulp, using waste paper for pulp production can significantly reduce the thermal energy demand. The papermaking process in Indonesia has a weighted average thermal and electric energy intensity of 6.1 GJ/t and 792 kWh/t, respectively (Table 16).

Compared to the BAT, Indonesia's pulp and paper industry can still be improved. It is expected that the energy intensity of all the key processes can be reduced to the BAT level by 2060 in the Near Zero 2060 Scenario by adopting energy-efficient technologies as well as innovations in technologies that can reduce heating demand and increase heat recovery, such as advanced steam-cleaning technologies, non-thermal water removal systems, and drying paper without water (IEA 2023c).

Table 16. Energy intensity of pulp and papermaking in Indonesia (2020)

Process	Heat Demand (GJ/t)	Electricity Demand (kWh/t)	BAT - Heat Demand (GJ/t)	BAT- Electricity Demand (kWh/t)
Virgin pulp (Kraft process)[a]	16.5	631	12	556
Pulping from recycled fibers[b]	1.2	700	0.54	611
Papermaking[c]	6.1	792	4.8	694

Source: LBNL analysis

Notes: (a) Heat and electricity intensities for virgin pulp (Kraft process) does not include heat and electricity generated from the cogeneration facility. Energy recovery from black liquor is an important component of the integrated pulp and paper mill, and this recovery provides heat and electricity to both pulp and papermaking processes. (b) The energy intensity of pulp-making from recycled paper varies by the type of waste paper used. (c) The energy intensity of papermaking varies based on the type of paper products produced. Indonesia energy intensity for papermaking is calculated based on the weighted average of the energy intensity of the paper products.

Many energy-efficient technologies exist (Table 17) to improve the energy intensity of the pulp and paper industry. Technologies that improve the efficiency of chemical pulping (such batch digester modification and steam cycle washing), chemical recovery (e.g., black liquor concentration and gasification), papermaking (such as dry sheet forming), and energy management practices can save fuel and/or electricity.

Table 17. Energy-efficiency technologies and saving potential in pulp and paper industry

Process	Energy Efficiency Technologies	Final energy savings (GJ/t or % of energy reduction)	Energy Savings Type
Chemical Pulping	Batch digester modifications	3.2	Fuel
Chemical Pulping	Continuous digester modifications	0.97	Fuel
Chemical Pulping	Directed Green Liquor Utilization Pulping	25%	Fuel
Chemical Pulping	Microwave Pre-treatment for Chemical Pulping	2.11	Fuel
Chemical Pulping	Steam Cycle Washing	40% overall	Fuel
Chemical Pulping	Low Energy Flotation	Reduces flotation energy use by 33%	Electricity
Chemical Recovery	Falling film black liquor evaporation	0.8	Fuel
Chemical Recovery	Black liquor concentration	0.76	Fuel
Chemical Recovery	Lime kiln modifications	0.46	Fuel
Mechanical Pulping	Chemical Pre-treatment with Oxalic Acid for Mechanical Pulping	20%–30% refiner energy use savings	Electricity
Mechanical Pulping	Biological Pre-treatment for Mechanical Pulping	25%–40% refiner energy savings	Electricity
Mechanical Pulping	Refiner improvements	1.1	Electricity
Mechanical Pulping	Heat recovery in thermo-mechanical process mill	2.66	Fuel
Pulp Bleaching	Chlorine dioxide preheating	0.59	Fuel
Papermaking	High-efficiency double-disc refiners	0.06	Electricity
Papermaking	Shoe press	1.49	Fuel
Papermaking	Stationary siphons	0.89	Fuel
Papermaking	Turbulent bars	0.59	Fuel
Papermaking	Enclose paper machine hood	1.59	Fuel
Papermaking	Air system optimization	0.2	Fuel
Papermaking	Waste heat recovery	0.5	Fuel
Papermaking	Anaerobic wastewater treatment and methane utilization	0.2	Fuel (produce fuel)
Papermaking	Sludge recovery and utilization	0.28	Fuel (produce fuel)
Papermaking	Vacuum system optimization	0.02	Electricity
Papermaking	Dry Sheet Forming	50% energy reduction at the drying stage	Electricity
Papermaking	Fibrous fillers	Reduce overall energy consumption by 25%	Electricity and Fuel
General Measures	Adjustable-speed drives	0.04	Electricity
General Measures	Energy-efficient lighting	0.05	Electricity
General Measures	Steam traps maintenance	1.79	Fuel
General Measures	Condensate return	0.21	Fuel
General Measures	Real-time energy management system	0.4	Fuel

Sources: Kong, Hasanbeigi, and Price 2016; Kong et al., 2017.

3.4.3.3 Industrial electrification and renewable heating

Some of the most important levers to decarbonize the pulp and paper industry are through electrification of the processes, increased onsite renewable electricity generation, and use of low-carbon fuels. As the cost of renewable technologies continues to decline and the power sector decarbonizes, electrification is an increasingly promising low-carbon option for industry. While decarbonizing high-temperature manufacturing processes will be challenging, increasing the rate of electrification using zero-carbon electricity is an important near term strategy to decarbonize lower temperature industrial processes, such as low-temperature pulping using recycled fibers and paper drying in papermaking processes. The use of zero-carbon electricity has other non-energy benefits, such as increased productivity, improved product quality, enhanced operational and worker safety, increased manufacturing flexibility, reduced waste production, and reduced cost of environmental compliance (Rightor and Elliott 2020).

Commercialized electrotechnologies are available, and more are emerging. A selected list of electrotechnologies that may be applicable to provide industrial heat is presented in Appendix C (Table C-1). Electric boilers, hybrid boilers, and low-temperature industrial heat pumps are already commercially available and can be adopted in many industries that have steam demand. Higher-temperature industrial heat pumps are also emerging to further electrify process heat.

In addition to electrotechnologies which rely on electricity to provide industrial heating, renewable heat technologies, such as solar and geothermal heating technologies, can be considered. These technologies can provide relatively high temperature (up to 200°C) (US EPA 2023 and Figure 66).

In the virgin pulp production process, we estimated about 80% of the current fuel inputs in Indonesia are from biomass (including black liquor). The remainder of the fuel inputs are from a combination of coal, natural gas, and diesel products. In the Near Zero 2060 Scenario, fossil fuels are to be phased out by 2060; while the use of biogas (through biomass gasification and black liquor gasification) and renewable heating will be increased (Figure 50).

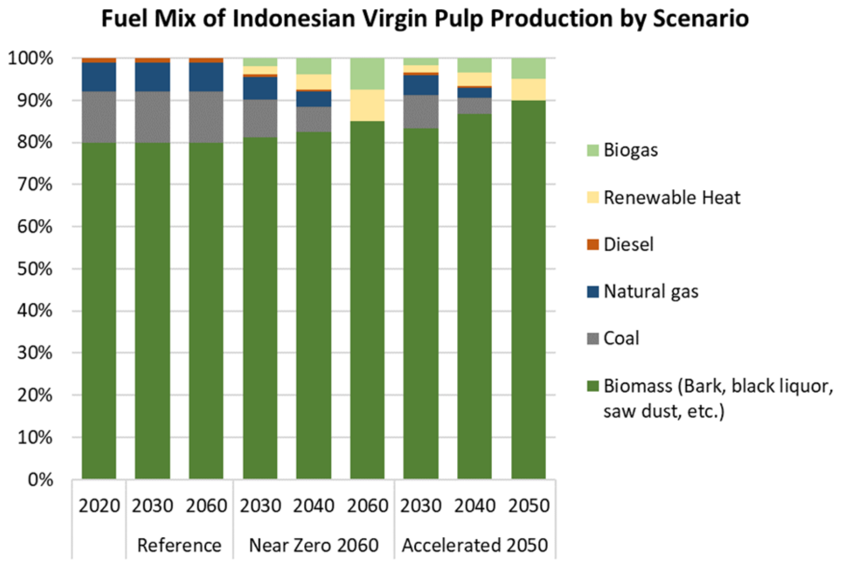

Figure 50. Fuel mix of virgin pulp production in Indonesia by scenario

Source: LBNL analysis.

In the pulping process based on recycled paper, the major processes are dissolving waste paper, re-pulping, mechanically removal impurities, deinking (if needed), and bleaching (if needed). The process requires relatively low-temperature heat and electricity. Currently, we estimated in Indonesia, about 60% of the fuel inputs to the recycled fiber process are biomass (e.g., utilizing recycled papers in integrated pulp and paper mills). In the Near Zero 2060 Scenario, the uses of fossil fuels are to be significantly reduced from 40% in 2020 to 5% by 2060, while the shares of electrified heat and renewable heat will increase to 30% and 5% by 2060, respectively (Figure 51).

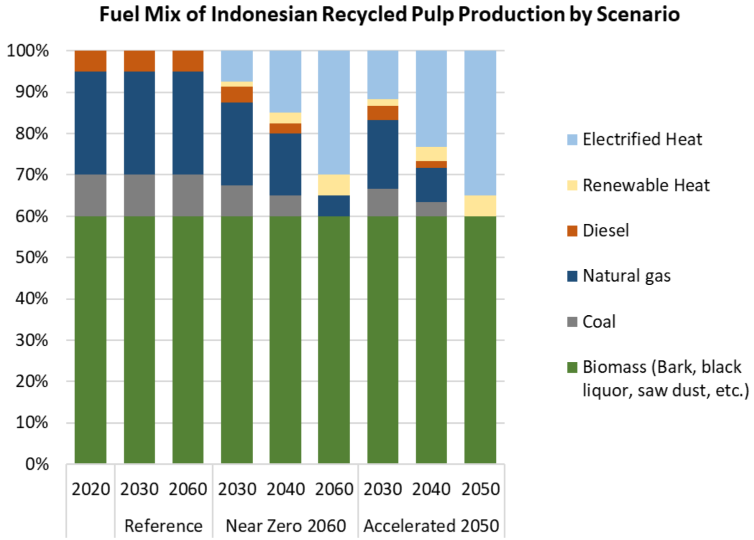

Figure 51. Fuel mix of recycled pulp production in Indonesia by scenario
Source: LBNL analysis.

In the integrated papermaking process, the share of biomass (including black liquor) in total fuel inputs of papermaking slowly increases from 50% in 2020 to 60% by 2060 in the Near Zero 2060 Scenario. Electrified heating and renewable heating, such as using industrial heat pumps, electric boilers, concentrated solar, and geothermal, will be increased, together accounting for 30% by 2060 (Figure 52). Coal and diesel products are phased out by 2060.

Considering that stand-alone paper mills have limited access to biomass, we assumed biomass only accounted for 10% of the final fuel use in this process in Indonesia, and that it stays at this level through 2060. In the Near Zero 2060 Scenario, the use of coal and other fossil fuels will be significantly reduced, replaced by use of electrified heating and renewable heating. By 2060, the share of non-fossil fuel supply represents 80% of the total fuel inputs in the stand-alone papermaking process (Figure 53).

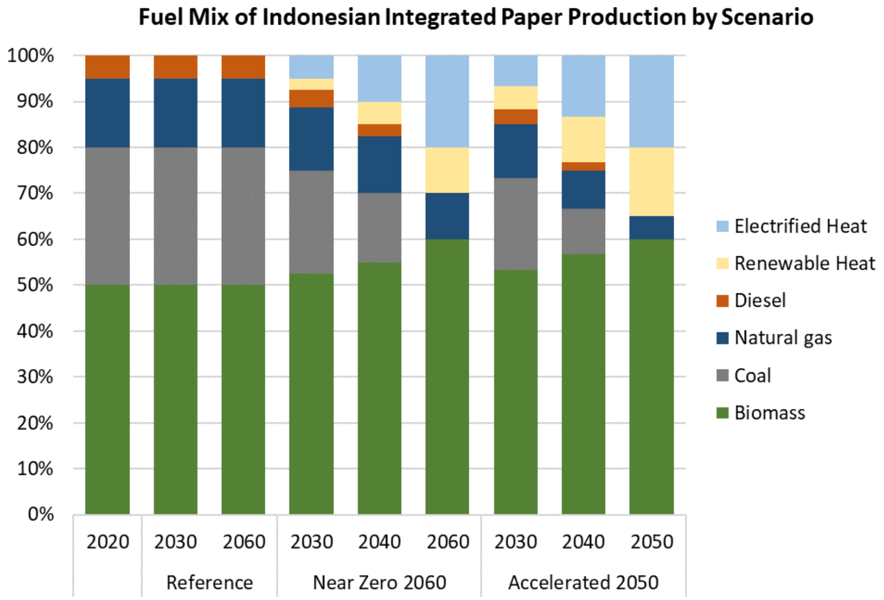

Figure 52. Fuel mix of integrated paper production in Indonesia by scenario
Source: LBNL analysis.

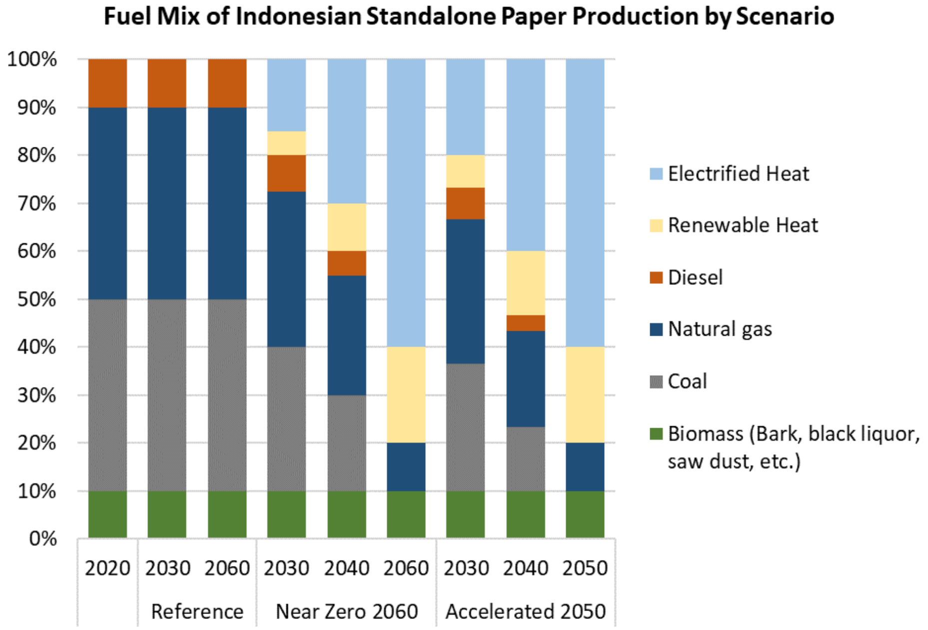

Figure 53. Fuel mix of stand-alone paper production in Indonesia by scenario
Source: LBNL analysis.

3.4.3.4 Increased recycling and utilization of waste paper

As shown in Table 16, producing pulp and paper from recycled waste paper can significantly reduce energy demand and also potentially CO_2 emission reductions.[10] Recycled waste paper can avoid emissions from incineration or landfills, while also providing an alternative to virgin pulp. The pulping process from recycled paper is much less energy-intensive than the chemical pulping process, as it only requires dissolving the shredded paper in hot water to separate fibers mechanically (Rahnama Mobarakeh, Santos Silva, and Kienberger 2021).

Recycled pulp can be utilized by both integrated mills and stand-alone paper mills. In this analysis, we considered the share of recycled pulp in total pulp production. Given the current (year 2020) waste paper utilization rate in industrialized countries reached, on average, more than 50% (43% in the United States, 56% in European Union, 76% in Japan) (Ministry of Economy, Trade and Industry of Japan 2022), in the Near Zero 2060 Scenario, we expect the share of recycled fiber in total pulp-making to increase to 50% by 2060 in Indonesia. This would significantly exceed the utilization rate assumption of recycled paper (20% in total pulp production by 2060) under the Reference Scenario (Figure 54).

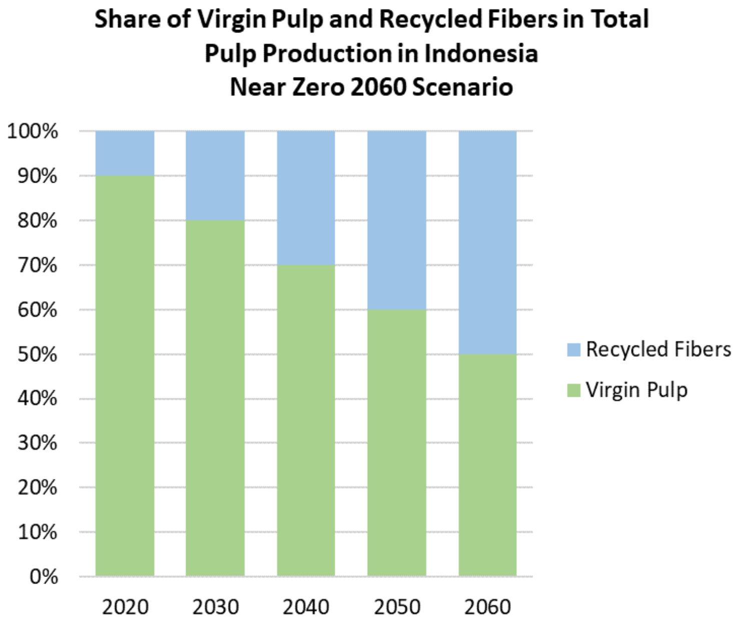

Figure 54. Share of recycled pulp in Indonesia's total pulp production: Near Zero 2060 Scenario
Source: LBNL analysis.

To achieve this, Indonesia needs to improve and strengthen the current waste paper collection, sorting, and recycling systems. Advanced technologies to sort, recover, and reuse various types of waste papers need to be adopted.

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[10] Environmental impacts of recycled fibers and virgin pulp vary by types of wastes papers, pollutant categories, and key variables (e.g., transportation distances). Studies generally found recycled paper products have lower environmental impacts (Laurijssen et al. 2010; Hong and Li 2012; Gemechu et al. 2013).

3.4.3.5 CCS

Globally, the pulp and paper industry has been exploring the option of CCS. In an integrated pulp and paper mill or a stand-alone pulp mill, biomass accounts for the vast majority of energy inputs. It is reported that 75% to 100% of the CO_2 emissions from a modern integrated or stand-alone pulp mill is biogenic (Onarheim et al. 2017). Thus, capturing and permanently storing CO_2 emissions from the pulp and paper mills can potentially support the facility to be carbon neutral or even carbon negative. Bioenergy with carbon capture and storage (BECCS) can capture CO_2 emissions in the flue gasses from the recovery boilers, bark boilers, and auxiliary boilers (that are using fossil fuels) in integrated or stand-alone pulp mills. In addition, CCS systems also can be installed in stand-alone paper mills.

Studies showed that currently post-combustion capture of CO_2 emissions using amine (MEA) from recovery and bark boilers may offer the highest CO_2 reduction potential (Furszyfer Del Rio et al. 2022). Performance of post-combustion CCS retrofits on existing pulp and paper mills can be very site specific, as thermal and electrical energy demand depend on the existing power and steam production onsite (Onarheim et al. 2017). In terms of cost, studies on the European and global pulp and paper industry reported a range of CO_2 mitigation costs, from €18 to €100 per tCO_2 avoided (\$19 to \$105 USD/tCO_2)[11] (Yang, Meerman, and Faaij 2021; Furszyfer Del Rio et al. 2022).

For Indonesia, this study did not consider large-scale adoption of CCS or BECCS systems in the pulp and paper industry. In both scenarios, CCS systems are implemented, but with limited adoption rates, increasing from zero in 2020 to 3% by 2030 and 8% by 2060 in the Near Zero 2060 Scenario (8% by 2050 in the Accelerated 2050 Scenario). This consideration was based on the technical demand of the significant engineering capacity required to design, build, construct, and operate complex CCS systems that are compatible with existing onsite power and steam production, the economic demand to invest and finance the CCS system, and the infrastructure challenge to transport and store the captured CO_2.

3.4.4 Decarbonization pathways

Unlike the other sectors covered in this report (iron and steel, cement, ammonia, and textiles), for the pulp and paper industry this analysis focused only on Scope 1 CO_2 emissions, i.e., CO_2 emissions associated with fossil fuel onsite combustion. Recognizing that Scope 2 CO_2 emissions (CO_2 emissions from grid electricity) is a significant contributor to the industry's overall CO_2 emissions, and that decarbonizing the pulp and paper industry requires fast decarbonization of the power sector in Indonesia, we focus on Scope 1 to highlight the potential and pathways to achieve net-zero in the pulp and paper industry itself.

3.4.4.1 Near Zero 2060 Scenario

Our analysis showed that in the Near Zero 2060 Scenario, the pulp and paper industry in Indonesia can achieve near zero CO_2 emissions (Scope 1 emissions) by 2060, while total paper production increases 144% by 2060 from the 2020 level (Figure 55).

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[11] Based on 2022 average exchange rate of 1 Euro = 1.0538 USD. Source: https://www.exchangerates.org.uk/.

The largest emission reduction potential of Scope 1 emissions comes from increased industrial electrification and adopting renewable heat technologies to replace coal, natural gas, and other fossil fuel products in the pulp and paper making process.

To highlight the impact of industrial electrification and phasing out fossil fuels, we separated the electrification strategies into two possible routes: (1) switching from coal to biomass and renewable heating, and (2) switching from natural gas to electrification, as shown in Figure 50. However, depending on specific conditions at the pulp and paper mill, accessibility to biomass materials and renewable heat resources, any onsite renewable electricity generation, and the local cost of electricity, the facility may choose to switch directly from coal to electricity for industrial heating, or switch from natural gas to biomass/renewable heating technologies.

To reduce both Scope 1 and 2 CO_2 emissions, it is critical for Indonesia's power sector to decarbonize faster than the industrial sector, and realize a zero-carbon grid well before 2060.

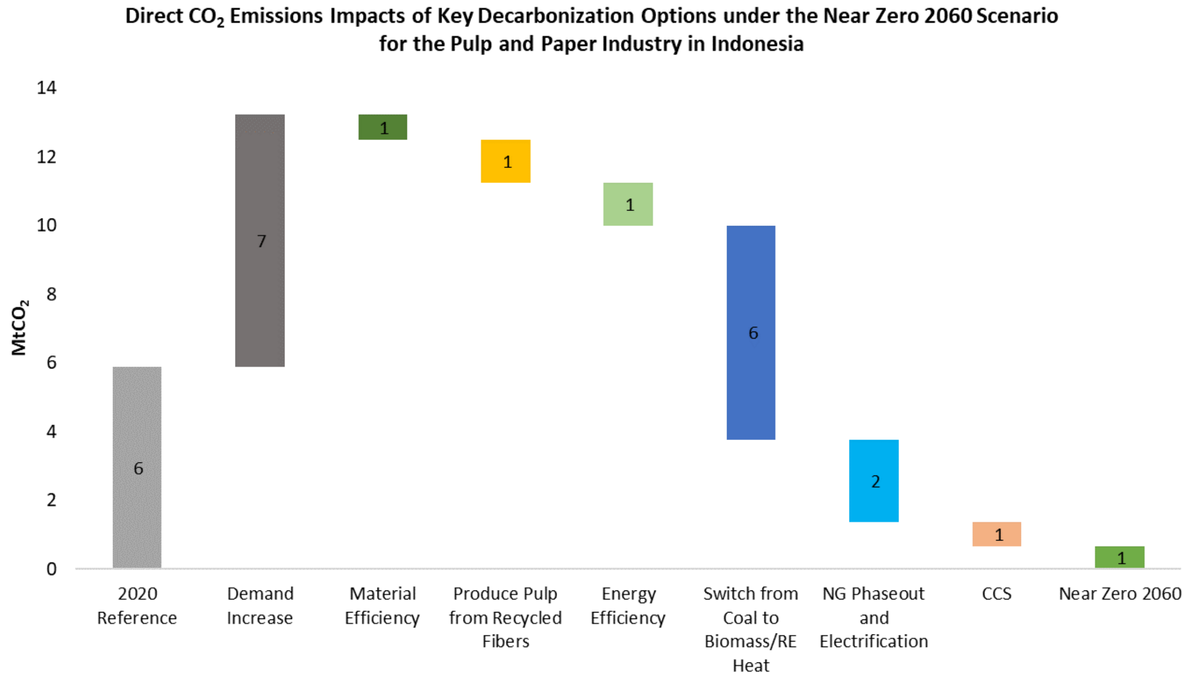
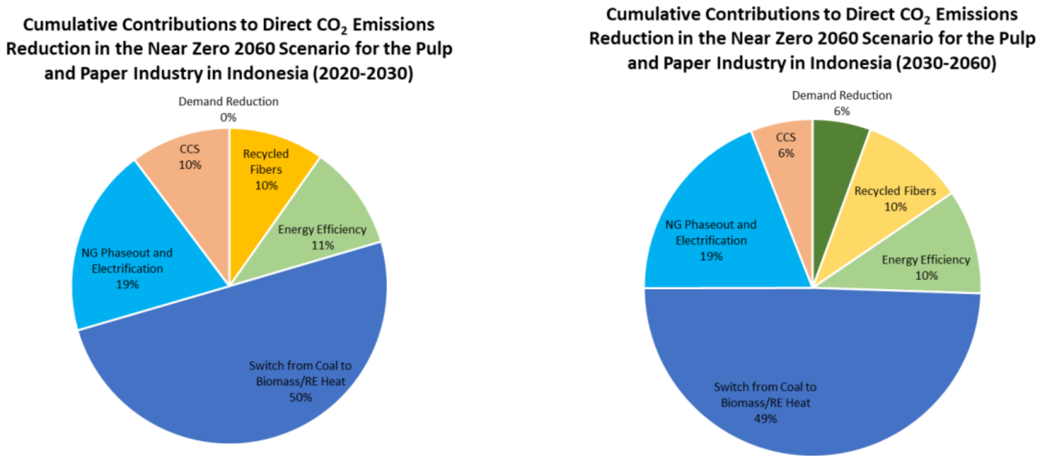


Figure 55. Direct CO_2 emissions impacts of key decarbonization options for the pulp and paper industry in Indonesia: Near Zero 2060 Scenario
Source: LBNL analysis.

Electrification and renewable heating technologies play the most important role in reducing CO_2 emissions in the Indonesian pulp and paper industry, in both the near term (2020–2030) and the mid to long term (2030–2060), accounting for 69% and 68% of the total cumulative CO_2 emission reduction potential during the respective periods (Figure 56).

The analysis also showed that increased use of recycled fibers to produce pulp and a continued strengthening of energy efficiency can each deliver 10% of CO_2 emission reductions by 2030. Demand reduction measures to improve material efficiency through digitalization and use of multimedia accounts for 6% of the total cumulative CO_2 reductions from 2030–2060.


Cumulative Contributions to Direct CO_2 Emissions Reduction in the Near Zero 2060 Scenario for the Pulp and Paper Industry in Indonesia (2020-2030)

Cumulative Contributions to Direct CO_2 Emissions Reduction in the Near Zero 2060 Scenario for the Pulp and Paper Industry in Indonesia (2030-2060)

Figure 56. Cumulative contributions of key strategies of pulp and paper industry decarbonization: Near Zero 2060 Scenario, 2020-2030 and 2030-2060

Source: LBNL analysis.

It should be noted that electrification of the current heating process in papermaking faces many barriers. First, as discussed earlier, heat and power in an integrated pulp and paper mill is complex and highly integrated. Thus, replacing fossil fuels with electrotechnologies or renewable heating technology may require facilities to change their current thermal/electrical energy systems significantly. Second, upgrading the existing industrial heating systems not only requires investment to new equipment, but may also potentially require expansion of the electrical infrastructure, either onsite, outside the facility, or both. Third, facilities may be required to have backup redundancy in production capacity. This would mean that facilities may need to invest in additional equipment for their heating supply.

In addition to the technical challenges, electrification in the pulp and paper industry also faces economic, institutional, and market barriers, such as: high electricity prices, high capital cost of new technologies, lack of access to affordable financing, lack of awareness and know-how of electrotechnologies and renewable technologies, lack of access to commercialized technology, lack of credible information on technologies, a lack of qualified suppliers and vendors, and lack of performance information on electrotechnologies and renewable heating technologies.

Policy support is needed to accelerate the electrification progress in the pulp and paper industry in Indonesia. Facilities should be incentivized to develop their own onsite renewable or zero-carbon electricity generation. Permitting and grid connection with the larger grid should be allowed. Mechanisms such as green electricity certificate schemes can further enhance the development of onsite renewable generation.

Further incentives such as tax rebates on low-carbon technologies and low-cost financing should be considered to promote the adoption of electrotechnologies and renewable heating technologies. Governments can set up innovation R&D funds for low-carbon heating technologies. The industry will also benefit from technology guidebooks, as well as private-public partnerships to pilot, verify, and improve innovative technologies.

3.4.4.2 Accelerated 2050 Scenario

The Accelerated 2050 Scenario showed that total Scope 1 CO_2 emissions of the Indonesian pulp and paper industry can be further reduced and achieve almost zero emissions by 2050. As shown in Figure 57, direct CO_2 emissions of the industry increase to 11 $MtCO_2$ by 2050 under the Reference Scenario, but decline to 0.4 $MtCO_2$ by 2050 in the Accelerated 2050 Scenario.

Compared to the Near Zero 2060 Scenario, the further reduction of direct CO_2 emissions in the Accelerated 2050 Scenario is driven by a combination of factors, including more aggressive and early adoption of electrotechnologies and renewable heating technologies, achieving BAT energy intensity levels by 2050 (instead of 2060), increased use of recycled paper to reduce virgin pulp needs, and demand reduction through material efficiency. CCS plays a relatively small role in both the Near Zero 2060 and Accelerated 2050 Scenarios.

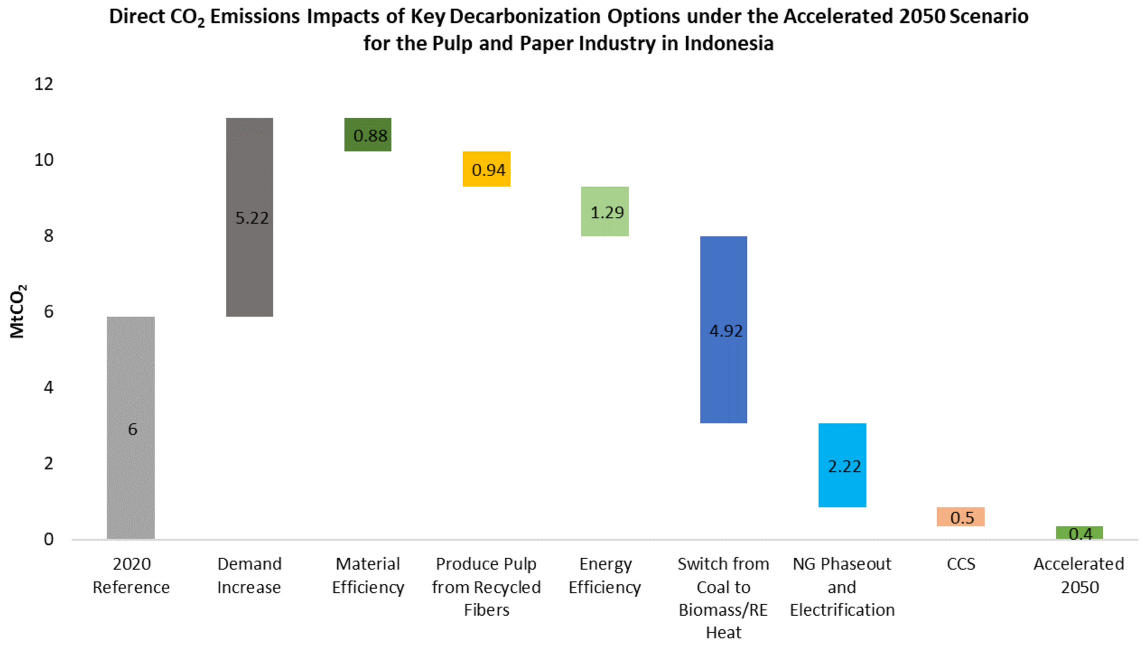


Figure 57. Direct CO_2 emissions impacts of key decarbonization options for the pulp and paper industry in Indonesia: Accelerated 2050 Scenario

Source: LBNL analysis.

3.5 Textile industry

3.5.1 Historical production and consumption

The textile industry plays an important role in Indonesia's economy. By 2020, the textile industry in Indonesia had about 540,000 enterprises, from fiber making to final product manufacturing. More than 99% of these are small and medium enterprises (SMEs) (USDA 2022), as shown in Table 18. The industry hired about three million people by 2021 (USDA 2022) and accounted for 6% of Indonesia's manufacturing value-added in 2021, or 1% of the national GDP (ARC Group 2022). In addition, Indonesian textiles and textile products produced an export value of $12 billion USD as of 2022 (Jakarta Globe 2023).

Table 18. Textile industry in Indonesia (2021)

Textile Industry	Fiber Making	Spinning	Weaving and Finishing	Garments	Other Textile	Total
Number of Large Companies	33	294	1,540	2,995	765	5,627
Number of Small and Medium Companies	14	-	131,000	400,000	-	531,014
Labor	33,087	244,059	678,360	1,788,265	89,507	2,833,278

Source: USDA 2022.

The COVID-19 pandemic significantly affected Indonesia's textile industry due to lockdowns, shop closures, and slowed consumption (Pearl 2022). Both yarn and fabric production declined, by 30% and 27%, respectively, in 2020 compared to the 2019 level (Figure 58). By 2021, production rebounded slightly, with a total yarn production of 1,637 thousand tonnes and a total fabric (weaving, knitting, and non-woven) production of 1,251 thousand tonnes (Indotextiles 2022).

Figure 58. Indonesia yarn and fabric production (2018–2021)

Source: Indotextiles, various years.

Indonesia’s fabric consumption per capita is much lower than the global average as well as the average level in advanced economies, as shown in Figure 59. In 2021, Indonesia’s per-capita fabric consumption was estimated to be 6.8 kg/capita, while the global average is reported to be about 10 kg/capita (Kohan Textile Journal 2022). Comparatively, the average level in EU-27 countries was estimated to be 14.8 kg/capita in 2020, with about 6.1 kg/capita of textiles demand in clothing, 6 kg/capita for footwear, and another 2.7 kg/capita for household textiles (European Environment Agency 2022). The average level in the US is even higher, estimated to be more than 30 kg/capita. The consumption of fabrics in Japan, Canada, and Australia is estimated to be in the range of 20–30 kg/capita (Kohan Textile Journal 2022).

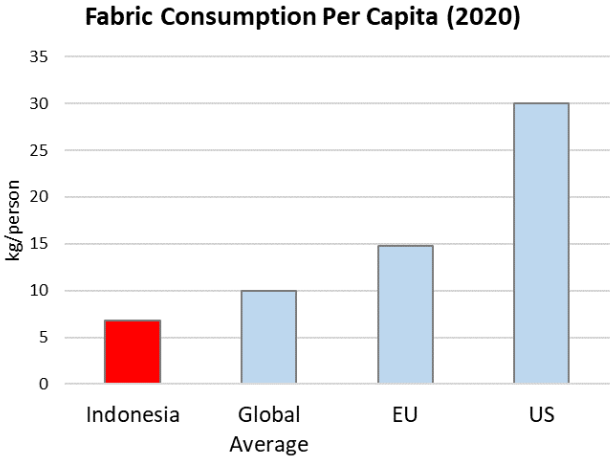


Figure 59. Fabric consumption per capita in Indonesia, world average, EU and US

Sources: Indotextiles, various years; Kohan Textile Journal 2022; European Environment Agency 2022.

3.5.2 Production forecast

In the Reference Scenario, we expect that Indonesia’s per-capita fabric consumption will continue to increase, reaching today’s global average level by 2035 and reaching a per-capita consumption level of 15 kg/capita by 2060. The Near Zero 2060 and Accelerated 2050 Scenarios considered the measures of circular economy, improvement in product quality, longer product lifetime, services for repair and reuse, and behavior changes to reduce fabric demand. The net imports of fabrics are fixed at 533 thousand metric tons, which was the average net imports amount between 2019 and 2021.

Total fabric production in Indonesia is projected to grow from 1,063 thousand metric tons in 2020 to 4,238 thousand metric tons by 2060 in the Reference Scenario, increasing at a rate of 3.5% per year on average (Figure 60). Total fabric production in the Near Zero 2060 Scenario has a slightly slower growth, increasing 3.2% per year on average during the same period. By 2060, total production increases to more than 3,800 thousand metric tons in the Near Zero 2060 Scenario. Total production in the Accelerated 2050 Scenario is almost the same as the Near Zero 2060 Scenario, reaching about 3,000 thousand metric tons by 2050.

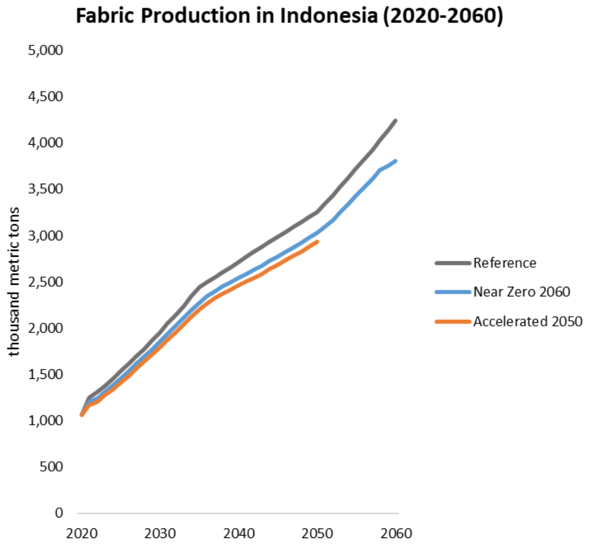


Figure 60. Fabric production in Indonesia (2020–2060)

Source: LBNL analysis.

3.5.3 Decarbonization strategies and technologies

3.5.3.1 Textile manufacturing processes

Upstream textile manufacturing includes fiber production and processing. Natural fibers such as cotton, linen, and wool, and manmade fibers such as polyesters and rayon, are commonly used in the textile industry. The cultivation, production, processing, and cleaning of the fibers also require a significant amount of energy, water, and materials inputs, such as diesel, fertilizers, water, and insecticides.

The core of textile manufacturing includes the following processes: spinning, surface structuring of weaving, knitting, non-woven processing, and wet-processing, as shown in Figure 61. The wet-processing stage also includes subprocesses such as pre-treatment, bleaching, dyeing, printing, and post-treatment (Palamutcu 2015). These are the key processes to turn fibers into yarn, make fabrics with the desired structures, and make fabrics with the desired colors and patterns. The downstream of the textile industry is garment manufacturing, where colored fabrics are cut up and sewed together to make specific intermediate and final finished products.

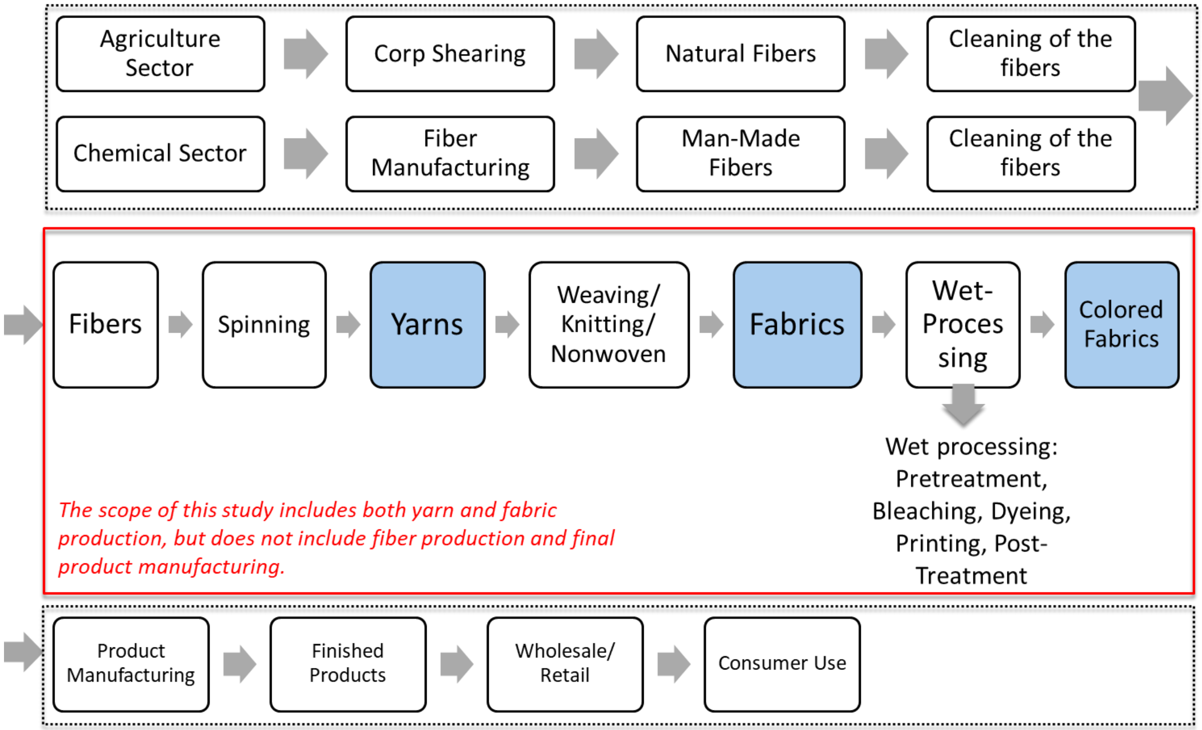


Figure 61. Simplified process flow of textile industry and scope of the analysis

Source: LBNL analysis.

It should be noted that not every textile manufacturing facility will have all of the manufacturing processes, although some integrated plants may have several processes in one single facility, while other plants may focus on niche areas and specialized products (Hasanbeigi and Price 2012). This analysis focused on the main textile manufacturing processes, including spinning, weaving/knitting/non-woven, and wet-processing, as circled in the red box in Figure 61.

In a typical integrated textile plant, where the processes of spinning, weaving/knitting, and wet-processing are all onsite, the spinning process consumes the most electricity, followed by the weaving process. As shown in Figure 62, studies show that spinning, weaving, and wet processing accounted for 41%, 18%, and 10%, respectively, of the total electricity end use at a typical textile plant. In terms of thermal energy demand, wet-processing (e.g., bleaching, desizing, dyeing, and printing) represented 50% of the total thermal energy demand. About 35% of the thermal energy demand is lost during steam production and distribution (Figure 62).

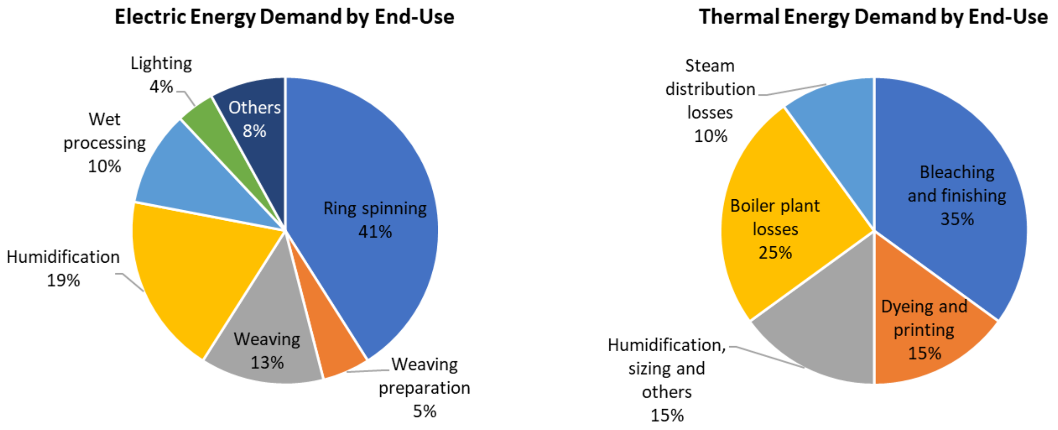


Figure 62. Typical electric and thermal energy demand by end-use in a typical integrated textile plant

Sources: Palamutcu 2015; Hasanbeigi and Price 2012; Sathaye et al. 2005.

3.5.3.2 Improving energy efficiency

The Indonesian Ministry of Industry developed a Green Industry Standard (Regulation No. 13/2019) for the textile industry. The purpose of the standard was to reduce the environmental impacts of key processes: dyeing, printing, and finishing. The standard established voluntary thresholds for electric and thermal energy demand for these processes, as well as the CO_2 emission intensity threshold (see Table 19). The standard could be improved by expanding the scope of the energy intensity thresholds to cover other key textile manufacturing processes, such as spinning, weaving, and wet-processing. Different levels of energy intensity benchmarks, such as maximum allowable and advanced (energy-efficient) levels also could be considered in the Green Industry Standard.

Table 19. Energy intensity thresholds in Indonesia's Green Textile Industry Standard

Process	Electrical Energy Intensity (kWh/tonne textile product)	Thermal Energy Intensity (kWh/tonne textile product)	CO_2 intensity (tonne CO_2/tonne textile product)
Dyeing, printing, and finishing	1,100	3,500	2.03

Source: Dewi et al. 2019.

Previous studies indicated that significant potential still exists in improving energy efficiency in Indonesia's textile industry. A study conducted in 2009 by the Japan International Cooperation Agency of 26 textile plants in Indonesia showed 20% to 35% of energy-efficiency improvement potential could be achieved through heat recovery in the dyeing process (Japan International Cooperation Agency 2009). Among the major processes, the study showed that the dyeing and finishing processes have the largest energy-saving potential (35%). Dewi et al. (2019) showed that by increasing the adoption of BAT measures, both coal and electricity demand in Indonesia's textile industry can be reduced by 2030.

Hasanbeigi and Price (2012) reviewed a total of 184 energy-efficiency measures that can be applicable to the textile industry, such as energy management systems; energy-efficient motors, pumps, fans, and compressed air systems; variable frequency drives (VFD) in motors; energy-efficient controls for humidification systems; ring diameter optimization; waste heat recovery systems; boiler energy efficiency measures; energy-efficient steam distribution systems; insulation improvement; and energy-efficient lighting systems. The key conclusion of the review was that a significant number of energy-efficiency measures already exist and are cost-effective today (with a short simple payback period).

The BAT techniques to improve energy efficiency in the textile industry include a combination of energy management practices, process optimization, and heat recovery measures (Roth et al. 2023), as shown in Table 20.

Table 20. BAT Energy Efficiency Techniques in the Textile Industry

Category	Energy-Efficiency Measures
Energy management practices	Establish an energy-efficiency plan
	Conduct regular (e.g., every year) energy-efficiency audits
	Set targets of energy efficiency (kWh/tonne of textile product)
	Implement actions to achieve targets
	Optimize scheduling of fabric batches to minimize idling time of the equipment
Process and equipment selection and optimization	
Use of energy-efficient techniques	Improve burner maintenance and control
	Implement energy-efficient motors
	Adopt energy-efficient lighting
	Optimize steam distribution systems
	Regularly inspect and maintain the steam distribution systems to prevent or reduce steam leaks
	Implement process control systems
	Adopt variable speed drives
	Optimize air conditioning and building heating
Optimizing heat demand	Reduce heat losses by insulating equipment components
	Optimize the temperature of the rinsing water
	Avoid overheating of the process liquors
Wet-on-wet dyeing or finishing of fabric	Apply dyeing or finishing liquors directly to the wet fabric
Cogeneration	Cogenerate heat and electricity
Heat recovery	Recycle of warm cooling water
	Reuse warm process liquor
	Recover heat from waste water
	Recover heat from waste gases
	Recover heat from steam use

Source: Roth et al. 2023.

In the Reference Scenario, we expect that the energy intensity of spinning, weaving, knitting, and wet processing will improve at a slow rate of 0.8% per year on average. In the Near Zero 2060 Scenario, adoption of BAT techniques and cost-effective energy-efficiency measures improves the energy efficiency level to 1.2% per year on average through 2060. Energy intensity levels of the textile manufacturing processes are further reduced under the Accelerated 2050 Scenario, improving 1.6% per year on average through 2050.

3.5.3.3 Industrial electrification

Textile manufacturing processes require both electric and thermal energy. Depending on the specific processes and structure of the textile industry, the share of electricity and fuels in total final energy use in the sector may vary from country to country.

In Indonesia, Vivadinar et al. (2016) estimated that in 2013 almost 50% of the total final energy used in the spinning process was fossil fuels based, while electricity only accounted for 48%. In the weaving process, the share of electricity was estimated to be 10%, while fossil fuels and biomass represented 53% and 37%, respectively. In the finishing process, the authors estimated that electricity only contributed to 10% of the total final energy use, while fossil fuels accounted for 71% of the total energy demand, mostly from coal (Figure 63).

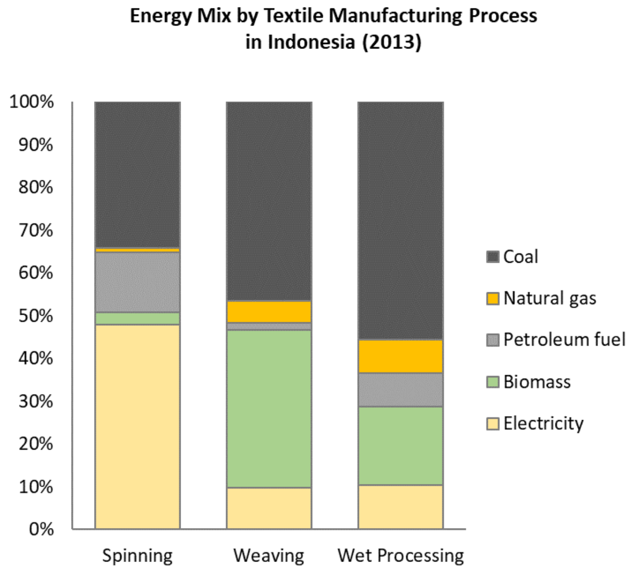


Figure 63. Energy mix by textile manufacturing process in Indonesia (2013)
Source: Vivadinar, Purwanto, and Saputra 2016.

Key processes such as spinning (together with twisting and texturing), weaving, and knitting require mechanical and air movements, machine drives, and air conditioning for the production facility (Table 21). These processes can be and are already mostly using electricity.

The wet processing stage, including bleaching, dyeing, and printing, requires hot water, steam, and/or hot dry air for the process. Wet processing is highly energy-intensive and conventionally has relied on the use of fossil fuels to meet the thermal energy demand. By producing and distributing the steam needed in fossil-fuel-based boilers, about 25%–30% of energy is lost due to steam generation and distribution losses (Figure 62 above).

Table 21. Energy requirements and energy types used in a typical textile plant

Production Process	Subprocess	Energy Requirements	Example Equipment	Typical Energy Types
Spinning	Fiber separation Ventilation Guidance	Mechanical and air movements	Roving machine Ring spinning machine Winding machine	Electricity
Surface structuring processes	Weaving Knitting Non-woven	Machine driving and air conditioning	Weaving machine Knitting machine Quality control machinery	Electricity
Wet processing	Pretreatment Bleaching Washing Dyeing/printing Posttreatment	Hot water, steam, and/or hot dry air	Pre-finishing line Washing line Drying line Dyeing line Dyeing machine Finishing line Volume machine Opening and rewinding machines Quality control machinery	Fossil fuels and/or electricity

Source: Palamutcu 2015.

Indonesia’s textile manufacturing processes present a significant opportunity to reduce GHG emissions through industrial electrification. This could be achieved through a combination of acceleration of electrification in electricity-dominated processes, and electrification of thermal energy demand in wet processing. As shown in Figure 64, spinning, weaving, and knitting processes already have achieved a very high level of electrification, reaching 93%, 85%, and 74%, respectively (Sharma 2013).

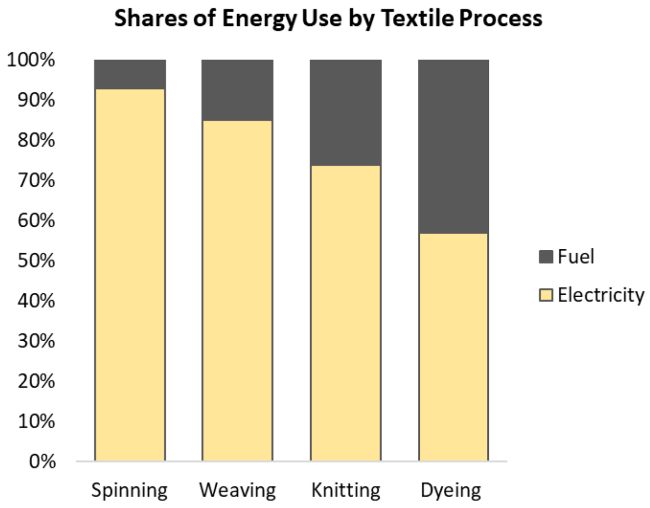


Figure 64. Share of energy use by textile manufacturing process

Source: Sharma 2013.

For wet processing, industrial heating is needed to produce hot water, steam, and/or hot dry air. Currently in Indonesia, coal and petroleum products are used to provide the industrial heat the process requires. However, wet processing in the textile industry requires only low-temperature heat, at or below 150°C (Rightor, Whitlock, and Elliott 2020). Electrotechnologies (see Appendix E) such as industrial heat pumps, electric boilers, and hybrid boilers can be considered as alternative solutions. Both electric and hybrid boilers are already commercialized. Low-temperature heat pumps that supply industrial heat less than 100°C are already available on the market. Medium-temperature industrial heat pumps that can provide a temperature up to 150°C are also emerging.

Industrial heat pumps have a working principle that is similar to a refrigerator, but in reverse. The heat pump extracts heat from a source (air, ground, water, or waste heat), amplifies it, and transfers the heat to where it is needed (IEA 2022a). Compared to a gas or coal-fired boiler, or an electric boiler, industrial heat pumps are several times more efficient, because heat is only transferred rather than generated.

Replacing onsite fossil fuel heat production with electrification technologies, such as switching from a coal-fired boiler to an industrial heat pump, can also reduce combustion losses and improve energy efficiency. In addition, it can bring other co-benefits, such as reduced maintenance cost, reduced insurance cost, improved productivity, and reduced air pollution.

In the Near Zero 2060 Scenario, the share of electricity in spinning, weaving, and knitting is expected to increase to 100% by 2060. The share of electricity in the wet processing stage also will be significantly increased, reaching 80% by 2060. The use of coal and other fossil fuels will be completely phased out by 2060 as well (Figure 65).

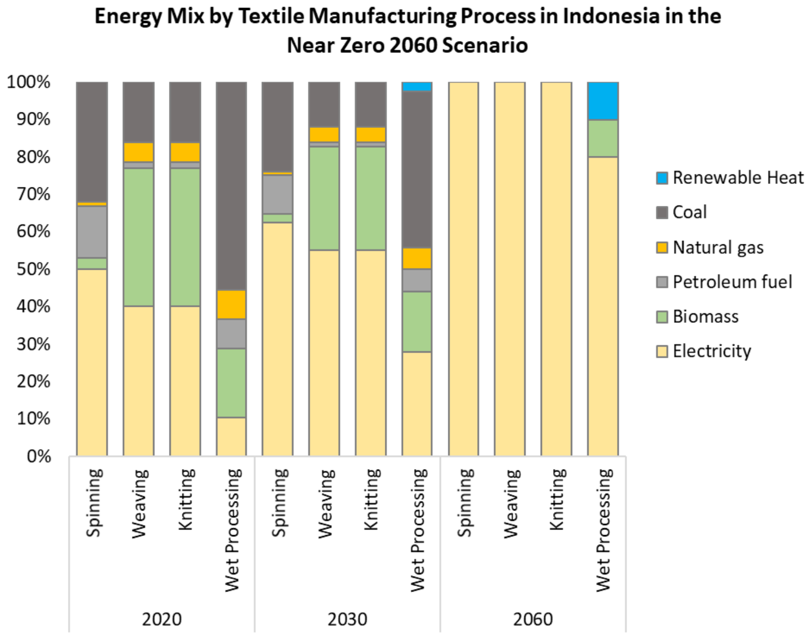


Figure 65. Energy mix by textile manufacturing process in Indonesia: Near Zero 2060 Scenario
Source: LBNL analysis.

3.5.3.4 Use of renewable heat technologies

Given the relatively low temperature requirements (up to 150°C) for thermal energy in the textile industry, studies have explored the use of renewable energy sources to replace fossil fuels, focusing on solar technologies, such as concentrated solar (parabolic trough collector), flat plate collector, and evacuated tube collector.

For example, Kumar et al. (2022) analyzed the potential of solar thermal systems for cotton-based textile industries in India. The study assessed the feasibility of flat plate and parabolic trough collectors in meeting the demands of the processes. The authors showed that solar-based process heating systems have potential cost advantages over conventional process-heating practices (Kumar et al. 2022). Nauroz Ali et al. (2022) conducted technical feasibility of two types of non-concentrating collectors: a flat plate collector and an evacuated tube collector for the application of preheating boiler feedwater in the textile industry in Pakistan (Nauroz Ali et al. 2022).

In addition to solar heating technologies, other renewable heating technologies also exist, such as the use of geothermal and biomass. As shown in Figure 66, geothermal renewable heat technologies and biomass heating can provide low to medium temperatures that are needed in several industrial applications, including wet processing in the textile industry.

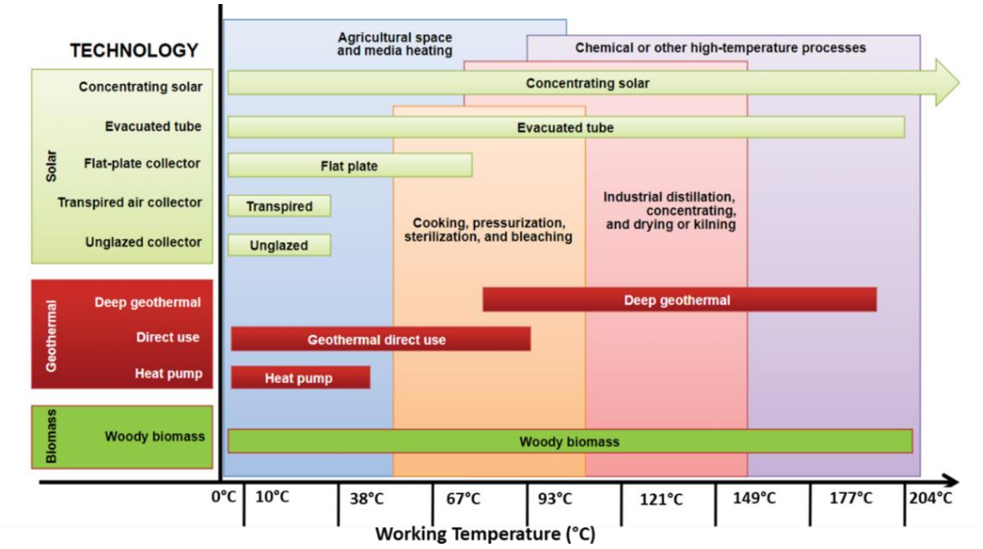


Figure 66. Renewable heat technologies

Source: US EPA 2023.

The Indonesian textile industry needs to maximize the potential of using renewable energy sources (solar, wind, water, geothermal, biomass) for onsite electricity generation, steam production, and hot water production in order to mitigate the CO_2 emissions associated with thermal energy demand in the textile manufacturing processes, especially in the wet processing stage. In the Near Zero 2060 Scenario, renewable heat will contribute to 3% of the total final energy demand in the wet-processing stage by 2030 and increase to 10% by 2060. Adoption of renewable heat technologies is scaled up at a much faster pace, with the share of renewable heat in the final energy use of wet processing increasing to 8% by 2030 and 25% by 2050.

3.5.4 Decarbonization pathways

3.5.4.1 Near Zero 2060 Scenario

The analysis showed that it is technically feasible to achieve zero emissions in the textile industry in Indonesia by 2060 (Figure 67). As shown in the Near Zero 2060 Scenario, Scope 1 and Scope 2 emissions can be reduced to zero through a combination of measures: improving the circular economy and demand reduction, improving energy efficiency, electrifying electric-intensive processes (spinning, weaving, and knitting), and electrifying and using renewable heat technologies in wet processing.

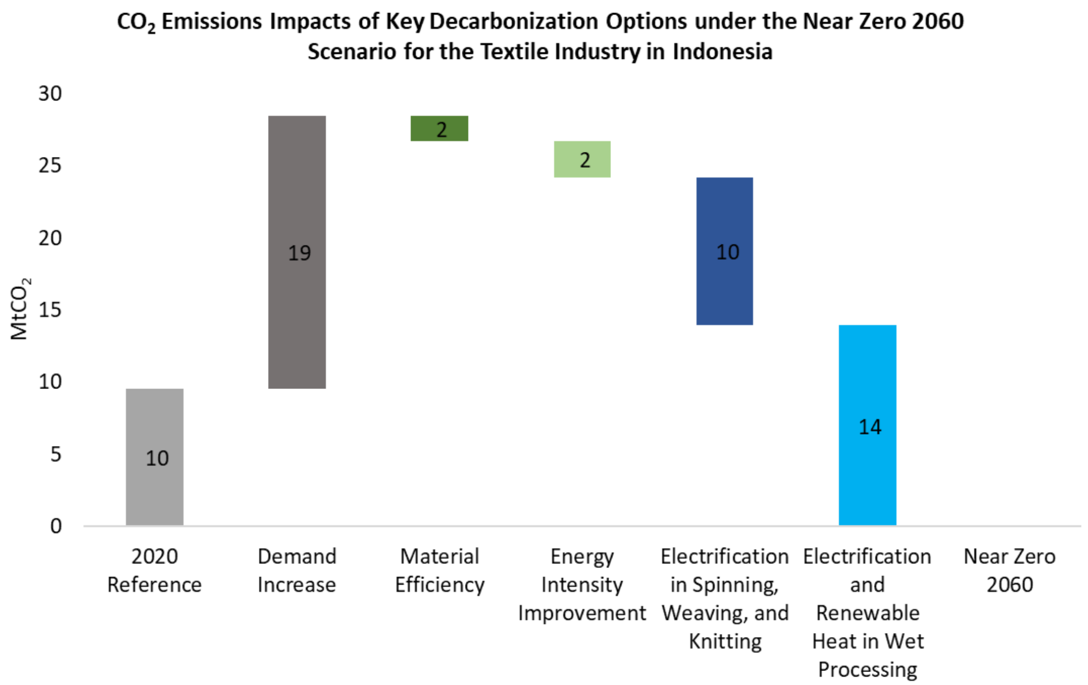


Figure 67. CO_2 emissions impacts of key decarbonization options for the textile industry in Indonesia: Near Zero 2060 Scenario

Source: LBNL analysis.

In the near term through 2030, material efficiency strategies to reduce demand and improve energy efficiency (e.g., energy management practices, adoption of energy-efficient technologies, optimization of heat demand, waste heat utilization and recovery practices) still play a significant role, contributing 25% and 20%, respectively to the total CO_2 emissions reduction potential by 2030.

In both the near and long term, electrification and the use of renewable heat in textile manufacturing processes contribute the most to the CO_2 emissions reduction potential. Specifically, electrifying spinning, weaving, and knitting can be achieved through implementation of commercialized, cost-effective technologies, as these processes are electric-intensive and can be relatively easily electrified. This measure accounts for 34% of the total CO_2 emissions reduction potential by 2030 and 36% by 2060 (Figure 68).

For the textile industry, thermal energy demand in wet processing is the most challenging to decarbonize. The analysis showed that by implementing electrotechnologies (e.g., industrial heat pumps, electric boilers, and hybrid boilers) and renewable heat technologies (e.g., concentrated solar, flat plate collector, evacuated tube collector, and other renewable sources such as geothermal and biomass) on-site fossil fuels can be replaced. This measure represents 21% of the total CO_2 emission reduction potential by 2030 and 47% by 2060 (Figure 68).

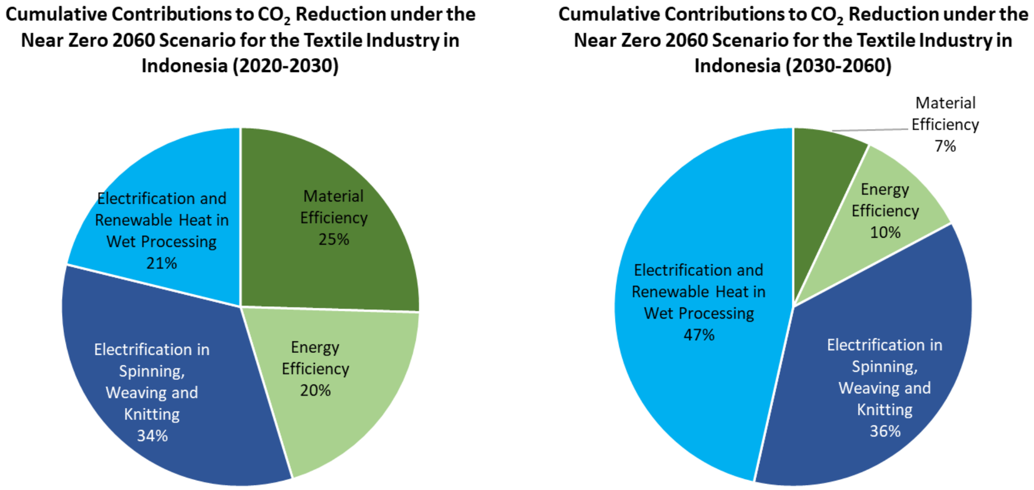


Figure 68. Cumulative contributions of key strategies of the textile industry decarbonization: Near Zero 2060 Scenario, 2020-2030 and 2030-2060

Source: LBNL analysis.

3.5.4.2 Accelerated 2050 Scenario

Decarbonization of the power sector is critical for the industrial sector to achieve net-zero emission goals. Assumptions for grid decarbonization are discussed in Section 2.1 Methodology and are applied in modeled industrial sectors in this analysis.

For the textile industry, the Accelerated 2050 Scenario highlighted that without a fully decarbonized grid, it will be very challenging and costly to achieve net-zero emissions in the textile industry in Indonesia. As shown in Figure 69, the Accelerated 2050 Scenario adopts even more aggressive measures to improve energy intensity, compared to the Near Zero 2060 Scenario. However, because the Indonesian grid is not yet zero-carbon by 2050, the contribution of electrification is diminished. By 2050, the total CO_2 emissions will be reduced from 10 $MtCO_2$ in 2020 to 6 $MtCO_2$.

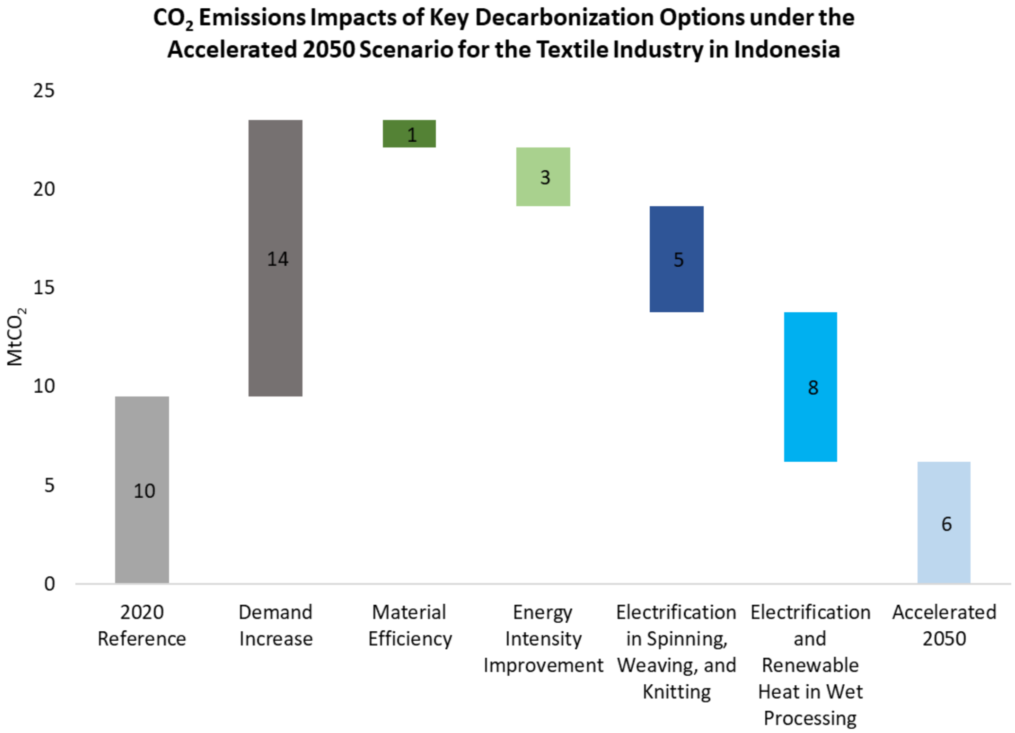


Figure 69. CO_2 emissions impacts of key decarbonization options for the textile industry in Indonesia: Accelerated 2050 Scenario

Source: LBNL analysis.

To support the Indonesian textile industry's energy transition, financial incentives for adopting electrification technologies and renewable technologies, such as onsite solar systems and industrial heat pumps, can be considered. Regulatory support to ease the permitting and interconnection also can speed the adoption of renewable technologies. Capacity building through technology dissemination and training workshops also can support the small and medium enterprises in the textile industry.

4. Policy Recommendations

A multifaceted policy approach is needed to encourage investment in industry decarbonization in Indonesia, including predictable and credible emission targets at the sectoral level, a policy framework that encourages fuel switching and energy efficiency investment, a new market for material efficiency, and a drive for a research development and innovation and demonstration project. At the same time, it is necessary to prepare the workforce with the skills, knowledge, and capabilities necessary to enable the transition to low-carbon solutions and enable local communities to benefit from the transition.

4.1 Main barriers to industrial low-carbon development

- **Long lived assets:** Heavy industry plants typically have long lifetimes of about 30–40 years, and the transition will take time. This long lifespan presents challenges when it comes to transitioning these industries to more sustainable and environmentally friendly practices.
- **High-temperature heat requirements:** Energy intensive sectors require high temperature process heat that cannot be electrified easily. While electrification is technically possible for all industrial processes (Deason et al. 2018), the electrification pathway is economically challenging due to the low cost of natural gas and other fossil fuels.
- **Competitiveness:** Energy intensive sectors are typically low margin businesses with well-established processes that are difficult to change. These industries are confronted with intense competition and may not have a level playing field. Revamping industrial processes can be risky and costly. First-movers to low-carbon solutions face both disadvantage and advantages in a global marketplace for their product.
- **Workforce:** Workforce challenges include lack of engineering resources, lack of information and data on envisioned new process technologies, lack of demonstrations, insufficient quantification of potential non-energy benefits (e.g., product yield, product quality, safety, process control), and the difficulty of re-engineering highly integrated industrial processes with optimized heat recovery and/or processes with combined heat and power.
- **Just Transition:** Industry is also a sensitive sector that employs a large number of employees (e.g., textile industry) and is an important driver of economic growth (e.g., iron and steel industry). For these reasons, the industrial sectors are often sheltered from climate policies such as the cap and trade scheme and industrial facilities have been allocated free GHG emission allowance with no emissions reduction cap.

4.2 Industry GHG emissions reduction targets and planning

While Indonesia has national climate change mitigation goals, there is a need to translate these economy-wide goals into specific targets at the sectoral and subsectoral levels. Because heavy industry plants require a long lifetime investment of about 30–40 years, it is imperative to set predictable, credible long term targets for GHG reduction at the subsectoral level that provide confidence that high-cost, high-risk innovation efforts on near-zero or zero emission industry technologies will pay off. Visibility into long term planning is essential for guiding today’s investments.

Below are some actions that can be taken to provide a clear signal to industry players to plan and start investing in GHG emissions reduction options:

4.2.1 Increase mandatory GHG emission reporting

MEMR already collects data on energy consumption from large energy users (≥ 6,000 tonnes of oil equivalent [toe] annually). However, these data are often missing or incomplete. A more robust tracking system is needed to monitor energy intensity progress and to determine GHG emissions. Reporting guidelines should include mandatory requirements and penalties for noncompliance as well as additional data on process emissions for calculating GHG emissions. MEMR needs to build up its energy reporting system to better track progress on clean energy development and work with MOEF to track GHG at the sectoral and subsectoral levels. Additionally, MEMR and MOEF could publish an annual brief update to share progress on industry GHG emissions with stakeholders.

In the medium term, a target for GHG emissions reductions in each sector should be determined and integrated in the cap-and-trade market to signal to industry companies that they will be included in the carbon market in the near future. Special provisions in GHG emissions regulations, such as free allocation of permits in emissions trading systems, help at first to reduce costs to highly tradable and exposed industries, but as the level of ambition is increased, such provisions need to be removed to incentivize increased GHG emissions reductions. Science-based methodologies building on Indonesian and international plants dataset should be considered to develop sub-sector targets. (MOEF, MEMR, MOI)

Example: *GHG emissions reporting is required by the California Global Warming Solutions Act of 2006 (AB 32) and the California Air and Resource Board (CARB) manages a transparent tracking system on industrial sources, fuel suppliers, and electricity importers. For reporters subject to the California Cap-and-Trade Program, submitted data are verified by a CARB-accredited independent third-party verifier. CARB provides an annual summary spreadsheet of GHG emissions data, and prior years' annual data are archived under the Historical Emissions Data section:* https://ww2.arb.ca.gov/mrr-data. *This requirement is being expanded with the passage of this new bill in CA.*[12]

4.2.2 Develop concerted subsectoral roadmaps

Building on the current MOI development of a Green Industry Roadmap 2040, engagement at the subsectoral level is needed to develop detailed sectoral roadmaps that assess the technical, economic, and social opportunities and provide a clear path to low-GHG development to guide investment and policy design. MOI can convey and coordinate these concerted industry roadmaps by subsector, with collaboration and inputs from the industries, industry associations, and worker associations, and discussion around the policy support needed for transitioning and for infrastructure development should be included.

Example*: The German state of North Rhine Westphalia passed a Climate Process Law that resulted in*

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[12] https://ghgprotocol.org/blog/statement-californias-climate-corporate-data-accountability-act-requires-companies-disclose

the adoption of a Climate Protection Plan that set subsector targets through a transparent stakeholder engagement process based on scenario development and identification of low-GHG options (Lechtenböhmer et al. 2015). For more information, see IN4Climate NRW at www.in4climate.nrw.

4.2.3 Infrastructure strategy

Infrastructure is a key enabler for transitioning to a low-carbon economy and it is also a key driver for growth and employment. It Is therefore strategic to establish the outlook for future infrastructure needs to allow for a just energy transition. For the industry sector in particular, there is a need to assess the necessary renewable energy buildout, hydrogen production and distribution, CCUS geologic reservoirs, and other activities that will be needed to transition to low-carbon development now and in the near future. The Ministry of National Development Planning (BAPPENAS) can build a strategic infrastructure plan for achieving the concerted subsectoral roadmaps.

4.2.4 Assess job impacts

The transition to a low-carbon economy is likely to have profound implications for the workforce and communities at large. Managing this transition effectively is essential to reduce negative impacts and create new opportunities. It is therefore critical to careful assess the impacts on job creation and livelihoods in local communities that can adopt new technologies and new practices (e.g., energy management, recycling, repairing, reusing). The industry sector employs 30% of the workforce in Indonesia, with a mix of skills that may need to evolve to support the installation and operation of low-carbon technologies. A thorough process addressing these implications can help the transition by creating workforce development programs that provide training and support for workers transitioning to green jobs.

Some local communities may be particularly affected by industrial transition. For example, geographical areas that are economically dependent on coal-based small industrial processes may need support to transition to new businesses. Policies and initiatives need to be designed to address these disparities, as vulnerable and marginalized communities often bear a disproportionate burden of transition costs. A transition to a domestic green industry should be a source of quality and safe jobs for all.

BAPPENAS and MOI are well positioned to assess these impacts and proposed recommendations to mitigate the disruption to economic activity and changes to the industrial composition.

4.2.5 Monitoring and verification:

Monitoring and verification is an important part of an effective program or policy. It can ensure effectiveness of the policies, mitigate potential risks, and establish proper channels to provide feedback to improve the current policies. It is recommended to develop the monitoring and verification process as a part of the initial development of a given program or policy (e.g., GHG reporting systems) (IEA 2017). Communication with key stakeholders about obligations and potential sanctions of non-compliance should be maintained throughout the design, implementation, monitoring, verification, and evaluation of the program or policy. Targeted monitoring and verification can be performed to focus on aspects or sub-sectors that are at the greatest risk of non-compliance. Transparency in monitoring requirements, processes, and third party verification are needed. Capacity building and training for monitoring and verification program staff as well as for key stakeholders can be beneficial.

The following table summarizes our recommendations for the target setting roadmap.

Table 23. Target Setting Roadmap

Timing	Actions	Lead Agencies
1–2 years	GHG reporting system developed	MEMR, MOEF
2–4 years	Concerted action plans with specific sectoral target established	MOI
	Infrastructure strategy developed	BAPPENAS, MOI
	Job and community impact assessment	
	Sectoral target included in GHG trading scheme for 2030	MEF
5 years	Monitoring and adjustment as needed	MEMR, MOEF

4.3 Innovation

Increased government funding for research, development, and demonstration of near-zero or zero emission industrial technologies will be important to leverage corporate efforts in bringing innovations to market by mitigating investment risks. Governments also can help with coordinating and stimulating knowledge sharing and innovation efforts among relevant actors.

4.3.1 Research, development, and innovation (RDI)

Research, development, and innovation plays a pivotal role in advancing decarbonization of economies and fostering competitiveness. Achieving industry decarbonization requires a shift in emissions reduction at a rate that is currently not possible with existing technologies, or only achievable at excessive costs. Many of the technologies for decarbonizing the industry sector are still at a lower TRL than what is needed to achieve their full deployment potential. The International Energy Agency (IEA) estimates that 40% of the technologies analyzed for decarbonizing a full economy (including the industrial and other sectors) are not commercially available today, and 35% are at the early adoption phase, meaning they are still significantly dependent on innovation to improve performance and reduce costs (IEA 2020b). The highest proportion of low TRL of decarbonization technologies are in the industry sector (IEA 2020b).

For that matter, RDI programs are crucial to drive advancements in knowledge, technology, and science, to reduce the cost of decarbonization and increase industry competitiveness. RDI programs should support research on new technologies, international partnership and knowledge exchange programs, and public-private partnership demonstrations.

4.3.2 Demonstration programs

Bringing a technology or innovation from the research and development (R&D) phase to the market, where it can be commercialized and adopted by industry players, requires the demonstration that the technology can be scalable and operational on a field scale, in the real world. To fast-track this phase of development, governments can support tech-to-market partnerships that bring together government, industry, and research to finance the demonstration of innovative technology such as H_2-DRI, molten oxide electrolysis, green hydrogen production, green ammonia production, CCS projects in cement, heat pump and other electrification technology industrial application, lightweight building design, and others. The goal is that funding from the government to support decarbonization is leveraged with investment from the private sector through a cost share agreement.

Examples: *The European Commission has developed an EU Innovation Fund for the demonstration of innovative low-carbon technologies* (European Commission 2022). *The funding for this fund comes from the proceeds of the auctioning of EU Emissions Trading System (ETS) allowances. Therefore, the money raised from polluters for emitting GHG emissions is reinvested into supporting large-scale projects that demonstrate innovative low-carbon technologies. The third call for the Innovation Fund was launched in July 2022 with a budget of €3 billion. It had the goal of boosting the deployment of industrial solutions to decarbonize Europe and reduce the EU's dependence on Russian fossil fuels.*

In the US, the Inflation Reduction Act (IRA) (The White House 2023) *was signed in 2022 to build a new clean energy economy, enhance U.S. competitiveness, drive the creation of good-paying union jobs, and tackle the climate crisis while ensuring access to benefits for disadvantaged communities. As part of the IRA, the U.S. Department of Energy is soliciting applications for projects that will demonstrate the production of low-carbon products in the highest emitting industries where rapidly deployed decarbonization technologies can have the greatest impact* (US DOE n.d.). *Projects to be considered have to show a minimum of 50% cost sharing from the private sector and the contribution to the goal that 40% of the overall benefits of the government's investments in clean energy and climate solutions goes to disadvantaged communities to drive the creation of accessible good-paying jobs. When combined with private sector cost share, the DOE's solicitation represents more than $12 billion of investment to advance high-impact transformational low-carbon technology development to significantly reduce GHG emissions in energy-intensive industrial subsectors.*

4.3.3 Leadership programs

Transformational changes need encouragement beyond financial support. Leadership programs can help spur innovation, reward risk takers, and spread the word on the feasibility of net-zero-carbon technology applications in the industry sector. Champions of low-carbon development should be recognized and praised for their innovative contributions to the national commitment to reduce emissions and for their leadership in showing the potential for others to reduce emissions.

Leadership programs can be designed to cultivate and develop first-of-a-kind development in heavy industry at the national level. These programs can be established and supported by governments, with help from non-profit organizations, industry associations, or other entities with the goal of identifying and nurturing future industry leaders who can contribute to the advancement of their country.

In Indonesia, MOI and the Coordinating Ministry for Economic Affairs are supporting the Green Industrial Indonesia trade show,[13] which brings together companies presenting their innovative solutions and advanced technology for greening industry. Awards are also given to companies implementing green industrial solutions. This could be expanded to more formally recognizing leadership in difficult-to-decarbonize sectors.

Example*: Mission Innovation is organizing the Net-Zero Industries Award 2023 to honor the world's best innovations for industrial decarbonization in three distinct categories: Outstanding Projects, Female Innovators, and Young Talents* (Mission Innovation n.d.)*. A jury of experts will evaluate the applications, and the winners in each category will be announced in a ceremony at the United Nations Climate Change Conference (COP28).*

The following table summarizes our recommendations for the innovation policy roadmap.

Table 24. Innovation Policy Roadmap

Timing	Actions	Lead Agencies
1–2 years	Development and adoption of an Industry Decarbonization RDI and Demonstration Bill to allocate significant budget to co-fund low-carbon technology uptake in Indonesia	MOI, MOF and MEMR
2–4 years	First round of solicitation of RDI projects and demonstration projects Launch of the Indonesia Industry Decarbonization Leadership Program	
5 years	Second round of solicitation of RDI projects and demonstration projects	

4.4 Electrification

Industry electrification with renewable energy is a critical strategy for reducing GHG emissions and promoting sustainable industrial practices. This transition involves replacing fossil fuels and other non-renewable energy sources with electricity generated from renewable sources such as solar, wind, hydro, and geothermal power. Developing an enabling environment to encourage fuel switching and prevent investment in fossil fuels for new plants is therefore an important strategy to consider.

4.4.1 Renewable energy self-generation and purchase

The leading government institution overseeing renewable energy industry development is MEMR. Local governments can also play a significant role in expediting renewable energy projects in their areas. A range of policies and regulations can help to create a favorable enabling environment for industry companies to invest in renewable energy. The following bullet points outline the types of policy and

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[13] Green Industrial Indonesia. https://greenindustrial.id/

regulatory support that can unlock the potential of renewable energy investment:

- Allowing and streamlining permitting processes for industrial facilities wanting to install renewable power generation on site. Indonesian Law 30/2009 requires a captive power license (or Izin Usaha Penyediaan Tenaga Listrik – IUPTL) to install capacity higher than 500 kW per electrical power installation.
- Enabling enterprises to enter into direct power purchase agreements (PPA) with independent power producers (IPPs) through standardized and streamlined processes (World Economic Forum 2022b). Corporate PPA are limited in Indonesia, as only PLN (Perusahaan Listrik Negara [State Electricity Company of Indonesia]) and private power developers that have the relevant business area approval can sell electricity to end users. Corporate renewable PPAs allow companies to procure renewable energy directly from an energy producer and, in turn, help support the growth of renewable energy in the country. PPA standardized agreements can facilitate the process instead of assessment and negotiation on a case-by-case basis, simplifying the process and increasing transparency and investor confidence.
- Implementing power-wheeling guidelines allowing IPPs to use the PLN's infrastructure to supply power to companies, reducing barriers to access the grid, and considering compensation for excess generation to be exported to the grid (e.g., net metering, feed-in tariffs, two-way rates).
- Establishing financial and fiscal mechanisms such as tax credits or grants to improve the economic viability of renewable energy investment.

Example*: India has seen impressive growth in corporate renewable sourcing and was the second largest growth market after the US in 2019, with an addition of 1.4 GW of capacity* (wbcsd 2021)*. The regulation enables large consumers to procure electricity from independent producers through direct PPAs or by setting up their own captive generation plants. The consumer can use the state's transmission and distribution infrastructure to procure this power.*

4.4.2 End use electrification

End-use electrification refers to the transition from traditional energy sources (such as fossil fuels) to electricity to power various applications and processes across industries. Industrial process heat accounts for more than two-thirds of the total energy consumption in industry, and half of this process heat demand is low- to medium-temperatures (< 400°C). In Indonesia, approximately 40% of industrial energy consumption is covered by coal, 22% by natural gas, and 11% by petroleum and biomass each. Heavy industry processes have very high energy demands, and achieving the required temperatures electrically can be technologically challenging and expensive. Key challenges for electrifying heat in industrial applications are the relatively low prices of fossil fuels, the lengthy payback times (> 3 years), and the inertia in replacing technologies that are established. Policymakers such as MOF can allocate funding and work with PLN and/or MOI to compensate the relative higher price of electricity and provide financial incentives to attract investment in electrification.

However, the right moment to start electrifying may depend on the expected local power mix. Electricity companies, such as PLN, have therefore an important role to play to ensure that clean electricity can be delivered to manufacturers at a reasonable cost.

Here are some policy options to consider:

- Incentivize the adoption of technologies such as industrial heat pumps, electric boilers, resistance heating, induction heating, industrial microwaves, electric arcs furnaces, and others.
- Consider setting GHG emissions requirements on new built production capacity in heavy industry, such as the iron and steel and cement industries.
- Develop phase-out agreements and repurposing plans of existing infrastructure (e.g., blast furnaces).

Example: *In 2022, the Ministry of Economic Affairs and Employment of Finland set up a fund to compensate for the indirect costs of carbon trading on the price of electricity* (Finish Government 2022). *The Act on Electrification Subsidy for Energy-Intensive Industries entered in force in July 2022 for a determined period of four years and has goals to mitigate carbon leakage risk, safeguard the cost competitiveness of energy intensive industries, and encourage manufacturers to develop their industrial production in a more carbon neutral direction.*

4.4.3 Clean hydrogen and CCUS

Low-carbon hydrogen and CCUS are two major emerging solutions to decarbonize the industry sector, and both are likely to play a pivotal role in the near future. However, both solutions come at a significant cost, and little regulation and financial incentives exist to enable this transition. It is therefore imperative to develop low-carbon hydrogen and CCUS regulatory frameworks that will govern the properties, safety, fuel used for production, storage, transportation, distribution, and associated infrastructure of hydrogen and CO_2, as well as strategies to allow these new mitigation options to be developed with the necessary support to unlock public and private investment.

Example: *The South Africa Hydrogen Society Roadmap sets clear targets to deploy 10 GW of electrolysis capacity in Northern Cap by 2030 and produce about 500 kilotons of green hydrogen annually by 2030. This growth is forecasted to create 20,000 jobs annually by 2030 and 30,000 by 2040. South Africa's hydrogen ambitions are driven partly by its decarbonization goals, and partly by a desire to support economic growth and exports.*[14]

The following table summarizes our recommendations for the electrification roadmap.

Table 25. Electrification Roadmap

Timing	Actions	Lead Agencies
1–2 years	Revise permitting process to facilitate renewable energy captive power and corporate investments	MEMR, Local Gov
2–4 years	Incentivize the adoption of industrial heat pumps, electric boilers, resistance heating, induction heating, industrial microwaves, electric arcs furnaces, etc. Consider setting GHG emissions requirements on new built production	MEMR, PLN, MOI, MOF

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[14] More information available at: https://www.csis.org/analysis/south-africas-hydrogen-strategy

	capacity in heavy industry, such as iron and steel, and cement industries. Develop phase-out agreements and repurposing plans of existing infrastructure (e.g., blast furnaces). Develop low-carbon hydrogen and CCS development strategies.	
5 years	Monitor progress and revise incentive programs.	MOI, MOF

4.5 Energy efficiency

Improving energy efficiency in industry is an essential way to advance decarbonization, reduce energy demand, and provide cost savings to companies.

4.5.1 Minimum Energy Performance Standards

Minimum energy performance standards (MEPS) are particularly effective policy tools for increasing the efficiency of energy-using appliances, equipment, and lighting by accelerating the penetration of energy-efficient technology into the marketplace.

MEPS programs for standalone electric motors are in place in many countries[15] and primarily focus on three phase, low voltage, AC induction electric motors. Other regions such as EU 28 and the USA have later started to develop MEPS for motors and their application such as fans, pumps, and compressors. Accordingly, the IEA Electric Motor System Annex's best practice for national policy makers recommends to implement MEPS sequentially (Kulterer 2015): (1) by targeting individual components of the motor system[16] and (2) by focusing on the integrated motor with variable frequency drives, or on the motor and its application.

4.5.2 Energy management systems

Indonesia Government Regulation No. 70/2009 requires entities consuming ≥ 6,000 toe per year to implement energy management systems, and report energy consumption annually to the government (Industrial Decarbonization Accelerator 2019). The law also allows for financial incentives to promote energy efficiency. An evaluation of the impact of the implementation of the existing requirement would help determine the energy savings, implementation successes and lessons learned, and how the implementation of more stringent requirements and/or additional incentives can help double the impact in the next five years. The government should leverage and expand existing energy efficiency programs to compel large energy users to achieve greater savings and emissions reductions.

4.5.3 Set energy performance schemes

The government can set energy efficiency mandatory requirements for key industries to require

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[15] E.g. EU 28, Canada, Mexico, USA, South Korea, Switzerland, Japan, China, Australia, Brazil, Turkey, Costa Rica, Israel, Taiwan, Egypt, Singapore.

[16] i.e. standalone electric motors, variable frequency drives, transmissions, gears, and the application or driven unit such as the pump, fan, or compressor.

industrial plants to meet GHG emissions reduction targets or specific energy consumption (SEC) levels. Some governments have also set up voluntary agreements with individual companies and/or industry sector associations to reduce their emissions with commitments and time schedules negotiated by both parties. Often these programs are negotiated under the threat of future regulations or GHG emissions taxes as a motivation for participation. Supporting programs and policies for a higher chance of success include energy audits, industry benchmarking, monitoring, information dissemination, and financial incentives. These types of mandatory or voluntary agreements can be developed in collaboration with the mandatory reporting described in Section 4.2 and be developed by MOI with coordination of MOEF and MEMR.

Example: *The India Perform, Achieve, and Trade (PAT) program: The Bureau of Energy Efficiency (BEE) of India set individual targets for large energy users to reduce their SEC, i.e., the energy consumed per unit of production. Large energy users submit action plans and annual energy consumption reports to BEE and at the end of three years, they submit a performance evaluation audit report and receive Energy Saving Certificates (ESCerts) if their SEC exceeds their targets. These ESCerts can be traded or kept for the next cycle. BEE estimates that the first three PAT cycles have saved about 8.67, 14.08, and 1.75 Mtoe, respectively, in their target years* (Chunekar 2023).

The following table summarizes our recommendations for the energy efficiency roadmap.

Table 26. Energy Efficiency Roadmap

Timing	Actions	Lead Agencies
1–2 years	Evaluate industry energy efficiency remaining potential and recommend how to expand current policies to incentivize a doubling of the impacts. Consider setting MEPS for motors consistent with international best practices	MOI, MEMR, MOEF
2–4 years	Set up an energy performance target scheme for large energy users.	MOI, MEMR, MOEF
5 years	Monitor progress and update targets to more efficient levels.	MOI, MEMR, MOEF

4.6 Material efficiency and circular economy

Industries with cleaner production have a competitive advantage that needs to be recognized. Industries need institutional structures and arrangements to certify the embodied carbon of production so it can be valued in global and national markets. Policies can help create markets for near-zero emission materials produced using these low-carbon materials and products. A circular economy (CE) is another effective approach to mitigate industrial GHG emissions by avoiding the production of virgin material which leads to significant carbon emission reductions. Moving away from a linear mode of production, CE promotes the design of durable goods that can be easily repaired, with components that can be reused, remanufactured, and recycled.

4.6.1 Standardization and certification

Material efficiency refers to using less material to deliver the same goods and services. It is considered to be a major strategy for reducing GHG emissions in industry according to the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2022). It can be implemented at every stage in the lifecycle of materials and products, such as designing products with less primary material, as well as measures to improve the reusability, recyclability, and durability of products.

Establishing and adopting standards can help provide guidance on how a product or a service can be made or provided with less material and at the same time ensure product safety, performance, and reliability. There is a need to develop material standards to allow the use of low-carbon materials such as materials used to reduce clinker content in cement (e.g., BF slag, fly ash, calcined clay, limestone, recycled concrete fines) and alternative blinders. MOI and MOEF have made progress on developing standards such as the Standar Industri Hijau (SIH) for green industries and Ecolabel for construction materials. They should continue to stimulate industries to adopt better practices and prioritize products and services that require a significant amount of material from heavy industries (e.g., green steel, low-carbon cement). Standards should be developed to help industries compete in markets with Carbon Border Adjustment Mechanism (CBAM), like the European Union, where importers will have to report the GHG emissions embedded in volumes of iron and steel, aluminum, cement, electricity, fertilizers and hydrogen imported (European Commission n.d.).

Example: *Green Building Codes: Providing sheltering to people and businesses is typically a service that can be done with less material. Globally, the emissions related to building construction represent 11% of energy-related carbon emissions worldwide, resulting from manufacturing building materials and products such as steel, cement, and glass. An increasing number of jurisdictions worldwide are addressing the carbon footprint associated with building materials and construction processes. For example, the Danish government introduced a requirement in the building regulations for whole life carbon, which includes both operational and embodied carbon. This amendment came into effect in 2023 for all buildings over 1,000 square meters (m^2), and those buildings will be required to meet an initial limit value of 12 kg CO_2e/m^2/year with an endorsement label for buildings that meet a limit value of 8 kg CO_2/m^2/year. The goal is to tighten the limit value every other year until 2029* (Birgisdottir 2021).

4.6.2 Green procurement

A third of government expenditure goes to public procurement for infrastructure development, general equipment, and miscellaneous goods. Governments can leverage that purchasing power to choose products and materials with a reduced environmental impact and make an important contribution toward green production. Procurement policies are an important strategy for driving innovation and increasing low-carbon production across the globe. By using their purchasing power, local, regional, and national authorities help guarantee markets for green products and materials, and therefore contribute to creating lead markets for these products.

Example: *U.S. Buy Clean Policies: Originally led by a coalition of environmental organizations, business* *associations, and labor unions advocating for the embedded emissions of industrial products like steel and glass to be considered in California state agencies' contracting of infrastructure projects, the buy clean concept rapidly spread at the federal level* (BlueGreen Alliance 2021)*. In 2021, President Biden released an executive order to use federal procurement power to help achieve net-zero emissions economy-wide by no later than 2050. Buy Clean policies require supply chain emissions disclosure, generally in the form of environmental product declarations (EPDs), which are documents that report the lifecycle assessment of a product based on the international ISO 14025 standard. Requiring disclosure encourages manufacturers to produce quality data and to lower their GHG impacts.*

4.6.3 Circular economy strategy

Many different steps are needed to establish a circular economy, including the adoption of regulations that extend product lifetime, ban single use products, and increase the recycling rate (e.g., policies such as demolition fees and building refurbishment incentives can target longer lifetimes of buildings and structures). It often necessary to start by developing a National Circular Economy Law or Strategy to transition toward a more circular economy and improve channels for end-of-life material collection, sorting, and recycling; increasing reparability requirements. The law or strategy can also encourage reuse of products, especially ones that use energy intensive materials such as plastic, aluminum cans, glass, and paper. Indonesia can build on the work already done by BAPPENAS as described in *The Future is Circular: Concrete Steps for Circular Economic Initiatives in Indonesia* (UNDP 2022).

Another important policy to implement is extended producer responsibility schemes, which require producers to take responsibility for the end life of their outputs and to cover the cost of recycling of materials, or otherwise responsibly manage problematic wastes. The development of data collection and indicators is nascent and needs to ramp up to quantify the impacts and provide evidence to improve circular economy and materials efficiency policies.

Finally, another important strategy to consider is to foster market opportunities for circular product exchange, notably through industrial symbiosis clusters and trading platforms and facilitate waste exchanges between facilities, where by-products from one industry is used as a feedstock to another. Systematic assessment of wastes and resources is carried out to assess possible exchange between different supply chains and identify synergies of waste streams that include metal scraps, waste plastics, water heat, bagasse, paper, wood scraps, ash, sludge, and others.

Example: *The United States Business Council for Sustainable Development (USBCSD), a nonprofit business association, launched a Materials Marketplace program to connect businesses to develop and scale new reuse and recycling market opportunities. More than 2,200 businesses and organizations are using the Materials Marketplace and have diverted 5,300 tons of materials to higher and better use (USBCSD 2023). The program is now expanding across North America and have been adopted in several other countries.*

The following table summarizes our recommendations for the material efficiency and circular economy roadmap.

Table 27. Material Efficiency and Circular Economy Roadmap

Timing	Actions	Lead Agencies
1–2 years	Developing a national circular economy law or strategy. Develop standards and certifications.	BAPPENAS MOI MOEF
2–4 years	Develop green procurement. Adopt regulations that extend the lifetime of a product, ban single use products, and increase the recycling rate. Extended producer responsibility schemes. Foster market opportunities for a circular products exchange.	MOF, MOEF, MOI, BAPPENAS
5 years	Monitor and revise strategy and set new goals.	MOF, MOEF, MOI, BAPPENAS

4.7 Workforce and local communities

Decarbonization of the industrial sector needs to include labor and equity objectives to ensure a just energy transition. Workforce development and technical assistance programs can help ensure that the transition improves health outcomes and long term job prospects for local communities. Governments can develop re-skilling centers and tie their funding allocated to industry to support innovation to requirements on re-skilling programs and worker protection. Different tools exist for governments to help prepare the workforce for the transition, ensure that benefits and cost are distributed fairly, and incentivize companies to include plans for workforce development and local community engagement.

4.7.1 Develop green industry training hubs

To build capacities in engineering design and manufacturing, job training centers should be developed to help workers to gain expertise in the installation of key industrial processes such as DRI-EAF, recycling technologies, industrial heat pumps, green hydrogen production, material efficiency, life cycle assessment, GHG embodied certification, light building construction, and more. Reskilling and upskilling trainings should also be designed to help capacity in SMEs.

Example: *India's government established the Skill Council for Green (SCGJ)*[17] *in 2015 as a not-for-profit, autonomous, industry-led society to improve skills for green business industries and integrate environmental awareness into job training across skilling programs. It is organized by the Ministry of New and Renewable Energy (MNRE) and Confederation of Indian Industry (CII). Since its establishment, SCGJ has developed 44 nationally approved qualifications across various subdomains (e.g., renewable energy, circular economy, industry). In addition to developing training materials, it has trained over 504,000 trainees and has a network of over 400 affiliated training institutions/centres and over 4,000 trainers across the country delivering trainings across the green business domain.*

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[17] Skill Council for Green Jobs. https://sscgj.in/.

4.7.2 Develop an incubator program

A clean technology incubator program provides support to assist early-stage entrepreneurs in developing their business ideas, products, or services. These programs offer a range of resources and support services to help startups grow and succeed. Incubators are typically temporary, helping for a short period of time, usually several months to a few years, to help launch a new technology.

Example: *In the US, the Department of Energy worked with its national laboratories to develop the Cradle to Commerce*[18] *program, which curates compelling climate technologies developed by inventors. It is a public-private program that helps connect inventors and entrepreneurs by providing coaching for pitch skills, mentoring for business models, and access to pilots, prototyping, and critical resources like state-of-the-art test beds, prototyping facilities, and scientific resources for technology advancement.*

The following table summarizes our recommendations for the workforce and local communities roadmap.

Table 28. Workforce and Local Communities Roadmap

Timing	Actions	Lead Agencies
1–2 years	Develop green industry training hubs. Consider designing programs that promote a just energy transition.	MOI, MEMR, BAPPENAS
2–4 years	Develop an incubator program. Expand the number of green industry training hubs.	MOI, MEMR, BAPPENAS
5 years	Assess impacts and develop new programs that ensure transition-improved health outcomes and long term job prospects for local communities.	MOI, MEMR, BAPPENAS

5. Conclusion

The Government of Indonesia has pledged to achieve net-zero emissions by 2060 or sooner. The project showed that it is technically feasible to achieve near-zero emissions in Indonesia's industrial sector by 2060. The scenario analysis indicated that in order to achieve net-zero emission by 2050, as aspired in the government's Paris Agreement Enhanced Nationally Determined Contributions, extraordinary efforts are required to accelerate the adoption of low-carbon technologies and practices in the industrial sector.

The analysis showed that it is possible to grow and develop the industrial sector by adopting clean, low-carbon, and innovative technologies. Some of these technologies are already commercialized and cost-effective, while others will become so over time with supportive policies. Investment in research, development, and deployment of breakthrough technologies is also critical for deep decarbonization and meeting the net-zero goals.

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[18] Cradle to Commerce. https://c2c.lbl.gov/home.

The industrial sector in Indonesia needs to consider a portfolio of technologies and measures for industrial decarbonization. Key pillars of decarbonization should expand from conventional energy efficiency improvement and fuel switching to electrification, innovative low-carbon technologies, material efficiency/demand reduction, and CCUS when appropriate.

The project findings show that the Indonesia government needs to consider develop strategies for key materials (e.g., cement, steel, ammonia, paper, textiles), but also green energy carriers, such as hydrogen and ammonia. National roadmaps or plans on cross-cutting technologies, such as industrial heat pumps and CCS applications, need to be developed to provide the enabling policy and market framework. Infrastructure development and coordination among key stakeholders will be another deciding factor on the pace and progress of the energy transition.

Although power sector decarbonization is not in the scope of this analysis, the project team fully recognizes that industry decarbonization cannot or will not occur without a fast-decarbonizing power sector. In fact, the decarbonization progress of many industries, such as steel, ammonia, pulp and paper, and textiles, is strongly dependent on whether they can develop or access clean, low-cost electricity.

Finally, a multifaceted policy approach is needed to encourage investment in industry decarbonization in Indonesia, including clear and credible emission targets at the sectoral level, a policy framework that encourages fuel switching and energy efficiency investment, a new market for material efficiency, and investment for research development and innovation and demonstration projects. At the same time, it is necessary to prepare the workforce with the skills, knowledge, and capabilities necessary to enable the transition to low-carbon solutions and enable local communities to benefit from the transition.

Industry investment and policy decisions made today have important implications for 2050 and 2060. If Indonesia is going to meet its updated NDC goal of carbon neutrality by 2060 or sooner, industry development will need to be met by clean, low-carbon, and cost-effective technologies combined with policy strategies that create the right market conditions to speed and scale up adoption.

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Appendix A. Stakeholder Mapping

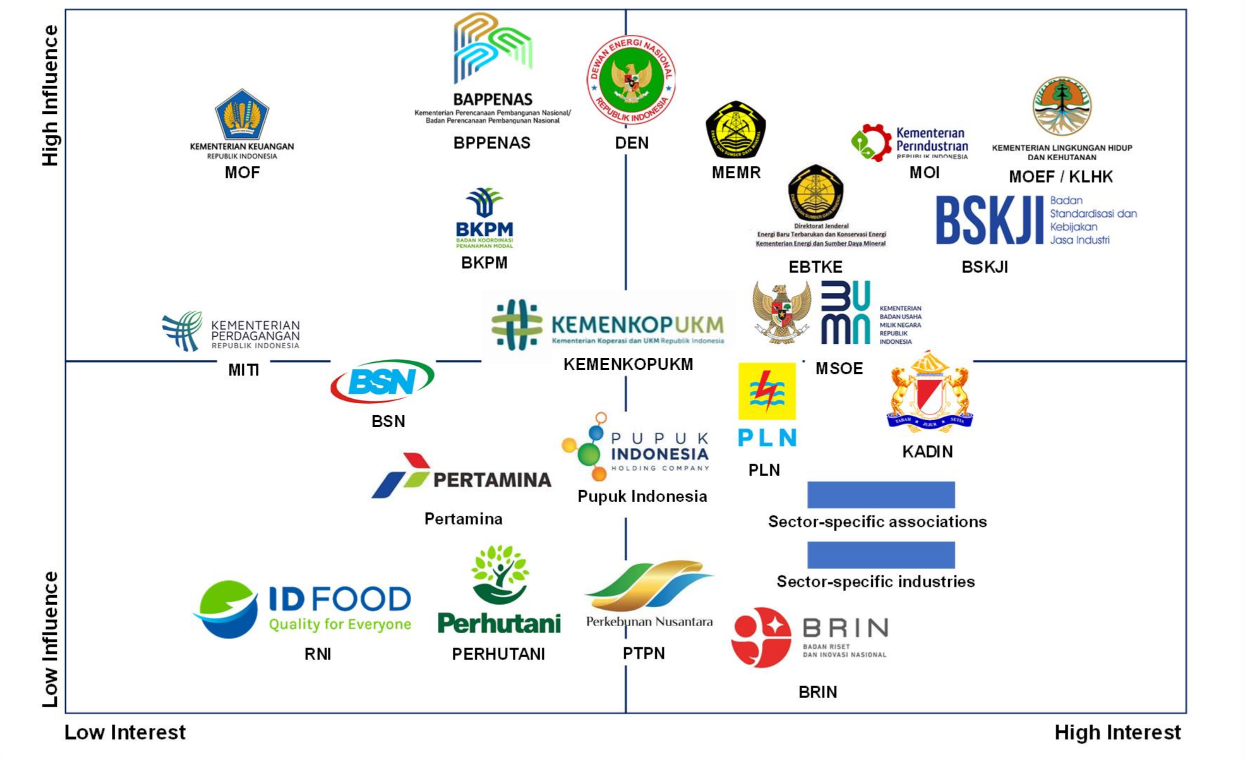

Figure A-1. Cross-sectoral key stakeholders

Source: *IESR Analysis, 2023.*

In regard to industrial decarbonization, as illustrated in Figure A-1, the Ministry of Environment and Forestry (MOEF/KLHK) is Indonesia's main stakeholder in mitigating climate change and environmental issues, including global warming and greenhouse gas emissions. Meanwhile, the Ministry of Industry (MOI) is the main stakeholder in matters pertaining to the industrial sector and the governance of industrial initiatives in Indonesia. The Ministry of Energy and Mineral Resources (MEMR) is the main stakeholder in matters of national energy security, energy utilization governance, and the issue of the energy transition towards net-zero emissions (NZE) in Indonesia.

Regulators

- **Ministry of Environment and Forestry (MOEF/KLHK)**
  The government agency that oversees government affairs related to the environment and forestry. In particular, the Directorate General of Climate Change Control (DJPPI) has the authority for coordinating the formulation and implementation of policies in the field of climate change control including the functions of mitigation, adaptation, reducing greenhouse gas emissions, reducing and eliminating ozone-depleting substances, resource mobilization, greenhouse gas inventory, monitoring, reporting and verification of climate change and controlling forest and land fires to support decarbonization and energy transition.

- **Ministry of Industry (MOI)**
  The government agency that oversees industrial affairs. MOI has the authority for the formulation, determination and implementation of policies in the industrial sector including energy use and

emission control. In particular, the Industrial Services Policy and Standardization Agency (BSJKI), which is responsible for implementing the transition to a low-emission and environmentally friendly industry under its Green Industry Center (PIH).

- **Ministry of Energy and Mineral Resources (MEMR)**
  Government agency that oversees government affairs in the field of energy and mineral resources. MEMR has the authority for formulating and implementing policies regarding oil, gas, electricity, minerals, coal, new energy, renewable energy, energy conservation, as well as geology and mineral resources. In particular, the Directorate General of New, Renewable Energy and Energy Conservation (EBTKE) that is responsible for geothermal activities, bioenergy, various new and renewable energies, and energy conservation.

- **National energy Council (DEN)**
  As a national institution, independent, that responsible for planning, development and managing Indonesian National Energy Policy (Kebijakan Energi Nasional or KEN) as well as General National Energy Plan (Rencana Umum Energi Nasional or RUEN). The DEN is led directly by the President of Indonesia, with the Vice President serving as Vice Lead and the Ministry of MEMR serving as Daily Chief Executive. Efforts for decarbonization and national energy transition, including the industrial sector, power generation, transportation and others are included in KEN and RUEN.

- **Ministry of National Development Planning (BAPPENAS)**
  The government agency that oversees government affairs in the field of national development planning. BAPPENAS has the authority for formulating themes, targets, policy directions, national strategic projects, and development priorities, as well as synchronizing and synergizing national strategic policy planning, budgeting, and activities, as Coordinating Ministries, coordinating related Ministries/Agencies, including KEN and RUEN's derivatives.

- **Ministry of Finance (MOF)**
  Government agency that oversees state finances affairs. MOF has the authority for formulating, determining, and providing recommendations for fiscal and financial sector policies, including fiscal incentives such as, tax exemption, subsidy, government financial support, customs clearance etc. including in the procurement of technology and natural resources in decarbonization and the energy transition.

- **Ministry of State-Owned Enterprises of the Republic of Indonesia (MSOE)**
  The government agency that oversees government affairs in the field of state-owned companies or SOE, either directly or indirectly, according to applicable regulations. MSOE has the authority for formulating, determining, coordinating, and synchronizing the implementation of policies for the preparation of strategic business initiatives, strengthening competitiveness and synergy, improving performance, creating sustainable growth, restructuring, business development, and increasing the capacity of SOE business infrastructure including efforts in decarbonization and the energy transition in SOE.

- **Ministry of cooperatives and SMEs (KEMENKOP UKM)**
  Government agency that oversees government affairs in the field of cooperatives and SME within the government. KEMENKOP UKM has the authority for formulating and establishing policies related to cooperatives and SMEs, including efforts in decarbonization and the energy transition in cooperatives and SMEs that have diversified types of industry, which also support large industries.

- **Ministry of Investment / Indonesia Investment Coordinating Board (BKPM)**
The government agency that oversees government affairs in the field of the investment sector and coordinates the implementation of policies and services in the investment sector based on the provisions of statutory regulations. BKPM has the authority to coordinate and implement national policies in the field of investment, carry out promotions and cooperation, in carrying out investment activities, including in encouraging decarbonization and energy transition efforts.

- **Ministry of Trade (MITI)**
Government agency that oversees government affairs in the field of trade within the government. MTI is primarily responsible for formulating, establishing, and implementing policies related to strengthening and developing domestic trade, consumer protection and orderly trade, foreign trade, increasing market access for goods and services in international forums, developing national exports, as well as developing, coaching, and overseeing commodity futures. MITI has the authority to regulate sold and non-sold commodity to support decarbonization and energy transition efforts.

- **National Standardization Agency (BSN)**

  BSN is a Non-Ministerial Government Institution (LPNK) mandated by the Indonesian government to foster and coordinate all standardization and conformity assessment activities. BSN has the authority to propose standardization and certification to the relevant ministries and can also stand alone in encouraging decarbonization and energy transition efforts.

- **Indonesian Chamber of Commerce and Industry (KADIN)**
KADIN is the umbrella organization that represents Indonesia's business associations and chambers of commerce. It represents all types of business in Indonesia, including state business, cooperative business, and private business. It focuses on trade, industry, and services. It has 34 regional chambers and 514 district branches across Indonesia. One of the KADIN initiatives is to assist the private sector on the road to net zero encourages companies to disclose their climate actions, both in terms of their ESG performance and impact asset management with Kadin Net Zero Hub platform.

State-owned companies

- **PLN**
PLN, a state-owned enterprise, controls transmission, distribution, retail and production of electricity in the country.

- **Pertamina**
Pertamina, as a state-owned company, is the main pillar for oil and gas distribution and retail and is currently expanding into renewable energies to prepare for the transition away from oil and gas in various sectors, especially transport and industrial.

- **Pupuk Indonesia**
Pupuk Indonesia is a state-owned company that produces ammonia and fertilizer and plans to become a producer of green hydrogen and ammonia which can be used for decarbonization and the energy transition.

- **Perkebunan Nusantara III (PTPN)**
PTPN is a state-owned company holding plantations and engaged in the management, processing, and marketing of plantation commodities commodity include: palm oil, rubber, sugar cane, tea,

coffee, cocoa, tobacco, various woods, fruit and various other plants with covering area of 817,536 Hectares and plasma plantations covering an area of 457,794 Hectares. PTPN produces waste which is used as raw material for biomass, bioethanol and biodiesel and in progress to develop bioenergy end products.

- **PERHUTANI**
  PERHUTANI is a state-owned company that oversee forest utilization, which includes area utilization, environmental services utilization, utilization of timber and non-timber forest products, collection of timber and non-timber forest products with a managed area reaching of 2.43 million Hectares in Java island. PERHUTANI also produces biomass such as wood pellets and production of mixed raw materials for making bioethanol and biodiesel and in progress to develop bioenergy end products.

- **Rajawali Nusantara Indonesia (RNI/ID Food)**
  RNI is a state-owned company that oversees national food sovereignty and security. The RNI currently manages a prosperous program of land development with other state-owned enterprises (SOEs), having cultivated 518,932 hectares for rice, palm oil, sugar cane, corn, and coffee. As part of this program, RNI has also implemented the national sugar self-sufficiency program and has been able to realize 124,751 hectares of sugar cane land from the predicted 700 thousand hectares, which will also serve as a source of bioethanol and other bioenergy.

Government research institution

- **BRIN**
  The government agency oversees government duties in the fields of research, development, study, and application, as well as invention and innovation, nuclear energy administration, and integrated national space administration including in encouraging decarbonization and energy transition efforts.

Summary of Key Stakeholders

Industry	Summary		
	National production capacity	Players	Main energy sources
Cement	119.1 MMT	7 companies (1 SOE) makes up ~90% of national production capacity	Electricity and coal
Iron and steel	Iron & steel: 11.9 MMTPA Crude steel: 19.6 MMTPA	5 companies (1 SOE) makes up ~90% of national production capacity	Electricity and natural gas
Textile	6.92 MMTPA	Big companies dominating the industry; 10 big companies across upstream, midstream & downstream	Electricity, coal, and biomass
Pulp and paper	Pulp:11.5 MMTPA Paper: 20.7 MMTPA	7 pulp and 6 paper companies (no SOE) makes up ~90% of national production capacity	Electricity and biomass
Ammonia	Ammonia: 7.85 MMTPA Urea: 9.4 MMTPA	1 urea, 3 ammonia producer (1 SOE) makes up 90% of national production	Electricity and natural gas

In several industrial sectors, state-owned enterprises (SOEs) dominate national production capacity, including cement, iron & steel and ammonia, as follows: 47% for cement (1 SOE), 35% for iron & steel (1

SOE) and 13% for crude steel (1 SOE), 85% for Ammonia (1 SOE) (not included for Urea production).

Cement industry sector

No	Company	Production Capacity (MMT)	Domestic Market Share	Export (MMT)	Workers
1	PT Semen Indonesia Tbk (SOE)	56.45	50%	5.29	10,442
2	PT Indocement Tunggal Prakarsa Tbk	25.5	Java: 33.1% Sumatra: 13.1% Kalimantan: 23%	0.66	3,349
3	PT Cemindo Gemilang Tbk	11.9	6.95%	0.43	3,746
4	Bosowa Group	7.2	n/a	n/a	466
5	Conch Group	5.91	n/a	n/a	n/a
6	PT Sinar Tambang Arthalestari	5	n/a	n/a	200
7	PT Semen Jawa (SCG Group)	1.8	n/a	n/a	326

Iron and steel industrial sector

No	Company	Production Capacity (MMT)	Domestic Market Share	Export (KMT)	Workers
1	PT Krakatau Steel Tbk	Steel: 4.15	HRC: 40.30% CRC: 20.66%	266	2,730
		Crude steel: 2.5			
2	PT Gunung Raja Paksi	Steel: 2.4	7%	4.6	4,033
		Crude steel: 2.2			
3	PT Krakatau Posco	Steel: 1.5	n/a	40	2,400
		Crude steel: 4.5			
4	PT Dexxin Steel Indonesia	Steel: 1.5	n/a	50	200
		Crude steel: 4			
5	PT Gunawan Dianjaya Steel	0.46	n/a	15	463

Ammonia industrial sector

No	Company	Production Capacity (MMT)	Domestic Market Share	Export (% of sales)	Workers
1	PT Pupuk Indonesia	6.62	98.3%	10%	n/a
2	PT Surya Esa Perkasa	0.7	n/a	100%	n/a
3	PT. Kaltim Parna Industri	0.53	1.7%	80%	n/a

Pulp industrial sector

No	Company	Production Capacity (MMT)	Domestic Market Share	Export (MMT)	Workers
1	PT Indah Kiat Pulp and Paper Tbk	3.10	n/a	n/a	11,722
2	PT OKI Pulp and Paper	3.00	n/a	n/a	2,741
3	PT Riau Andalan Pulp and Paper	2.80	n/a	n/a	n/a
4	PT Pindo Deli Pulp and Paper	1.1	n/a	n/a	6,042
5	PT Lontar Papyrus Pulp and Paper Industry	1.05	n/a	n/a	1,573
6	PT Tanjung Enim Lestari Pulp and Paper	0.49	n/a	n/a	1,600
7	PT Toba Pulp Lestari Tbk	0.24	n/a	n/a	1,238

Paper industrial sector

No	Company	Production Capacity (MMT)	Domestic Market Share	Export (MMT)	Workers
1	PT Indah Kiat Pulp and Paper Tbk	3.91	n/a	n/a	11,722
2	PT Unipa Daya	3.76	n/a	n/a	480
3	PT Pindo Deli Pulp and Paper	2.4	n/a	n/a	6,042
4	PT Paper Factory Tjiwi Kimia Tbk	1.89	n/a	n/a	5,600
5	PT Fajar Surya Wisesa Tbk	1.69	n/a	n/a	3,366
6	PT Riau Andalan Kertas	1.15	n/a	n/a	n/a

Textile industrial sector

No	Company	Production Capacity (KMT)	Domestic Market Share	Export (% of sales)	Workers
1	PT Asia Pacific Fibers Tbk *(Fibers Production-Upstream)*	1008	16%	21%	n/a
2	PT Indo-Rama Synthetics Tbk *(Yarn and Fabric-Midstream)*	478	17%[1]	61%	5,542
3	PT Sri Rejeki Isman Tbk *(Yarn and Fabric-Midstream)*	420	7%[1]	61%	16.879
4	PT Asia Pacific Rayon *(Fibers Production-Upstream)*	237	7%[1]	55.7%	700
5	PT Pan Brothers Tbk *(Garment-Downstream)*	117	13%[1]	92%	31,682
6	PT Ricky Putra Globalindo Tbk *(Fabric & Garment-Midstream & Downstream)*	46	2%[1]	25%	3,472
7	PT Asia Pacific Investama Tbk *(Yarn and Fabric-Midstream)*	28.44	2%[1]	n/a	4,547
8	PT Eratex Djaja Tbk *(Garment-Downstream)*	9.2	2%[1]	99%	7,451
9	PT Trisula International Tbk *(Fabric & Garment-Midstream & Downstream)*	6	2%[1]	n/a	5,104
10	PT Century Textile Industry Tbk *(Yarn and Fabric-Midstream)*	3,988[2]	n/a	76,5%	367

Note: [1]Market share is based on total sales over the Indonesian textile market; [2]Production data is based on the 2020; [3]Production capacity is stated in different units, a conversion to tons is performed.

Appendix B. Green Hydrogen Direct Reduction of Iron Projects

Table B-1 provides a summary list of green hydrogen and green hydrogen-based ironmaking project, updated through April 2023. This list is grouped by the scale of the projects, whether they are in full industrial scale, pilots, demonstration, or R&D partnerships. The projects are ranked by the "Year Online", to indicate their status. All the project listed here produces hydrogen via electrolysis and zero-carbon electricity.

Table B-1. Green hydrogen and green DRI projects in the world (by April 2023)

Company	Country (in which project/investment is taking place)	Location	Technology Category	Hydrogen Type	Year Online
Project scale: full scale					
Fortescue Metals	Australia	Pilbara	H-DR	Green electrolytic	2023
H2 Green Steel	Sweden	Svartbyn	H-DR	Green electrolytic	2024
Liberty Steel	Australia	Whyalla	NG-DR --> H-DR	Green electrolytic	2024
ArcelorMittal	Germany	Bremen	Hydrogen production	Green electrolytic	2024
Enagas	Spain	Asturias	Hydrogen production	Green electrolytic	2024
ArcelorMittal	Spain	Gijon	H-DR & EAF	Green electrolytic	2025
H2 Green Steel	Spain	To be confirmed	H-DR	Green electrolytic	2025
Thyssenkrupp	Germany	Duisburg	NG-DR --> H-DR	Green electrolytic	2025
Tata Steel	Netherlands	Ijmuiden	Hydrogen production	Green electrolytic	2025
Thyssenkrupp	Germany	Duisburg	Hydrogen production	Green electrolytic	2025
ArcelorMittal	Germany	Bremen	NG-DR --> H-DR	Green electrolytic	2026
Blastr Green Steel	Finland	Inkoo	DR --> H-DR	Green electrolytic	2026
Hydnum Steel	Spain	Puertollano	H-DR	Green electrolytic	2026
Thyssenkrupp	Germany	Duisburg	H-DR	Green electrolytic	2026
ArcelorMittal	Canada	Hamilton	NG-DR --> H-DR & EAF	Green electrolytic	2028
LKAB	Sweden	Kiruna, Malmberget, Svappavaara	H-DR	Green electrolytic	2029
ArcelorMittal	Belgium	Ghent	NG-DR --> H-DR & EAF	Green electrolytic	2030

ArcelorMittal	Netherlands	North Sea (Dutch region)	Hydrogen production	Green electrolytic	2030
Salzgitter	Germany	Salzgitter	H-DR	Green electrolytic	2033
Liberty Steel	France	Dunkirk	NG-DR --> H-DR	Green electrolytic	Not stated
POSCO	South Korea	Not stated	Hydrogen production	Green electrolytic	Not stated
Tenaris	Italy	Dalmine	Hydrogen production	Green electrolytic	Not stated
Project scale: pilot					
Voestalpine	Austria	Linz	Hydrogen production	Green electrolytic	2019
SSAB	Sweden	Luleå	H-DR	Green electrolytic	2021
ArcelorMittal	Germany	Eisenhüttenstadt	H-DR	Green electrolytic	2026
Project scale: demonstration					
Salzgitter	Germany	Salzgitter	Hydrogen production	Green electrolytic	2021
Salzgitter	Germany	Salzgitter	Hydrogen production	Green electrolytic	2021
Calix	Australia	Bacchus Marsh, Victoria	Hydrogen production	Green electrolytic	2024
SSAB	Sweden	Gällivare	H-DR	Green electrolytic	2026
Project scale: R&D partnership					
Stahl Holding Saar GmbH	Canada	Not applicable	H-DR	Green electrolytic	2021
ArcelorMittal	Spain	Asturias	Hydrogen production	Green electrolytic	2025
Salzgitter	Germany	Wilhelmshaven	H-DR	Green electrolytic	N/A
Thyssenkrupp	Netherlands	Rotterdam	H-DR	Green electrolytic	Not stated
Bluescope	Australia	Not applicable	H-DR & biomass	Green electrolytic	Not stated
POSCO	Australia	Not applicable	Hydrogen production	Green electrolytic	Not stated
ArcelorMittal	South Africa	Vanderbijlpark	Hydrogen production	Green electrolytic	Not stated
Salzgitter	Germany	Wilhelmshaven	Hydrogen production	Green electrolytic	Not stated

Source: Stockholm Environmental Institute 2022.

Notes: NG-DR: natural gas based direct reduction of iron production; H-DR: hydrogen based direct reduction of iron production.

Appendix C. Energy-Efficiency Measures in the Cement Industry

Many commercialized technologies are available for improving energy efficiency in the cement industry, as shown in Table C-1.

Table C-1. Commercialized energy-efficiency measures in cement manufacturing

Fuel preparation
Efficient coal separator
Efficient roller mills for coal grinding
Installation of variable frequency drive (VFD) & replacement of coal mill bag dust collector’s fan
Raw materials preparation
Raw meal process control for vertical mill
High efficiency classifiers/separators
High efficiency roller mill
Efficient transport system
Raw meal blending (homogenizing) systems
VFD in raw mill vent fan
Bucket elevator for raw meal transport
High efficiency raw mill vent fan with inverter
Clinker making
Replacing vertical shaft kilns with new suspension
Conversion to grate cooler
Upgrading to a preheater/precalciner kiln
Kiln shell heat loss reduction (improved refractories)
Membrane-method oxygen-rich combustion
Energy management & process control systems
Older dry kiln upgrade to multi-stage preheater kiln
Upgrading preheater from 5 stages to 6 stages
Optimize heat recovery / upgrade clinker cooler
Optimize grate cooler
Combustion system improvements
Low temperature waste heat recovery for power generation
Adjustable speed drive for kiln fan
Low pressure drop cyclones for suspension preheater
Bucket elevators for kiln feed
Use of high efficiency preheater fan
Efficient kiln drives
VFD in cooler fan of grate cooler
Finish grinding
Energy management & process control in grinding
Replacing a ball mill with vertical roller mill
High pressure roller press for ball mill pregrinding
Improved grinding media for ball mills
High-efficiency classifiers (for finish grinding)
High-efficiency cement mill vent fan
General measures
High-efficiency motors
Adjustable speed drives

Sources: Worrell, Kermeli, and Galitsky 2013; Hasanbeigi et al. 2012.

Appendix D. Low-Carbon Ammonia Projects

Table D-1 summarizes a list of ongoing and announced green ammonia projects in the world. These projects utilize renewable electricity (hydropower, grid-connected renewable power, solar photovoltaic, wind, and others) to produce green hydrogen, and then produce green ammonia through ammonia synthesis.

Table D-1. Green Ammonia Projects in the World (as of October 2022)

Project Name [Company]	Country	Status	Source of Renewable Electricity	Date Online	Capacity (MW Electrolyzer)
Industrial Cachimayo [Industrias Cachimayo]	Peru	Operational	Hydropower	1975	19.4
Carbon2Chem [Thyssenkrupp]	Germany	Operational	Grid excess renewable electricity	2018	2
Fertiberia/Iberdrola - Puertollano I [Iberdrola]	Spain	Operational	Solar PV	2022	20
OCP Group demo project [OCG Group]	Morocco	Under construction	Various	2022	1.5
Green fertilizer project Porsgrunn-Heroya phase 1 [Yara]	Norway	Under construction	Unknown	2023	24
REDDAP [Topsoe/Skovgaard Energy/Vestas]	Denmark	Final investment decision made	Various	2023	10
Green H2 New Zealand – Taranaki [Balance]	New Zealand	Final investment decision made	Various	2023	4.2
Unigel, phase I [Unigel]	Brazil	Final investment decision made	Onshore wind	2023	60
Helios Green Fuels – Neom [ACWA Power/Air Products/NEOM]	Saudi Arabia	Under construction	Various	2026	2,200

Source: IEA 2022b.

Table D-2 summarizes a list of ongoing and announced blue ammonia projects in the world. Captured CO_2 emissions have been used mostly for enhanced oil recovery (EOR), but gradually, as seen in recent project announcements, CO_2 emissions are used for chemical production or stored.

Table D-2. Blue Ammonia Projects in the World (as of 2022)

Company	Location	Technology Category	Year Online
Koch Nitrogen Company, Chaparral Energy	Enid, US	Natural gas + CC + EOR	1982
Dakota Gasification Company	Beulah, US	Natural gas + CC + EOR	1991
CVR Energy, Chaparral Energy, Blue Source	Coffeyville, US	Natural gas + CC + EOR	2013
Nutrien	Geismar, US	Natural gas + CC + EOR	2013
Nutrien	Redwater, Canada	Natural gas + CC + EOR	2020
SAFCO	Jubail, Saudi Arabia	Natural gas + CC + EOR/Utilization (methanol synthesis)	2021
OCI Nitrogen	Beaumont, US	Natural gas + CC + EOR	2025
Yara	Pilbara, Australia	Natural gas + CC + utilization	2024/2025
Horisont Energy, Haldor Topsøe	Finnmark, Norway	Natural gas autothermal reforming + CCS	2025
ADNOC	Ruwais, UAE	Natural gas + CCUS	2025
PAU, Mitsubishi, Jogmec, Bandong IoT	Central Sulawesi, Indonesia	Natural gas + CCS	2026 or earlier
Air Products	Ascension Parish, Louisian	Natural gas + CCS	2026
Yara, Enbridge	Texas, US	Natural gas + CCS	2027/2028
JERA, Uniper, ConocoPhillips	Gulf Coast, US	CCS-based (and electrolysis-based) ammonia production	Late 2020s
CF Industries	Billingham, UK	Natural gas + CCS	TBD
CF Industries	Ince, UK	Natural gas + CCS	TBD

Sources: IRENA 2022; Klesty and Nickel 2023; JERA and Uniper 2022.

Notes: CC: carbon capture; EOR: enhanced oil recovery; CCS: carbon capture and storage.

Appendix E. Electrotechnologies for Process Heating Systems

What are process heating systems?

Process heating systems supply heat to materials for manufacturing purposes in furnaces, melters, heaters, kilns, ovens, lehrs, calciners, and other heating systems. These systems include a variety of heating processes, such as steam generation, fluid heating, calcining, drying, heat treating, metal treating, metal and non-metal melting, smelting, agglomeration, curing, and forming. Process heating temperatures can range from as low as 100°C to as high as 1,600°C. Process heating systems use many different types of energy sources to generate heat, such as fuels (e.g., coal, natural gas, biomass), electricity, steam, hot water, liquids (e.g., fuel oils), and others. Globally, process heating energy use accounts for about one-third of all industrial energy use, and about 90% of that is generated by fossil fuels.

Electrification of process heating systems

As the cost of renewable technologies continues to decline and the power sector decarbonizes, electrification is an increasingly promising low-carbon option for industry. While decarbonizing high-temperature manufacturing processes will be challenging, increasing the rate of electrification using zero-carbon electricity is an important near term strategy to decarbonize lower temperature industrial processes. In addition to reducing emissions of GHGs and key air pollutants, the use of zero-carbon electricity has other non-energy benefits, such as increased productivity, improved product quality, enhanced operational and worker safety, increased manufacturing flexibility, reduced waste production, and reduced cost of environmental compliance (Rightor and Elliott 2020).

Key technologies to electrify process heating systems

A number of commercially available or emerging electrotechnologies are presented in Table E-1. Electric boilers, hybrid boilers, and low-temperature industrial heat pumps are already commercially available and can be adopted in many industries that have steam demand. Higher-temperature industrial heat pumps are also emerging to further electrify process heat. For more details on the technology, opportunities, and barriers to industrial heat pumps, please see IEA report on heat pump technologies (IEA 2022c) and the resources developed by the American Council for an Energy-Efficient Economy (ACEEE 2023).

Other commercially available electrotechnologies such as infrared heating, induction heating, and resistance heating can be used in industries with metal or chemical processing needs, or in processes with lower temperature demand (e.g., drying and evaporation). There are also many other emerging electrotechnologies with potential applications in industries such as primary metals, food, textiles, automotive manufacturing, and machinery.

Table E-1. Selected Electrotechnologies for Process Heating Systems

Technology	Maturity	Cost	Industry Applications
Electric boiler	Commercial	Low-Medium	Many industries, with steam demand
Hybrid boiler	Commercial	Medium	Many industries, with steam demand
Heat pump	<100°C: commercial 100°C–150°C: emerging >150°C: R&D	Low Medium High	Many industries, with corresponding temperature needs
Infrared drying	Commercial	Low-Medium	Industries with drying, evaporation, melting, reacting, processing, mold forming needs
Resistance heating	Commercial	Low-Medium	Industries with metal, plastics, chemical processing needs
Extrusion porosification	Commercial	Low-Medium	Industries with melting, reacting, and processing needs
Induction heating	Commercial	High	Industries with melting, reacting, and processing needs
Friction heating	Commercial	High	Industries with melting, reacting, and processing needs
Ohmic drying	Emerging	Medium	Industries with drying, evaporation, melting, reacting, processing, heat treating needs
Microwave, radiofrequency	Emerging	High	Industries with drying, evaporation, melting, reacting, processing, and sterilization needs
Pulsed electric field	Emerging	High	Industries with sterilization, melting, reacting, and processing needs
Ultrasound	Emerging	High	Industries with enhanced drying, sterilization needs
Pulsed light	Emerging	High	Industries with sterilization needs
Ultraviolet	Emerging	High	Industries with sterilization and curing needs
Electroslag, vacuum, plasma	Emerging	High	Industries with higher temperature needs

Sources: Rightor, Whitlock, and Elliott 2020; Deason et al. 2018; Jadun et al. 2017.