MISSION INNOVATION

Roadmap towards **Net-Zero Industries**

Content

List of acronyms

BOF	Basic Oxygen Furnace
CBAM	Carbon Border Adjustment Mechanism
CCU	Carbon Capture and Utilization
CCUS	Carbon Capture, Utilization and Storage
CO_2	Carbon Dioxide
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
FEED	Front-End Engineering Design
Gt	Gigatons
H_2	Hydrogen
LNG	Liquefied Natural Gas
MI	Mission Innovation
NZI	Net-Zero Industries
R&D	Research and Development
R&I	Research and Innovation
RD&D	Research, Development and Demonstration
SMR	Small Modular Reactors
TRL	Technology Readiness Level

Acknowledgments

This roadmap document was coordinated by the MI Net-Zero Industries Co-Leads Austria and Australia, with the support and contributions of the MI Net-Zero Industries member countries and associations (names in alphabetical order):

Adriana Vargas Colwill, Alan Monaghan, Alberto Ortega, Alfonso Chinnici, Alois Mhlanga, Asa Ekdahl, Bernhard Gahleitner, Burrell Leisa, Christian Schützenhofer, Christopher Pearce, Claudia Bernading, Daniel Stähr, Dawn Adin, Elvira Lutter, Emerson Clarke, Eun Ji Park, Felicity Lloyd, Fredrik Backman, Gerwin Drexler-Schmid, Gökçe Mete, Gudrun Haindlmaier, Graham Nathan, Jürgen Tiedje, Karl-Heinz Leitner, Katja Hollmén, Louisa Esdaile, Ludo Diels, Luis Humberto Umanzor Hernandez, Luis Janeiro, Marcel Silva, Martina Lyons, Muna Al Amoodi, Nina Eneroth, Olle Olsson, Orduna Angels, Peta Olesen, Petra Schwager, Radhika Lalit, Raghunath Reddy, Rana Ghoneim, Rizwan Janjua, Robert Watt, Rod Janssen, Sabine Mitter, Sangita Kasture, Sarah Diouri, Shengping Wang, Solmaz Parsa, Sophie Huber, Stela Ivanova, Thomas Kienberger, Tom Rollason, Ulrich Schmid, Will Hall, Wolfram Rhomberg, Yvonne Leung

Application potentials – towards a roadmap for Net-Zero Industries	CEMENT & LIME	CHEMICALS	IRON & STEEL
Electrification of production and processes	medium	medium	medium
Use of clean hydrogen	low	very high	very high
Carbon Capture and Storage (CCS)	very high	low	low
Carbon Capture & Utilisation (CCU)	high	medium	low
Alternative fuels and feedstocks (excl. H_2), bio-based resources, and integration of renewable energy	medium	medium	low
Alternative materials and more energy efficient processes	very high	high	high
Materials efficiency, secondary resources and waste valorisation	high	high	high

Roadmap Towards Net-Zero Industries – Executive summary

THE CHALLENGE – Heavy industries like steel, cement and chemicals require extremely high temperatures and use massive amounts of energy. These sectors also encounter high investment costs for process equipment with long payback periods and a lifetime of over 20 years. Unlocking emission reduction at the end of their refurbishment cycles could prevent nearly 60 Gt CO_2 and help put industrial sectors on a pathway to net zero emissions by 2050.

THE GOAL – The Net-Zero Industries (NZI) Mission aims to catalyse the development and demonstration of cost competitive solutions for the efficient decarbonization of energy intensive and hard to abate industries worldwide by 2030. Energy intensive industries are responsible for around 25 % of global greenhouse gas emissions. RD&D will be critical to validate innovative industrial processes and technologies that enable radical CO_2 emission cuts beyond 2030 at competitive costs. This Mission will support industry by providing evidence, knowledge sharing and collaboration opportunities and therefore help them to make decisions towards reducing carbon outputs as soon as possible. By 2030, the Mission pursues the goals of implementing **at least 50 large-scale demonstration projects** in energy-intensive industries; fast-tracking the development to TRL 8 of new and radical breakthrough low-emission technologies as well as reducing the capital expenditure of low-emission innovative technologies by more than 15 %. Together these goals will enable the scaling up and deployment of net-zero industries solutions that are cost-competitive with incumbent technologies by 2050.

THE ROADMAP TOWARDS NET-ZERO INDUSTRIES – This mission is part of the missions to support MI's commitment to a decade of clean energy innovation. A roadmapping process with core member countries and organisations led to several priority innovation pathways per sector.

Knowledge sharing as a major activity of all Missions will create alignment and a coordinated effort to emission reductions both between pillars and externally with existing initiatives and stakeholders. Timelines and pathways to develop and deploy technologies will be further detailed within the **Mission's action plan**. The roadmap also provides an extensive **list of key technical and non-technological barriers** to overcome, in order to create supporting eco-systems for effective development and deployment of net-zero energy solutions. The report also **highlights enabling factors** such as financing and uptake of affordable solutions, provision of green energy, supply of materials and raw materials, circular economy and workforce skills, all of which will play a crucial role for net-zero industries.

1 The way towards the Net-Zero Industries Roadmap

Background and motivation

Energy intensive industries are responsible for around 25 % of global greenhouse gas emissions. Research, development and demonstration (RD&D) over the next decade will be critical to develop and validate innovative industrial processes and technologies that enable radical CO_2 emissions cuts beyond 2030 at lowest cost.

Sustainable energy-intensive industries can unleash dynamic and competitive economic forces that generate employment and income. However, energy-intensive industries are currently responsible for around 25 % of GHG emissions worldwide and the decarbonization of the energy-intensive industry is currently significantly more expensive than for other sectors, while many low carbon technologies are not yet available at commercial scale.

The Net-Zero Industries (NZI) Mission aims to demonstrate the required technologies for energy intensive industry to achieve deep and ambitious emissions reductions. 2050 is one investment cycle away, making the availability of new technologies at scale a critical issue.

If the right technologies can reach the market in time for the next 25-year refurbishment cycle – due to start around 2030 – they can prevent nearly 60 Gt CO_2 or 38 % of projected emissions from existing equipment in energy-intensive industries (IEA 2020)[1]. This means that at the end of this decade, there will be a once-in-a-generation opportunity to reshape the future. To ensure that this happens, it is critical to connect and align both national and multinational RD&D efforts to showcase net-zero emission industry model solutions in large scale demonstration projects for energy intensive industry. In response to this need, the Net Zero Industries Mission is pursuing decarbonization pathways for energy intensive industries in the form of a challenge driven initiative for RD&D efforts. As Industry needs better information and trust in the cost/benefit and technical performance of various decarbonisation options to help them make decisions towards reducing carbon outputs as soon as possible, this Mission will support them by providing evidence, knowledge sharing and collaboration opportunities. By doing so, the Mission will ensure that key technical solutions are developed and demonstrated by 2030, to enable an effective and efficient decarbonization of energy intensive industries by 2050, in multiple regions of the world.

To reach these ambitious goals, this joint roadmap has been developed by the NZI member countries and associations to articulate a common vision and strategic objectives. Promising Research and Innovation (R&I) themes & technology pathways within specific sectors and cross-sectorial areas have been identified. Timelines and pathways to develop and deploy technologies, as well as investment needs to develop these shortlisted technologies, and framework conditions and measures that enable the development and deployment of technologies, are also assessed within this Roadmap document.

[1] See www.iea.org/reports/world-energy-outlook-2020

The Mission Roadmap also outlines the top global innovation priorities as discussed among the MI members and within the public consultation, assessing their potential contribution to achieving the tipping points across the Mission's three pillars, as well as outlining criteria for the selection of most valuable demonstration projects to be developed on specific innovation priorities.

The coalition – core members and governance

The Mission brings together a dynamic, ambitious, and delivery-focused alliance of governments, corporations, investors, and research institutes to accelerate innovation and, consequently, the implementation of industrial decarbonisation.
The following governments and organisations have committed to advancing the Mission's goal of developing and showcasing reliable, cost competitive and net-zero emissions production of energy-intensive industrial processes with relatively high emissions, such as those used in the steel, cement, and chemicals industries, by 2030.

Co-leads:
- Australia, Department of Climate Change, Energy, the Environment and Water
- Austria, Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology

Core coalition MI members:
- Canada, Natural Resources Canada
- China, Ministry of Science and Technology
- European Commission, DG Research and Innovation
- Finland, Ministry of Economic Affairs and Employment
- Germany, Federal Ministry for Economic Affairs and Climate Action
- Republic of Korea, Ministry of Trade, Industry and Energy
- United Kingdom, Department for Business, Energy and Industrial Strategy

International activities and partner organisations:
- CEM Industrial Deep Decarbonisation Initiative (IDD)
- The International Energy Agency (IEA) Technology Collaboration Programme on Industrial Energy-related Technologies and Systems (IEA IETS)
- The International Renewable Energy Agency (IRENA)
- The Leadership Group for Industry Transition (LeadIT)
- Mission Possible Partnership (MPP)
- A.SPIRE, World Steel Association
- Global Wind Energy Council (GWEC)
- The United Nations Industrial Development Organization (UNIDO)
- First Movers Coalition (FMC)

Other countries, international initiatives, investors, organisations from research and industry will be encouraged to join in the future.

2 Vision and strategic objectives

MI Missions mobilise global action behind ambitious and inspirational innovation goals that can lead to tipping points in the cost and scale of net zero energy solutions across all sectors. This Mission contributes to Mission Innovation's commitment to a decade of clean energy innovation, galvanising actions that will enable every country to have the confidence to set ambitious clean energy and climate targets.

As energy intensive industries are responsible for around 25 % of global greenhouse gas emissions, RD&D over the next decade will be critical to develop and validate innovative industrial processes and technologies that enable radical emissions reductions at lowest costs. There is a need to accelerate the development of key technologies to become commercially available no later than 2030, to ensure that they can be taken up in the market in time for the next 25 year refurbishment cycle.

The following targets and milestones to achieve the Mission goal of developing and demonstrating cost competitive solutions for the efficient decarbonization of energy intensive industries by 2030 can be stated:

- implement at least two large-scale demonstration projects for each of the Mission's key innovation fields and sectors;
- fast-track the development to TRL 8 of new and radical breakthrough low emissions technologies
- target a reduction of more than 15 % in the Capex of low emissions innovative technologies.

The Mission will progress under three interlinked pillars:

- **Underpinning R&D**
  Underpinning R&D in new and radical breakthrough technologies beyond 2030, allowing different and cheaper routes to decarbonize industry
- **Creating enabling conditions**
  Creating enabling conditions for demonstration projects designed and conducted in the context of sustainable development. Examples are funding Front-End Engineering Design (FEED), feasibility studies, sharing of good practices on R&I policy, transparency requirements for reporting on emissions, actions and support[2], regulatory frameworks or market incentives.
- **Demonstrations**
  Setting up a solutions-driven demonstration initiative, realizing a portfolio of aligned national and/or joint multi-national calls that can showcase net-zero emissions industry model solutions in large scale demonstration projects for energy intensive industry in collaboration with the private sector.

Knowledge sharing
Sharing knowledge and creating confidence in the use of innovative solutions will be key to the success of this mission. To this end, knowledge sharing both between pillars and externally with existing networks and platforms will create alignment and a coordinated effort to emission reductions.

2 see also Working Group III contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, April 2022

Mission Ambition

Net-zero emissions is a global challenge. Innovation will be most effective if countries are able to share some of the high development and investment risks. The Mission will fill the need of:

- Increasing, connecting and aligning both national and multinational RD&D efforts into a challenge driven initiative
- Novel technology cooperation to reduce "time to market"
- Joining forces with existing networks organisations and platforms to raise awareness, create knowledge and confidence in the use of innovative solutions

The Mission will focus its ambitions and efforts towards achieving the Mission goal, which will be structured around the following innovation fields: **Process optimization & energy efficiency; fuel & feedstock switch; electrification of end use activities; CCUS; digitalization; flexibilization as well as circular economy[3] and sector coupling.** Together, these actions of Mission members will help to focus and ensure that by 2030, there is a suite of technical solutions available that are sufficiently effective and proven to facilitate the full decarbonization of energy intensive industry in multiple regions of the world, by 2050.

To work towards these objectives, the members of the mission will advance these joint efforts by adhering to the following principles (for details on Mission Goals and Mission Governance please see Joint Mission statement):

- **Cooperation:** members will engage and work with other countries, their respective research, technology and laboratory agencies, the private sector and other related initiatives nationally and internationally.
- **Transparency:** members will share information, expertise, and analysis, as appropriate, to help advance Mission objectives in accordance with the structures and frameworks as set by the mission. The Mission acknowledges the importance of protecting intellectual property rights (IPR). IPR will be negotiated amongst individual project consortia.
- **Participation:** members will provide dedicated points of contact for mission engagement, including regular attendance in meetings, including a commitment to attend meetings at a rotating time zone to accommodate all members inclusively, and actively support mission objectives of the pillar of interest through providing access to analysts, private sector industry experts or project management capabilities as needed.

3 For examples please see table 1: Reference framework on technological pathways

- **Accelerate action:** members will agree and focus on key barriers and challenges to speed up innovation toward the stretch goal and stimulate more action, either individually or collaboratively, through new policies, programs, roadmaps or funding.
- **Build demand:** members will identify the "demand-pull" efforts needed to diffuse and deploy solutions that emerge through the Mission and partner with initiatives or actors that can deliver those activities.
- **Review, reflect, improve:** members will remain agile, reviewing progress and modifying actions to remain at the frontiers of innovation and ambition, and being flexible to changing national circumstances of members.

3 Technological options for decarbonization of energy-intensive industries by pathways

This brief description of the following technological pathways for the decarbonization of industrial processes focuses on the sectors "Cement & Lime", "Chemicals", "Iron & Steel", but also gives examples from other sectors of energy intensive industry (especially for aluminium/alumina as this is particularly advanced in some mission countries and provides learnings for other sectors and synergies – see below). Also, potential *cross-sectoral* R&D topics and technological options are listed[4]. The elaboration of these technological pathways is based on a detailed deep-dive analysis of single technological options for industrial decarbonization, based on current key studies and roadmaps. [5] The focus is on R&D topics for TRL 1-9 (TRL low: 1-3, medium: 4-6, high: 7-9). The list is not a prioritization, but a structured overview and framework for technology options in relevant sectors for the mission as well as supporting the identification of cross-cutting issues to other sectors than the prioritised ones. Also the third dimension of what TRL these technologies are already at are taken into account (besides the technology pathways and the sectoral focus points as presented below) as well as the country-specific priorities and the current state-of-the-art (see table 3). In the ongoing elaboration of the Mission in the Action plan, this technology options will be mapped against the Mission pillars that need to be involved, as well as the demonstration projects in the countries.

[4] E.g. Digitalisation & flexibilisation is primarily understood as a cross-cutting issue and has therefore not been further elaborated as a separate pathway resp. was integrated into the other pathways (especially in process optimisation/ energy efficiency and circular economy/cross-sector coupling).

[5] Sources included: European Commission (2021), Pilot Industrial technology prospect report – R&I evidence on EU development of low-carbon industrial technologies; Processe4Planet Roadmap; Clean Steel Roadmap; Fraunhofer Study; High-Level Group on Energy-intensive Industries (HLG EII) Study and Addendum; Capgemini Study; Materials Economics Study; Exponential Roadmap; ETC Mission Possible Roadmap; EP (ITRE) Roadmap; EP (STOA) Carbon-free steel routes; IEA International Energy Agency Technology Outlook & NetZero 2050; Written input/feedback from various business associations

Table 1: Reference framework on technological pathways for the decarbonization of industrial processes

		INDUSTRIAL SECTORS			
		Iron and Steel	Cement	Chemicals	Alumina
Fuel Switch	**Non-conventional / renewable energy sources**	Use of alternative fuels (bioenergy and waste)	Alternative fuels (incl. biomass)	Biomass and plastic waste as an alternative feedstock	Replacing NG with H_2 for calcination
	Integrated hydrogen production	Direct reduction using Hydrogen	Integrated H_2 production for CCU	Integrated production of Hydrogen	Integrated production of Hydrogen
Process optimisation & energy efficiency		Improved thermal efficiency — coke dry quenching, waste heat recovery in iron kiln pelletisers	Improved thermal efficiency — kiln conversion and waste heat recovery	Process effciency	Heat re-use, regenerative burners
Electrification		Direct reduction using electricity, adaptation of Electric Arc Furnaces	Electrification of sintering and calcination processes. Electrochemical formation of calcium hydroxide	Electrification of crackers and chemical processes	Steam electrification
CCUS		CCU / CCUS	CCU / CCS	CO_2 / CO as an alternative feedstock	CCU from alumina refineries
Digitalisation & flexibilisation		E.g. process control and automation, temperature upgrade of excess heat, smart management of variable energy resources such as PV and wind power, hybridisation of different sources, Excess heat to power or cold, flexibility in power generation/utilization including bottleneck management and redispatch			
Circular economy, materials efficiency & cross-sector coupling		Harnessing by-products from one industry as alternative inputs to another industry and technical upgrading of by-products, industrial symbiosis, carbonation of mineral resides, alternative binding materials in cement			

The electrification of production and processes

This pathway includes the electrification of process steps, the electrification of thermal processes (kilns, crackers, burners, furnaces, boilers) and the introduction of electrochemical processes, e.g. electrolysis. For Mission implementation, a prioritization of the energy sources for certain applications is needed or striven for[6]. In order to enable electrification, regulatory frameworks for the build-out of renewable energy are needed or currently in negotiation at national level. Furthermore, in short and medium term perspective, bridge technologies might be necessary.

- Cement & Lime: Electrification of kilns, sintering and calcination processes e.g. via plasma generators or microwave options (also in combination with hydrogen), electric heating and cracking, electrochemical formation of calcium hydroxide and electrified cement
- Chemicals: Indirect electrification for heat at low (e.g. boilers) and high temperature (e.g., e-cracker) and steam generation or upgrade; Direct electrification of chemical processes (electrochemical processes and electricity-driven separation)
- Iron & Steel: Electrified primary steel: electrochemical reduction of iron ore and use of green electricity for EAF or for ore reduction (iron ore electrolysis); Replacement BF/BOF with DRI-EAF route; Generation of oxygen by electrolysis for combustion processes; Electrification of process steps e.g., sintering or reheating of furnaces

Crosscutting for (some) sectors: Electrification of thermal processes (furnaces) and process steps including steam electrification for the alumina sector; industrial heat pumps for low/medium and high temperature processes; electrically driven separation; electrochemical processes and liquid electrolyte high temperature processes.

Use of clean hydrogen

This pathway includes the use of clean hydrogen for combustion/heating purposes and as a reducing agent (e.g. substitution of natural gas by H_2). It also comprises the use of clean hydrogen[7] to produce chemicals and hydrocarbons, so the use of clean hydrogen will also play an important role for the transition of the chemical sector to climate-neutrality.

- Cement & lime: Use of clean hydrogen as a fuel both standalone and in combination with other fuels, particularly refuse derived fuels
- Chemicals: Use of clean hydrogen for chemical production (e.g., ammonia[8], methanol, polymers), hybrid ammonia production; Water electrolysis and methane pyrolysis for integrated production of clean H_2
- Iron & Steel: Use of green hydrogen in direct ore reduction, and plasma reduction (smelting reduction); blending of H2 into commercial production routes (combustion)

Crosscutting for (some) sectors: Use of clean hydrogen for better combustion in furnaces of high temperature process industries, including partial or total replacement of fossil fuels with hydrogen in the calcination of alumina.

[6] See studies such as IndustRiES, NEFI_LAB, TransformIndustry where this is done, e.g. within the Innovation Priorities.

[7] Clean H_2 refers to H_2 from renewables and also includes low-carbon hydrogen from natural gas via SMR with carbon capture or methane cracking

[8] Hydrogen and its derivatives are at the core of the Clean Hydrogen Mission, so the Net Zero Industries Mission will seek linkages and synergies here.

Carbon capture & storage (CCS)

This pathway includes the direct capture/separation and adsorption/absorption of CO_2 process and combustion emissions and its storage.

- Cement & Lime: Direct capture/separation and adsorption/absorption of process emissions; Carbonate/CO_2 looping (using limestone, with oxyfuel, through mineralization); Oxy-fuel combustion; Post-combustion technologies
- Chemicals: Capture of CO_2 from process and combustion emissions (amine based, adsorption, absorption, direct separation)
- Iron & Steel: Generation of CO_2-rich waste gas to facilitate CCS; DRI + CCS: physical adsorption and chemical absorption; CCS on top gas of blast furnace; H2 enrichment in blast furnace and chemical absorption; Smelting reduction with CCS and/or bio-cokes

Crosscutting for (some) sectors: Capture and storage of CO_2 from process emissions and combustion emissions; novel technologies for simultaneous beneficiation of low-grade iron ore and activation of non-valuable components for CCS via mineralisation

Carbon capture & utilization (CCU)

This Pathway includes the capture, purification, and valorisation of CO_2 into chemicals, polymers synthetic/alternative fuels and raw materials, and also the use of CO_2 exhaust gases in other processes. Furthermore, CO_2 as alternative feedstock is also to be considered under circularity options where CO_2 is a circular source of feedstock next to waste and biomass.

- Cement & Lime: CCU in Cement Production and on process emissions; CCU on cement and lime kilns; Carbonization of solid raw material/curing with CO_2; Mineral CO_2 and CO_2 scrubbing (Cement & Lime)
- Chemicals: Utilisation of captured CO_2 (and CO from "industrial waste gases") for the production of chemicals (including basic and fine chemicals) and polymers through various processes (Chemicals)
- Iron & Steel: Reuse and valorization of waste/slag and gases esp. from the BF/BOF into chemicals/products/raw materials. Synergies with chemical industry

Crosscutting for (some) sectors: (Flexible) CO_2 capture and purification technologies for CO_2 valorisation

Alternative fuels and feedstocks (excluding H_2), bio-based resources, and integration of renewable energy

This pathway focuses mainly on the integration of bio-based fuels and feedstocks as replacement of fossil fuels and as resources and for heating/combustion, power generation and the production of chemicals and polymers. It also comprises the integration of energy/heat from renewables into production processes.

- Cement & Lime: Use of concentrated solar heat and PV, syngas, waste and biomass as a replacement of solid fossil fuels (for heat and power generation); Biomass co-combustion under air- and oxy-fuel conditions; production of syngas from shredded material

- Chemicals: Utilisation of bio-based resources as a raw material/feedstock for chemicals and plastics; Biomass/waste and alternative energy for heat/energy generation; integration of renewables
- Iron & Steel: Integration of renewables in steelmaking and CO_2 upgrading (PV and wind power); replacement of coal by charcoal, biogas, biomass. Substitution of fossil materials with alternative materials and reductants; DRI-EAF with biogas; BF/BOF with biomass

Crosscutting for (some) sectors: Integration of renewables; processing of (non-recyclable) waste and biomass in high temperature furnaces; direct use of bio-based resources as feedstock in industrial applications/processes

Alternative materials and more energy efficient processes

This pathway includes the introduction of *alternative materials* and the reformulation e.g., of new cement types, and the pre-treatment, pre-heating and pre-reduction of raw materials; It comprises new kiln technologies and the design for *energy efficient kilns*, the *use of waste heat sources* (from off-gases, by heat exchangers), heat recovery technologies, and recuperative and regenerative burners. This Pathway includes more efficient *energy and process gas management*, the usage of high-pressure gas, energy recovery and the optimization of combustion processes. Besides *new drying techniques* (e.g. vacuum drying technologies), also *process intensification* including new membrane reactor technologies and new catalysts, and *new separation technologies* (e.g. thermal separation), as well as *smelting reduction* (metallurgy) are part of this pathway.

- Cement & Lime: New cement types and alternative raw materials: Low carbon, super sulphated and CO_2 activated cement; Alternative cements/CSH with low clinker content, clinker and aggregates substitutes (e.g. belite clinker) and alternative binders (e.g. from steel slag); Pozzolan-based concrete and cement-less concrete; High strength and carbon reinforced concrete; Lime carbonation and Advanced grinding technologies; New kiln technologies, e.g. vertical kilns, installing heat exchangers to capture and utilise waste heat; dry kilns, multistage cyclone heaters energy recovery and optimal combustion process.
- Chemicals: Membrane reactor technologies and other breakthrough technologies alternative to distillation; Process intensification, including reactor design/equipment, new catalysts, and improvements in monomer production; new separation technologies e.g. advanced technologies for thermal separation; more focus on downstream processing and the integration of conversion and DSP
- Iron & Steel: Smelting reduction; Increase of the scrap/hot metal ratio; replacement of iron ore or scrap by hot briquetted/direct reduced iron; Energy and process gas management, usage of high-pressure gas; Use of waste heat sources; heat reuse by heat exchangers; Coke dry quenching

Crosscutting for (some) sectors: New kiln technologies, installing heat exchangers; energy/waste heat recovery; process gas management and optimization of combustion processes; Drying technologies; process intensification, e.g., through next-gen catalysis

Material efficiency, use of secondary resources (incl. recycling) and industrial symbiosis

This pathway includes e.g., raw material development for a Circular Economy, redesigning products for material efficiency and circularity. It comprises better scrap recycling with new sensing and monitoring technologies, efficient physical scrap collection and sorting, new de-coating equipment, and new recycling technologies without wetting and drying. This pathway also addresses mechanical, dissolution and chemical recycling of waste and by-products, mineralization of concrete waste/slag, gas recycling, reprocessing of by-products into chemicals, and improved aggregate packing,

Cement & Lime: Recycling and reusing cement and concrete; Recycling waste and by-products from other EIIs (e.g., steel slag); usage of lime by-products; Lower clinker to cement ratio; ACT for fly ash; Mineralization of concrete waste; improved aggregate packing

- Chemicals: Mechanical, dissolution and chemical recycling of (mixed) plastic wastes into plastics, or monomers and feedstock for the production of plastics, chemicals and synthetic fuels; reprocessing of by-products into chemicals
- Iron & Steel: Better scrap recycling with new detecting technologies (such as digital or blockchain based "product passports"); melting of low-quality scrap with natural gas; scrap-based EAF; near net shape casting; redesigning steel-based products for material efficiency and circularity; utilization of residues from steel production internally or in other sectors

Crosscutting for (some) sectors: Industrial and Industrial-urban symbiosis and reuse; innovative materials and products for better life cycle performance; inherent recyclability of materials; upgrading of secondary resources; better detection, separation, and sorting technologies. Examples for cross-cutting digital enablers with application potential in several sectors are: AI, machine, and deep learning; 3D printing and digital fabrication; digitalisation of the design phase of processes and materials; digitalisation of plants; digitalisation of connected processes and supply chains (incl. industrial/urban symbiosis); traceability of raw materials and products; development of digital tools for monitoring and control in Net zero emission production processes; New predictive and dynamic models; advanced modelling and digital twin; strategic scheduling tools for industrial transition processes.

Mission Innovation Priorities and country-specific approaches

The Net Zero Industries Mission has defined common goals, tipping points and technology pathways that are relevant for decarbonization of industry. These common agreed goals as described in this roadmap are furthermore supplemented by specific country perspectives and national priorities. A summary of the activities noted by the Roadmapping WS delegates can be found in the Appendix of this roadmap and will be further taken up in the Action Plan, especially when it comes to the options for demonstration projects.

Prioritization during the Roadmapping workshop[9]
As shown in Figure 2 below, efficiency, electrification, clean hydrogen and alternatives fuels showed the most potential for applications across all sectors, although all pathways are highly relevant. Furthermore, the national "starting points" on the way to net zero might be quite different, so the figure is to be read as a snapshot from the roadmap process. The potential of clean hydrogen is especially high for chemicals and iron & steel, to a lesser extent for other sectors, whereas CCS is highly relevant for cement and lime. The alternative materials and more energy efficient processes also have a very high application potential for cement and lime.

A large number of demonstration projects is emerging for:

- **Hydrogen** – iron & steel, chemicals (fertilisers)
- **CCU/S** – cement, chemicals (reuse), LNG production
- **Bioenergy** – across various sectors (biomass + biogas)
- Some CCS technologies such as amines have reached high TRLs; the main barrier is scaling of the technology (other CCS technologies are still emerging, and smaller scale options also need to be tested)
- One potential RD&D focus could be on CCS of non-fossil CO_2 (bio-CCS)

Electrification is a high priority pathway for the Mission in all world regions. High temperature processes are close to the market; however, potential limits occur from e.g. obtaining permits and the development of electrochemical processes that requires enough lead up time. The further potential of technology development is particularly important in low-temperature processes, via heat pumps and MVR (steam, food-processing, drying, pulp-paper/alumina).

Industry collaboration with researchers is necessary to reach TRL8, as well as a need to work to protect Intellectual Property rights (IP), while supporting cooperation. Public procurement can play a key role in creating markets and digital platforms to assist with supply chain and material mapping for circularity. Furthermore, the certification of zero emissions products or other measures such as carbon pricing should be universal/standardized. It is important to consider the availability and rate of scale-up for key resources, as bioenergy will also be demanded by other sectors and clean hydrogen might be limited by the pace at which complementary technologies including renewables and CCUS are deployed. Circular economy and alternative materials are also one of the priorities of the mission (by-products from one process to displace energy intensive extraction/processing).

GHG abatement of GHG emissions in the chemical sector (including scope 3) will depend on a mix of solutions. Restricting the range of technological options will lead to costlier pathways, will not allow adaptation to regional specificities and is likely to be undermined by limited availability of resources (e.g. biomass). Therefore, the Mission will pay special attention to the limited availability of feedstocks by mapping out potential resource availability to better target further Mission activities.
In the short to medium term, alternative sources of carbon and renewable hydrogen should be prioritised towards alternative feedstock uses, which are more economically feasible.

Furthermore, it was has been suggested that CCS is facing more a policy/business challenge rather than technological questions.

9 54 participants from 15 MI countries; for more details please see Annex

Figure 2: Prioritization of technology pathways across three sectors (result roadmapping workshop)

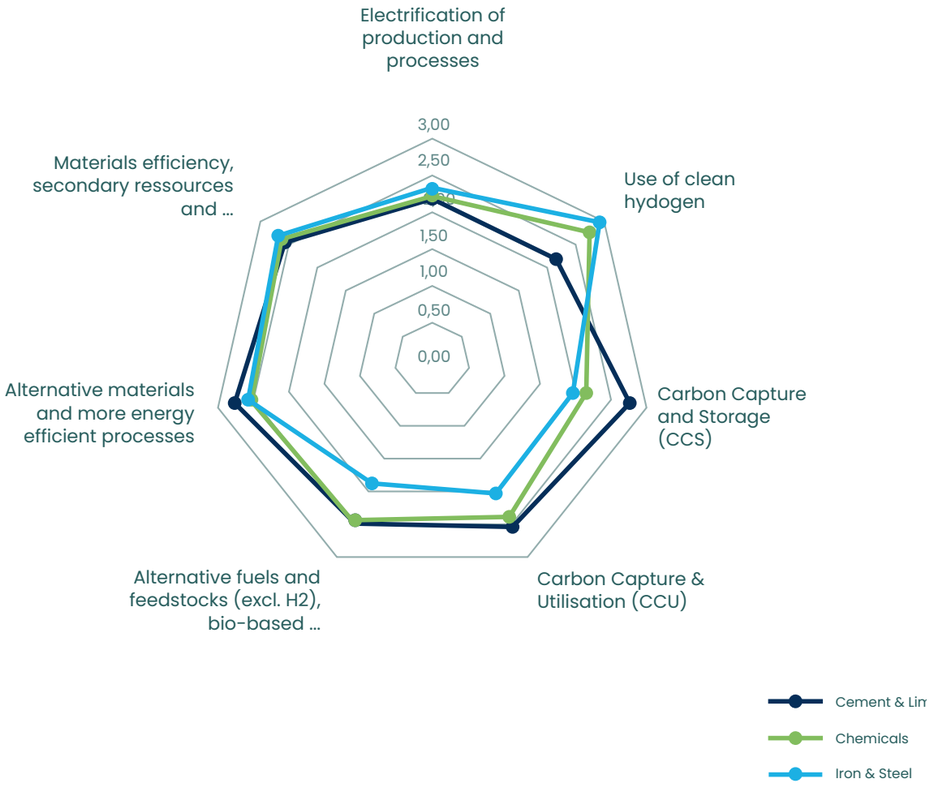


Table 2: Application potentials (result roadmapping workshop)

Application potentials – towards a roadmap for Net-Zero Industries	CEMENT & LIME	CHEMICALS	IRON & STEEL
Electrification of production and processes	medium	medium	medium
Use of clean hydrogen	low	very high	very high
Carbon Capture and Storage (CCS)	very high	low	low
Carbon Capture & Utilisation (CCU)	high	medium	low
Alternative fuels and feedstocks (excl. H_2), bio-based resources, and integration of renewable energy	medium	medium	low
Alternative materials and more energy efficient processes	very high	high	high
Materials efficiency, secondary resources and waste valorisation	high	high	high

Very high: average evaluation by workshop participants above 2,7 (out of 3)
High: average evaluation around 2,5 (out of 3)
Medium: average evaluation between 2,4 and 2,2 (out of 3)
Low: average evaluation below 2,2 (out of 3)

Other high application potential for any other energy intensive industry sectors have been named as follows:

- Alumina and Aluminium – Aluminium is also the front runner in certified low-carbon metals
- Electrification in non-ferrous, ceramics & minerals
- Utilization of low grade iron ore
- Glass manufacturing, mining and quarrying
- Aviation – sustainable aviation fuels (first bio-based, then hydrogen), same for shipping
- Wind energy is in a strong position to both decarbonise its own supply chain, while also providing clean energy to decarbonise industry
- Pulp and paper
- BioCCS ferroalloys
- Transport & logistics

By including other resource sector high energy and high heat industries the Mission can expand the demonstration sources and relevant industry partners who may help fund demonstrations. It will be key to recognise interactions with other activities, such as standard setting and procurement initiatives e.g. WorldSteel; GCCA; ResponsibleSteel; SteelZero; CEM IDDI; Lead IT; FMC as well as to recognise the different requirements of smaller businesses e.g. SMEs and place-based/cluster approaches (see Chapter 4 on enabling factors). In the context of framework conditions for industrial decarbonisation, common definitions on near zero emission production (e.g. of steel, cement) are a necessary ground for further progress towards market creation and upscaling and implementation of low emission technologies. The IEA Report "Achieving Net Zero Heavy Industries in G7 Members" is recognised as a starting point for such definitions by G7 climate and energy ministers. Mission Innovation will seek to interlink its activities with the proposed methodology and definitions where appropriate.

Country-specific priorities and state of the art

The following tables of country-specific state of the art has been based on the screening on existing (national and international) roadmaps and studies related to decarbonization of industry and was complemented by the assessment of the roadmapping workshop participants as well as the feedback collected during the public consultation. It is not a formal, fully comprehensive mapping, but provides a preliminary structured overview on important activities in the countries to be further taken up in the Action plan and future work of the Mission. The tables show – along the different pathways – which technological innovations and (systemic) solutions could be pursued and in which thematic areas (funded) R&D activities or potential industry applications have been named during the roadmapping process. The illustrative, yet not complete, listed demo projects make already existing starting points recognizable.

Table 3: Overview on country-specific priorities (results roadmapping workshop, to be further mapped out in the Mission Action Plan) for three main sectors

CEMENT AND LIME	LOW (R&D)	MEDIUM (TOWARDS A PILOT)	HIGH (DEMONSTRATION)	TRL 9 (EARLY COMMERIAL PLANT DEPLOYMENT)	POTENTIAL DEMOS	EXISTING DEMOS
Electrification of production and processes						
Use of clean hydrogen					Chile, UK	UK
Carbon capture and storage (CCS)					UK	US, NOR, SWE
Carbon capture and utilization (CCU)						US, AUS
Alternative fuels and feedstock						AUS, UK
Alternative materials and more energy efficient processes						
Materials efficiency, use of secondary resources & industrial symbiosis						

CHEMICALS						
Electrification of production and processes						
Use of clean hydrogen					UK, AUS	AUS
Carbon capture and storage (CCS)						US
Carbon capture and utilization (CCU)					AUS	AUS, NOR, UK
Alternative fuels and feedstock						AUS, EU
Alternative materials and more energy efficient processes						
Materials efficiency, use of secondary resources & industrial symbiosis						AUS

IRON & STEEL	LOW (R&D)	MEDIUM (TOWARDS A PILOT)	HIGH (DEMONSTRATION)	TRL 9 (EARLY COMMERIAL PLANT DEPLOYMENT)	POTENTIAL DEMOS	EXISTING DEMOS
Electrification of production and processes					UK, SWE, AT, US, Korea	
Use of clean hydrogen						
Carbon capture and storage (CCS)					US, UEA, BE, FR, NOR	
Carbon capture and utilization (CCU)						BE, China, GER
Alternative fuels and feedstock						Brazil
Alternative materials and more energy efficient processes						AT
Materials efficiency, use of secondary resources & industrial symbiosis					AUS	

Table 4: Details on country-specific priorities (results roadmapping workshop, to be further mapped out in the Mission Action Plan)

Cement & Lime

	TOPIC SUMMARY	DEMO	TRL ASSESSMENT *
Electrification of production and processes	Electrification of process heat fort pure CO_2 stream & CO_2 capture. Electric furnaces and kilns		R&D / towards a pilot
	Electrolysis based cement		R&D / towards a pilot
	Electric heating and cracking: through plasma generators, microwave, and ultrasound		R&D / towards a pilot
Use of clean hydrogen	Use of clean hydrogen in high temperature applications	potential demo (e.g. Chile, UK); existing demo (e.g. UK)	towards a pilot / demonstration
Carbon capture and storage (CCS)**	Direct separation and adsorption/ absorption of process emissions; Carbonate/CO_2 looping; Oxy-fuel combustion; post-combustion technologies	potential demo (e.g. UK); existing demo (e.g. US, NOR)	demonstration / early commercial
	BIO-CCS/wood carbonization (negative emissions)	existing demo (e.g. SWE)	demonstration / early commercial
Carbon capture and utilization (CCU)	CCU in Cement & Lime Production and on process emissions; CCU on cement and lime kilns (usage as feedstock in chemical production)	existing demo (e.g. US)	towards a pilot / demonstration
	Recarbonisation of concrete; Carbonisation of solid raw material/ curing with CO_2; Mineral CO_2 and CO_2 scrubbing	existing demo (e.g. US)	towards a pilot / demonstration
	Utilisation of CO_2 in alternative building materials; mineral carbonation of CO_2	existing demo (e.g. AUS)	towards a pilot / demonstration
Alternative fuels and feedstock	Alternative fuel mix (syngas, waste, biomass) as a replacement of solid fossil fuels (particularly for heat generation); Biomass (co-)combustion	existing demos and sites (e.g. AUS, UK)	demonstration / early commercial
	Use of solar heat		towards a pilot
	Use of PV and wind energy for cement production (for power generation/electrification; see above)		towards a pilot / demonstration
Alternative materials and more energy efficient processes	Use of waste heat in co-generation of electricity; energy recovery		demonstration / early commercial
	New cement types and alternative raw materials		demonstration / early commercial
	Energy efficient kiln technologies, e.g. vertical kilns, installing heat exchangers for waste heat recovery; dry kilns, multistage cyclone heaters and optimal combustion processes		demonstration / early commercial
	Conversion of two shaft furnaces into a direct-counter current regenerative furnace		towards a pilot / demonstration
Materials efficiency, use of secondary resources & industrial symbiosis	Recycling waste and by-products, also from other EIIs (e.g. steel slag)		demonstration
	Recycling and reusing cement and concrete; mineralization of concrete waste (also part of CCU); calcined clays		towards a pilot / demonstration

* low: R&D;
medium: towards a pilot;
high: demonstration;
TRL 9: early commercial plant deployment

** CCS is an end-of-pipe technology and as such relevant as part of the overall solution, but not a priority for R&D projects under this mission.

Chemicals

	TOPIC SUMMARY	DEMO	TRL ASSESSMENT *
Electrification of production and processes	Electrification for heat at low temperature (e.g. boilers); integration of heat pumps		demonstration
	Electrification for heat at high temperature (e.g. e-cracker)		R&D / towards a pilot
	Direct electrification of chemical processes (electrochemical processes and electricity-driven separation)		R&D / towards a pilot
	Electrification of steam generation or upgrade and Electricity powered driers		demonstration
Use of clean hydrogen	Usage of clean H_2 as energy carrier in high temperature processes		towards a pilot / demonstration
	Usage of clean H_2 as feedstock	potential demo (e.g. UK, AUS); existing demo (e.g. AUS)	towards a pilot / demonstration
	H_2 recuperation		early commercial
Carbon capture and storage (CCS)**	Capture of CO_2 from process and combustion emissions	existing demo (e.g. US)	towards a pilot / demonstration
Carbon capture and utilization (CCU)	Utilisation of captured CO_2 to produce synthetic fuels/ gas, chemicals and polymers through various processes	potential demo (e.g. AUS); existing demos (e.g. AUS, NOR, UK)	R&D / towards a pilot / demonstration / early commercial
Alternative fuels and feedstock	Bio-based resources as a feedstock for chemicals and plastics; Biomass/ waste and alternative energy for heat/energy generation; Integration of renewables	existing demos (e.g. AUS, EU)	towards a pilot / demonstration
Alternative materials and more energy efficient processes	Technologies alternative to distillation; Process intensification; separation technologies, e.g. for thermal separation		towards a pilot / demonstration
Materials efficiency, use of secondary resources & industrial symbiosis	Industrial symbiosis	existing demo (e.g. AUS)	demonstration / early commercial

* low: R&D;
medium: towards a pilot;
high: demonstration;
TRL 9: early commercial plant deployment

** CCS is an end-of-pipe technology and as such relevant as part of the overall solution, but not a priority for R&D projects under this mission.

Iron & Steel

	TOPIC SUMMARY	DEMO	TRL ASSESSMENT *
Electrification of production and processes	Electric Arc Furnaces (DRI-EAF route)	existing demo (e.g. UK, SWE, AT)	towards a pilot / demonstration
	Electric Arc Furnaces with green electricity	existing demo (e.g. US)	demonstration / early commercial
	Electrolysis of iron ore	potential / existing demo (e.g. UK, US, Korea)	towards a pilot / demonstration
	Electrification of process steps (e.g. reheating furnaces, sintering)		towards a pilot / demonstration
	Electrowinning with green electricity		R&D / towards a pilot
Use of clean hydrogen	Hydrogen Direct Reduction of iron ore (H_2-DRI)	potential demo / existing demo (e.g. UK, SWE, AUS, AT)	demonstration / early commercial
	Blending of H_2 into commercial production routes (combustion); use of H_2 in BF/BOF and reheating furnaces		towards a pilot / demonstration
	EAF with H_2	potential / existing demo (e.g. SWE)	towards a pilot / demonstration
Carbon capture and storage (CCS)**	CCS through various processes and in various process-steps	existing demo (e.g. US, UEA)	towards a pilot / demonstration / early commercial
	Shipping CO_2 for storage	existing demo (e.g. BE, FR, NOR)	demonstration
Carbon capture and utilization (CCU)	Reuse and valorisation of waste and gases esp. from the BF/BOF into chemicals/fuels/raw materials	existing demo (e.g. BE, China, GER)	towards a pilot / demonstration
Alternative fuels and feedstock	Integration of renewable energy in steelmaking and iron ore upgrading	existing demo (EEIP, GWEC)	demonstration / early commercial
	DRI-EAF with biogas		demonstration
	Use of alternative carbon-bearing materials and alternative reduc–tants, e.g. biomass and charcoal in BF/BOF route	existing demo (e.g. Brazil)	demonstration
	Methods that measure, monitor and control effects of changing fuel mixes on processes and products		towards a pilot / demonstration
Alternative materials and more energy efficient processes	Use of waste heat, e.g. in cogeneration of electricity or to generate process steam		demonstration
	Large scale heat pumps	existing demo (e.g. AT)	towards a pilot / demonstration
	Better process control and racking temperature regulation		towards a pilot / demonstration
	More efficient electric arcs, rolling mills, sintering plants		towards a pilot / demonstration
Materials efficiency, use of secondary resources & industrial symbiosis	Materials efficiency, use of secondary resources & industrial symbiosis	potential demo (e.g. AUS)	demonstration / early commercial
	Use of by-products and of BF slag in other industries (cement) and in inno-vative applications (e.g. artificial reefs)		demonstration / early commercial
	Greater and better scrap recycling		demonstration
	Scrap-based EAF		demonstration / early commercial

* low: R&D; medium: towards a pilot; high: demonstration; TRL 9: early commercial plant deployment

** CCS is an end-of-pipe technology and as such relevant as part of the overall solution, but not a priority for R&D projects under this mission.

Other Sectors

	TOPIC SUMMARY	DEMO	TRL ASSESSMENT *
Electrification of production and processes	Heat Pump technology: Pulp & Paper, Wood & Fibre, food industry	existing demo (e.g. AT)	towards a pilot / demonstration
	New drying processes: Pulp & Paper, Wood & Fibre		towards a pilot
	Electrification of pulp & paper production process		R&D / towards a pilot
	Electrification of Food & Beverages (steam)		early commercial
	Electrification of alumina digestion	existing demo (e.g. AUS)	towards a pilot / demonstration
	Electrification of mining		demo / early commercial
	Electrical Furnaces: Glass, Ceramics	existing demo (e.g. AT)	towards a pilot / demonstration
Use of clean hydrogen	Hydrogen in float glass making	existing demo (e.g. UK)	towards a pilot / demonstration
	Clean Hydrogen use in calcination of alumina	potential demo (e.g. AUS)	demonstration
Carbon capture and storage (CCS)**	CCS in ferro-alloys		towards a pilot / demonstration
	CCS in Pulp & Paper		R&D / towards a pilot
Carbon capture and utilization (CCU)			
Alternative fuels and feedstock	Alternative fuels and feedstock (esp. Biomass) in Pulp & Paper		towards a pilot / demonstration
	Alternative fuels and feedstock in Food & Beverage		towards a pilot / demonstration
	Alternative fuels and feedstock in Agro Industry		towards a pilot / demonstration
	Renewables integration in Aluminium: Electrolysis flexible demand response and smelting	existing demo (e.g. AUS)	demonstration
Alternative materials and more energy efficient processes	More energy efficient processes in Pulp & Paper, e.g. CHP, heat pumps, new drying techniques	existing demo (e.g. AT)	R&D / towards a pilot / demonstration
	Energy efficient processes in Food & Beverage		towards a pilot / demonstration
	Energy efficient processes in Agro Industry		towards a pilot / demonstration
Materials efficiency, use of secondary resources & industrial symbiosis			

* low: R&D;
medium: towards a pilot;
high: demonstration;
TRL 9: early commercial plant deployment

** CCS is an end-of-pipe technology and as such relevant as part of the overall solution, but not a priority for R&D projects under this mission.

Cross-Sectoral Topics / Innovation Needs

	TOPIC SUMMARY	DEMO	TRL ASSESSMENT BY PATHWAY*
Electrification of production and processes	Electrification of process-heat; integration of electrochemical processes		**R&D / towards a pilot /** demonstration
	Electrification of CCU		
	Mechanical vapour recompression for steam generation, heat pumps		
Use of clean hydrogen	Use of blue/clean H_2 across all EII sectors (as fuel and feedstock)		R&D / **towards a pilot / demonstration**
	Use of clean H_2 in CCU		
	H_2 integration through sector coupling		
Carbon capture and storage (CCS)**	Capture of CO_2 from process and combustion emissions of EII		R&D / **towards a pilot / demonstration**
	Bio-CCS	existing demo (e.g. SWE)	
Carbon capture and utilization (CCU)	Bio-CCU for negative emissions	potential demo (LeadIT)	R&D / **towards a pilot / demonstration**
	CCU from different industrial sources and sectors	existing demo (e.g. AT)	
	CCU for fertilizers	existing demo (e.g. AT)	
	CCU for long time products		
Alternative fuels and feedstock	Use of biogas generated from waste		R&D / **towards a pilot / demonstration**
	Integration of renewables in different EII sectors	existing demo (EEIP)	
	Digitalisation and monitoring in Process industries	existing demo (e.g. AT)	
Alternative materials and more energy efficient processes	Energy efficiency in all EII sectors		R&D / **towards a pilot / demonstration**
	Energy efficient processes in small scale industries (need to catch up)		
	Alternative and advanced materials		
	More energy efficient comminution processes		
	Excess heat recovery and valorisation		
	Control management optimisation of electro motors and cooling distribution		
Materials efficiency, use of secondary resources & industrial symbiosis	Circularity of resources in processes, e.g. biowaste, water and energy		R&D / **towards a pilot / demonstration**
	Digitalisation of process industries	existing demo (e.g. AT)	
	Data ecosystems for demand / supply matching		

* (low/medium/high)
Highlighted in bold means that in this technology pathway most topics are in this/these TRLs

**CCS is an end-of-pipe technology and as such relevant as part of the overall solution, but not a priority for R&D projects under this mission.

Timeline and pathways to develop and deploy technologies

To be added within the Mission's action plan.

4 Barriers and enabling framework conditions

Barriers

There are key barriers that presently prevent the uptake of renewable energy and other low-carbon processes into the energy intensive industry sector. International collaboration, which is envisioned for this mission, is an ideal way to tackle some of the barriers described below. The Mission will continue its effort on involving relevant stakeholders to address the specific barriers as well as foresees a risk workshop to identify barriers that each industry sector, technology pathway and Mission pillar faces. This will help to make sure that the Action plan and implementation of the Mission covers all relevant areas avoid any pitfalls and gaps.

Technical barriers: Further RD&D is necessary to advance the performance of technologies. Technologies for the provision of net-zero emission processes and products remain in the demonstration phase while commercially viable technologies are limited. While new technologies are under development with the potential to achieve good technical performance at competitive costs, limited large-scale facilities are available to demonstrate them. These facilities are needed to mitigate commercial risks by demonstrating reliable operation for extended periods at sufficient scale, firm up predictions of cost and ensure reliable production can be maintained

Business barriers: While the demand is steadily growing (until 2060, an increase of 60 % per capita of consumption of resources is predicted (OECD, 2019)), the production of commodities such as iron, steel, cement and concrete is highly competitive, has low profit margins and requires capital-intensive plants. Currently, there is no existing market, or at least no market of size, ready to pay a premium on low-emission industrial products.

Financial barriers: This includes the risk-averse nature of the sector and the relatively low profit margin. These factors combined limit internal financial resources for investments in low-emission RD&D activities. This can even exclude cost-efficient low-emission projects, which might have a positive return on investment but are not competitive compared to other projects. Investors that could enable debt financing of such activities lack the required knowledge and information to evaluate the risk-return profile of new technologies.

Regulatory and policy barriers include the lack of a consistent (global) policy framework for CO_2 mitigation and industrial transformation together with a high uncertainty regarding the future development of such policies/regulations. The incoherent timing across different policy areas and different regions could be a major barrier to a global implementation of low-emission technologies in the global industrial value chains. IP-rights and international competition might make it difficult to establish knowledge sharing and needs to be addressed within the mission implementation.

Enablers

Beside technical aspects, other factors will need to play a vital role to enable an effective development and deployment of net-zero energy technologies. The Mission has specified a dedicated pillar on enabling conditions to expand upon these enabling factors and framework conditions, which will be pursued as one of the main activities of the Mission. At this stage, they can be characterized as follows:

- INTEGRATING non-technological aspects in Research and Innovation activities to improve the technological solution's effectiveness;
- CREATION of Community of Practices, industrial Eco systems and Hubs for Circularity;
- PROACTIVE adjustment of human resources and (digital) skills for technological development and implementation;
- SUPPORT actions for the creation of synergies, upskilling of the industrial workforce, fostering R&D&I collaboration, the creation of new markets, the uptake of successful technology developed and the global competitiveness of the industries. This includes INTERNATIONAL cost-sharing via harnessing complementary drivers and expertise from different countries. For example, countries rich in mineral and renewable resources can benefit from exporting value-added products, countries with downstream processing or manufacturing can benefit from accessing high-value sustainable products at lower cost, and countries supplying the new sustainable-energy technology can benefit from participating in the industrial transformation.

The Net-Zero Industries roadmapping process brought up an extensive list of enablers in the sense of eco-systems and support actions for non-technical innovations/drivers along these dimensions.

Research, development and innovation:

- Feasibility studies and small demonstrations to move up technology from TRL 4 to TRL 9 are key
- Active multilateral exchange of experience, knowledge, and collaboration, including industry, academia, and innovation centers is of high importance
- All efforts should follow the principle to minimize duplications and maximize additionalities
- Speeding up permitting procedures for demonstration
- Industry led R&D, and active role of industry
- Sector coupling to drive demand and scale
- PPPs for de-risking development and demonstration up to TRL9 (to reach the impact phase)
- Relaxing IP rules can speed up the uptake of new technologies

Provision of green energy

- Specific market conditions (market design) can set incentives for the co-location of the production of green energy
- Corporate power purchase agreements from utility-scale renewables are important

- Power Purchase Agreements, PPPs and government securities are important, too
- Ease and acceleration of the permitting process for major industry projects
- Legally enforce PV installations on roofs
- Hydrogen Pipeline-Network needs to be realized until 2030, existing ones to be improved
- Regulatory framework for introduction/ commercialization of renewable electricity and removing obstacles of permissions allows to make new energy source conveniently available
- Introduction of system flexibility mechanisms
- Electricity markets open for demand response
- Reform of electricity markets to increase viability of intermittent resources
- Increase of electricity grid capacity
- Improved permitting processes & stakeholder consultations, both for generation & transmission/distribution of green energy
- Monetary remunerations to local communities siting e.g., large wind projects

Materials and feedstock supply

- Supply needs for new input materials need to be considered: new supply chains required; improved supply chain traceability & transparency
- Mapping the supply and demand along the entire supply chain
- Scaling up mining of critical materials
- Resources for new industrial (recycling) plants
- Certification for new input materials is needed, together with reducing trade barriers to incentivize carbon mitigation: Essential to achieve real circularity of materials and feedstock
- Government incentives to unlock investment in circular economy

Financing and uptake of solutions

- EU Taxonomy
- Adaption of CBAM (Redirect CO_2/CBAM revenues to innovation/technology development & capacity building)
- EU Innovation fund from ETS for EII
- SME friendly ETS and support for SMEs
- Long term, credible de-carbonization targets and policy measures
- Early deployment: interaction with public and private procurement initiatives, e.g. IDDI, FMC
- Risk spreading through supply contracts to ensure “sales”
- Policies to help de-risk investments and insurances
- Inclusion of private sector with government
- Raising awareness on benefits of low carbon solutions in banking sectors
- Private capital funding for CDR (carbon dioxide removal)
- Offtake agreements
- Market pulls with green procurement policies, and contracts for difference

Carbon Capture and Storage

- Proximity of emissions source and sinks: need to co-locate industry and emissions with storage opportunity
- accelerate CCUS infrastructure development: Investment and buildup of (open source) transport and storage infrastructure to kickstart deployment
- Streamlined assessment and approval of storage sites; Global/local storage potential evaluation
- Public acceptance needs to be ensured
- Reduction of infrastructure costs
- Negative emissions: conversion of biomass into long-lasting materials
- Increasing the value of low CI products will increase CCS

Circularity and recycling

- Resource availability of reg. biomass/waste
- Simplification of rules for industrial symbiosis and use of co-products; clustering
- Timely material mapping (digital platform as enabler)
- Data ecosystems to match material demand with supply of recycled secondary resources
- Understanding feedstocks, locations, and potential usage
- Understanding of any possible contaminants
- Having separated streams of materials to repurpose.
- Positioning of co-processing higher in waste hierarchy
- Acceptance by the utilizing industries required
- Recyclability by design required
- Upcycling for more added value
- Limit to recycling e.g scrap metal for EAF
- R&D to address copper contamination in steel scrap

Regulatory issues and standardization

- CCU is counted as part of GHG reduction
- Development of regulatory frame for H2 applications
- Defining H2 (clean, green) and trade rules (EU/worldwide)
- Establishment of international standards for what constitutes e.g. green steel, cement, chemicals (see work of IEA for the German G7 Presidency)
- Creating lead markets for low carbon basic materials, e.g. through regulations and public green procurement guidelines
- Long-term perspective in the regulatory framework to de-risk the investment environment
- Enforcing regulation to make use of recycled feedstocks a reality
- Transparency/regulation of capture rate & crucial for definitions of products
- Alignment on carbon leakage measures
- Standards & certification for zero emissions product in the same quality and to be universal
- Balance of industrial regulation & investment support
- Shift in taxation burden of fuels (+ fossil fuels, - electricity); carbon pricing
- Intellectual Property Rights (project partners have concerns related to sharing information on technologies due to commercial sensitivities (IP); related to demonstration projects)
- Few places in the US have a carbon tax therefore most projects are using incentives
- Harmonisation across nations and regions essential
- Need industry standard guidelines help to offset investment risk and to encourage collaboration and sharing
- Training and safety are big issues with implementing new technologies AB

Others – capabilities, affordability and awareness

- Education: more technicians are necessary
- Workforce development with specialized skills, capabilities and knowledge; especially engineers, project managers and construction teams who can build the solutions we endorse
- Affordability
- COST – enable investment by addressing key cost drivers
- SMEs requirements are different
- Place-based approach/industrial clusters: regional authorities can play a role in setting up the symbiosis between different stakeholders
- Harmonized software development for CO_2 reporting/data compatibility
- Engage with consumers – public awareness
- Awareness/measuring of scope 3 and value chain emissions

Appendix

What has happened so far – process steps towards Mission roadmap

Scoping phase

The scoping phase of the mission was targeted towards a soft Mission Launch at the COP26 in November 2021. Therefore, several meetings with the mission secretariat and potential Mission members took place from April 2021 onwards. In these bilateral meetings, a first joint outline of the Mission proposal (Mission pitch) was established, based on current state-of the art and previous efforts on decarbonization of energy-intensive industry in different regions of the world. A Mission pitch was then presented to MI member states to raise interest in the Mission and to invite them for participation as well as to give feedback via an online survey. After the Mission proposal was endorsed by senior MI officials at the June MISC meeting, the scoping phase continued in order to refine the scoping analysis; establish tipping points and the stretch goal; build a Mission coalition (member engagement, partner engagement and potential contributions to the Mission); clarify commitments to participate and seek Ministerial buy-in. Two large scoping workshops with MI Member states representatives, associated partner organizations and technical experts in July and September 2021 were conducted to support these steps towards the soft Mission Launch at the COP26.

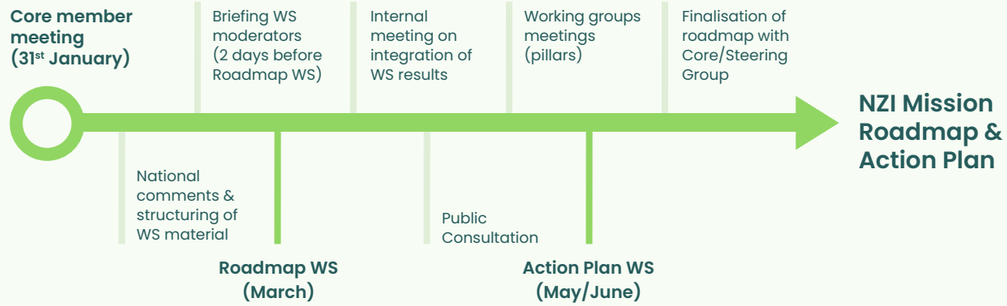
Roadmapping Workshop on 17th of March and public consultation

A roadmapping workshop, with 54 participants (technical experts and policy makers), from 15 MI member countries, observer countries as well as industries associations, met in March 2022 to pursue the following aims:

- Develop a Roadmap that would help to articulate and achieve the mission goals, that would focus on R&I development and collaboration;
- Identify and prioritize relevant technology development and technology pathways (if possible, also their contribution to the Mission tipping points); and
- Collect and structure barriers and enabling factors for net zero industries;
- Pave the way for technical experts to continue working on specific technologies and gaps after the roadmapping workshop.

The workshop was successful in identifying that a wide range of decarbonization activities are occurring within the nation-states of the delegates, which justifies the proposed work of the NZI Mission. Furthermore, some high-level trends were identified. The number of activities that were noted highlights the need to establish processes both to monitor their progress and to establish knowledge sharing processes to enable learnings from them to be shared widely between members. With such processes, these activities have potential to accelerate the commercial pathways for decarbonization. Without them, there is a risk that the outcomes from such activities may not become widely available, slowing the rate of implementation (for details please refer to the chapters on pathways below). To broaden the perspective, add to the findings of the roadmapping workshop and to close any gaps regarding country-specific approaches and national priorities, a discussion paper was released for public consultation in May 2022 for one month. The feedback from the public consultation was incorporated in the roadmap document accordingly.

Figure 1: Overview Roadmapping Process



Action Plan

The Action Plan will be further developed in May and June 2022 and will focus on concrete activities for the Net-Zero Industries mission with a short and mid-term perspective for the upcoming 2-3 years. It will contain ideas for R&I calls for demonstration projects, demonstration project design, coalitions & synergies, accompanying measures, financial & regulatory aspects etc.; thereby also providing interlinkages to related work done by other international initiatives related to industrial decarbonisation. It is envisaged to create a stakeholder map that covers multiple geopolitical domains to promote knowledge and project result sharing (effectively short circuiting the commercialisation process). By including interdependencies in the technology development and delivery process, this stakeholder map will highlight opportunities for international collaboration during projects as well. Furthermore, as process monitoring, process analytical technologies (PAT) and intensified inline-sensing to provide real-time data of the process and thus enable optimized process control are important, the Action Plan will take options and the need for monitoring into account.

Outlook – Joint Mission statement and further work of the Mission

This joint statement builds on the Mission Innovation 2.0 Launch Statement and does not constitute a legally binding commitment. This Joint Mission Statement will commence on **22 September 2022** and will continue in effect for four years, with the option to be amended by Mission members. After this period, the Mission may be extended for a further five years to support the delivery of the mission goal by 2030, subject to a review of Mission achievements.

Summary of the activities noted by the Roadmapping WS delegates

- **Sector summary:** Delegates identified activities in decarbonization in all of the main sectors; namely cement/lime, iron/steel, chemicals and other industries, including alumina/aluminium, pulp/paper, ferro-alloys and non-ferrous metals. However, fewer activities were noted in the chemicals sector than in the others.
- **Decarbonization method:** Delegates identified activities in all spheres of the decarbonization pathways, with perhaps slightly more activities in the two approaches of electrification and hydrogen. Nevertheless, numerous activities were also noted in each of the other methods including CCU/S, alternative fuels and alternative materials. In addition, there are some important sector-specific differences in which type of approach is preferred for each, as described below. Some country-specific differences could also be detected, the details of which will need to be explored in further NZI activities.
- **Electrification:** Activities in electrification were mostly noted in the following applications:
  - Low-temperature processes, via heat pumps and MVR: steam, food-processing, drying, pulp-paper/alumina
  - Applications where electrical paths are already advanced commercially, e.g. electric-arc and steel re-heating furnaces;
- **Hydrogen:** Activities in hydrogen were particularly noted in high temperature and energy intensive processes presently run with fossil fuels, where electrification is at an early stage, such as iron ore reduction (e.g. blast furnaces) and alumina calcination. Some activities in chemicals (as a feedstock), together with cement and lime were also noted:
- **CCU/CCS:** Activities in CCUS were identified in all applications. Nevertheless, some additional trends emerged:
  - There is particular interest for cement/lime, where CO_2 derives from the process rather than fossil fuels
  - It was noted that the production of long-lived carbon products from the re-use pathways has the greatest mitigation potential, particularly where these products are removed from the energy supply chain;
- **Alternative fuels** (e.g. RDF) are mostly of interest in cement, while significant interest in biomass was noted for iron/steel, particularly for alternatives to metallurgical coke in blast furnaces. Alternative fuels and bio materials should only be used as a last resort for marginal abatement as they are a reduced carbon solution, not a net zero solution. Not every country can make competitive hydrogen. Others (e.g. India, SE Asia, China) have new industrial equipment that would be better suited to retrofit with CCS rather than rebuild to make it hydrogen-compatible. CCS should be supported as an alternative abatement technology for steel and chemicals where local conditions make hydrogen too expensive/uncompetitive.
- **Circular economy and alternative materials** important – by-products from one process to displace energy intensive extraction/processing
- **Efficiency:** Some activities in improved efficiency were also noted

MISSION INNOVATION

Roadmap towards Net-Zero Industries