NET-ZERO INDUSTRIES MISSION

June 2022

Discussion Paper: Towards Net-Zero Industries

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NET-ZERO INDUSTRIES MISSION

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(1) The way towards the Net-Zero Industries draft Discussion Paper

Background and motivation

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 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. The decarbonization of energy-intensive industry is currently significantly more expensive than for other sectors, while many low carbon technologies are not yet available at commercial scale.

If the right technologies are able to reach the market in time for the next 25-year refurbishment cycle – due to start around 2030 – they can prevent nearly 60 Gt CO2 or 38 % of projected emissions from existing equipment in energy-intensive industries (IEA, 2020). 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.

The Mission will thus work to address this challenge and harness the potential outlined above. Its goal-including targets-will be revealed as part of the mission launch in the second half of 2022.

This draft Discussion Paper has been developed by the NZI coalition to facilitate the identification of a common vision and strategic objectives. The paper seeks to present the most promising R&I themes & technology pathways within specific sectors and cross-sectorial areas. 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 draft Discussion Paper.

This paper also seeks to identify global innovation priorities, evaluating their potential contribution to achieving the tipping points across the Mission's three pillars, as well suggesting a number of criteria for the identification of valuable demonstration projects that could be developed on specific innovation priorities.

What has happened so far?

The coalition

The Mission brings together a dynamic, ambitious, and delivery-focused alliance of governments, corporations, investors, and research institutes to accelerate innovation on industrial decarbonization.
The following governments and organizations have contributed to the preliminary work of the NZI and this draft Discussion Paper and have signalled their interest in advancing the work of the Mission into the future.

Co-leads:

- Australia, Department of Industry, Science, Energy and Resources (*new Ministry tbc*)
- Austria, Austrian Climate and Energy Fund; Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology

Contributing countries:

- 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 Energy
- United Kingdom, Department for Business, Energy and Industrial Strategy

Contributing international processes and organizations:

- 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)
- Process for Planet, World Steel Association
- Global Wind Energy Council (GWEC)
- The United Nations Industrial Development Organization (UNIDO)

A range of countries, international initiatives, investors, organizations from research and industry, will be encouraged to join the Mission.

Roadmapping Workshop on 17th of March

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;
- 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).

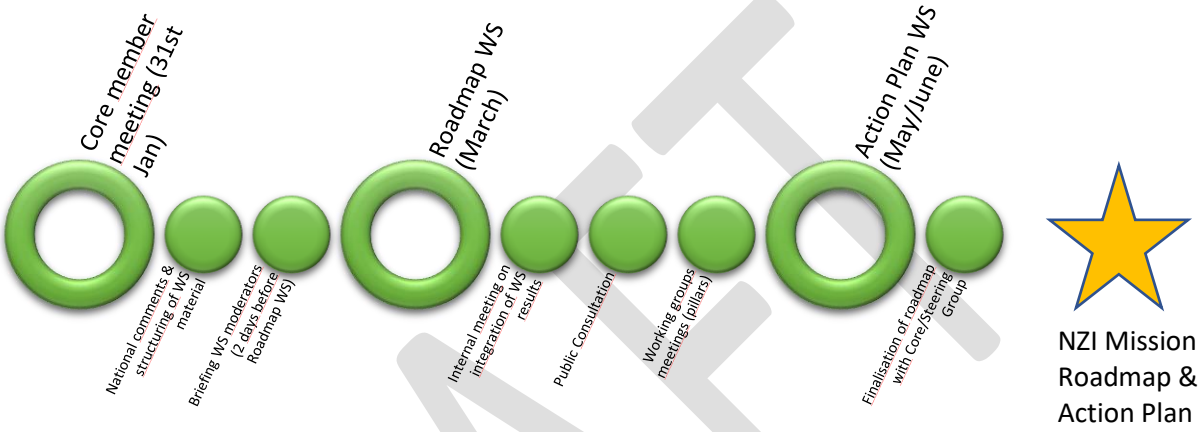

Figure 1: Overview Roadmapping Process

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 demonstration calls, demonstration project design, coalitions & synergies, accompanying measures, financial & regulatory aspects etc.

(2) Vision/Strategic objectives

The Net Zero Industries Mission will explore decarbonization pathways for energy intensive industries. This Mission will work to 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.

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 CO_2 emissions cuts beyond 2030 at lowest cost.

The Mission is part of the missions to support MI'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. 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. The Mission aims to progress under three pillars:

- **Demonstrations**
  Setting up a challenge-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.

- **Creating enabling conditions**
  Creating enabling conditions for demonstration projects. Examples are funding Front-End Engineering Design (FEED), feasibility studies, sharing of good practices on good R&I policy practices, regulatory frameworks or market incentives.

- **Underpinning R&D**
  Underpinning R&D in new and radical breakthrough technologies beyond 2030, allowing different and cheaper routes to decarbonize industry.

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 will align and coordinate with existing networks and platforms, setting a focus on emerging economies. Hence, knowledge sharing will underpin all of the Mission's activities and will be a foundation of its governance structure.

Mission Ambition

The Mission will focus on unlocking emissions reductions through demonstrations and cooperation across the steel, cement, chemical and other high temperature heat industrial users.

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. Hence, the Mission will seek to leverage action in the following areas:

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

Key fields of innovation will guide ambition and efforts to achieve the Mission goal: **Process optimization & efficiency improvement; fuel & feedstock switch; electrification of end use activities; CCUS; digitalization; flexibilization and sector coupling.**

All members of the mission will commit to:

- **Joint roadmap and Mission action plan:** members will work together to develop a roadmap identifying innovation gaps and publish an action plan for the Mission that defines the national and international effort needed over the next decade to achieve the Mission's goal.

- **Work within one or more pillar areas:** nominate focus areas to provide insights, resources, and project examples to add to the collective knowledge base of the Mission under an agreed knowledge sharing framework.
- **Invest in RD&D:** Provide funding or demonstrated committed funding of >€2m/ year investment in at least one innovation area.
- **Operational staff:** members will ensure that they have the necessary operational staff dedicated to work for the Mission.
- **Including national stakeholders:** members will include national industrial stakeholders from the private sector, for example CEOs of big industry companies or technology providers, in order to identify potential demonstration sites, project consortia etc.

In addition, Co-Leads of the mission commit to:

- **Large investments in RD&D projects (to fund demo projects & others):** members will contribute to the foreseen RD&D activities by providing >€5m/ year demonstrated commitment of funds to relevant innovation areas, leveraging co-investment from the private sector. This can include identifying at least 1 large- scale demonstration project.
- **Ministerial engagement**: This commitment should be underpinned by an active involvement at the ministerial level or nominated representative.
- **Operational staff resourcing**, including Mission Director (2-3 FTEs)

NGO's, IGO's and private sector representatives of the Mission commit to:

- **Nomination of a contact person:** members will have to nominate at least one person to actively support the further development and implementation of the Mission with the following activities: counterpart for roundtables, workshops and interviews, contribution to working papers, engagement of other stakeholders, as well as communication and dissemination of results

Members of the mission will advance this work by adhering to the following principles:

- 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. This should seek to included practical and tangible joint cooperative research projects.
- Transparency: members will share data, expertise, and analysis 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.
- 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 (particularly for aluminium/alumina - see below). Also, potential *cross-sectoral* R&D topics and technological options are listed. 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. [1] The focus is on R&D Topics TRL 1-9 (TRL low: 1-3, medium: 4-6, high: 7-9).

[1] 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

		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 efficiency	Heat re-use, regenerative burners
Electrification		Direct reduction using Electricity	Electrification of sintering and calcination processes. Electrochemical formation of calcium hydroxide	Electrification	Steam electrification
CCUS		CCU	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, management of variable energy resources, hybridisation of different sources, Excess heat to power or cold			
Circular Economy & cross-sector coupling		Harnessing by-products from one industry as alternative inputs to another industry, Industrial symbiosis, carbonation of mineral residues, 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.

- "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; 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 to produce chemicals and hydrocarbons.

- 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, 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.

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; H_2 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

- Cement & Lime: CCU in Cement Production and on process emissions; CCU on cement and lime kilns; Carbonization of solid raw material/curing with CO2; Mineral CO2 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 CO2 upgrading (PV and wind power); replacement of coal by charcoal, natural gas, 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 CO2 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; 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
- 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 detecting 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 (Cement & Lime)
- 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 (Chemicals)
- Iron & Steel: Better scrap recycling with new detecting technologies; 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

Mission Innovation Priorities and country-specific approaches

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.
- **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

Prioritization

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. 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)
- CCS technologies have reached high TRLs; the main barrier is scaling of the technology
    - 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 necessary to reach TRL8, 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 in other sectors and clean hydrogen might have limits regarding the (necessary) pace of renewables/CCUS deployment. 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).

Furthermore, it was mentioned that CCS is maybe more a policy/business question rather than a technological question.

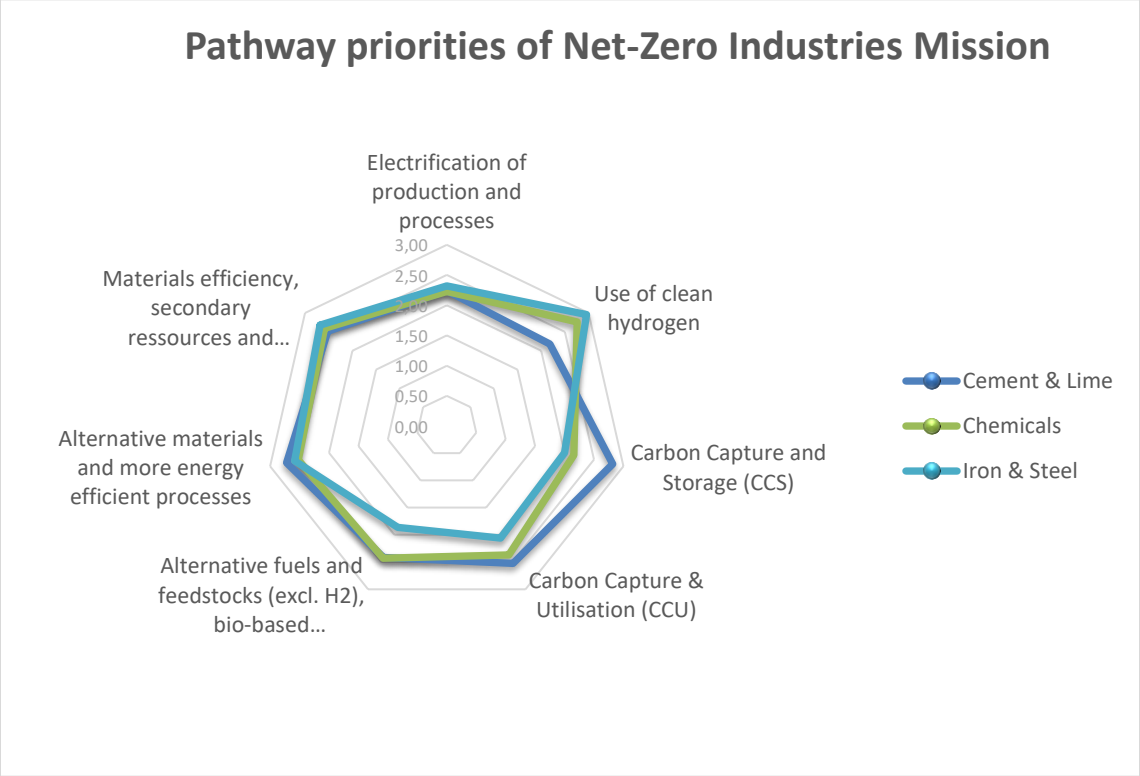

Figure 2: Prioritization of technology pathways across three sectors (result roadmapping workshop)

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. H2), 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
- 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

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; 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).

Country-specific priorities and state of the art

- The pathway alternative fuels and material has high relevance for other industries (cross-cutting) and particularly for countries such as India where efficiency gains could be exploited in many industries without implementing breakthrough technologies (low-hanging fruits). India also has a lot of small-scale industry
- For the US CCS and CCU is of high importance with substantial public funding
    - CCUS predominantly for chemical production – key demonstrations in China

Cement & Lime

Cement & Lime	**Topic summary**	**demo**	**TRL assessment** low: R&D; medium: towards a pilot; high: demonstration; TRL 9: early commercial plant deployment
Electrification of production and processes	Electrification of process heat fort pure CO2 stream & CO2 capture. Electric furnaces and kilns		R&D / towards a pilot
	Electrolysis based cement		R&D / towards a pilot

Cement & Lime	Topic summary	demo	TRL assessment low: R&D; medium: towards a pilot; high: demonstration; TRL 9: early commercial plant deployment
	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)[2]	Direct separation and adsorption/absorption of process emissions; Carbonate/CO2 looping; Oxy-fuel combustion; post-combustion technologies	potential demo (e.g. UK): existing demo (e.g. US, NOR)	towards a pilot / demonstration
	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 CO2; Mineral CO2 and CO2 scrubbing	existing demo (e.g. US)	towards a pilot / demonstration
	utilisation of CO2 in alternative building materials; mineral carbonation of CO2	existing demo (e.g. AUS)	towards a pilot / demonstration

[2] 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.

Cement & Lime	Topic summary	demo	TRL assessment low: R&D; medium: towards a pilot; high: demonstration; TRL 9: early commercial plant deployment
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; 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

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- **Chemicals**

Chemicals	Topic summary	demo	TRL assessment low: R&D; medium: towards a pilot; high: demonstration; TRL 9: early commercial plant deployment
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 H2 as energy carrier in high temperature processes		towards a pilot / demonstration
	Usage of clean H2 as feedstock	potential demo (e.g. UK, AUS), existing demo (e.g. AUS)	towards a pilot / demonstration
	H2 recuperation		early commercial
Carbon capture and storage (CCS)[3]	Capture of CO2 from process and combustion emissions	existing demo (e.g. US)	towards a pilot / demonstration

[3] 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 low: R&D; medium: towards a pilot; high: demonstration; TRL 9: early commercial plant deployment
Carbon capture and utilization (CCU)	Utilisation of captured CO2 to produce synthetic fuels/gas, chemicals and polymers through various processes	potential demo (e.g. AUS) and 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

Iron & Steel

Iron & Steel	Topic summary	demo	TRL assessment low: R&D; medium: towards a pilot; high: demonstration; TRL 9: early commercial plant deployment
Electrification of production and processes	Electric Arc Furnaces (DRI-EAF route)	existing demo (e.g. UK, AT)	towards a pilot / demonstration
	Electric Arc Furnaces with green electricity	existing demo (e.g. US)	demonstration /early commercial

Iron & Steel	Topic summary	demo	TRL assessment low: R&D; medium: towards a pilot; high: demonstration; TRL 9: early commercial plant deployment
	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 (H2-DRI)	potential demo / existing demo (e.g. UK, SWE, AUS, AT)	demonstration / early commercial
	Blending of H2 into commercial production routes (combustion); use of H2 in BF/BOF and reheating furnaces		towards a pilot / demonstration
	EAF with H2	potential/existing demo (e.g. SWE)	towards a pilot / demonstration
Carbon capture and storage (CCS)[4]	CCS through various processes and in various process-steps	existing demo (e.g. US, UEA)	towards a pilot / demonstration / early commercial
	shipping CO2 for storage	existing demo (e.g. BE/FR/NOR)	demonstration

[4] 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 low: R&D; medium: towards a pilot; high: demonstration; TRL 9: early commercial plant deployment
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 reductants, 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

Iron & Steel	Topic summary	demo	TRL assessment low: R&D; medium: towards a pilot; high: demonstration; TRL 9: early commercial plant deployment
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 innovative applications (e.g. artificial reefs)		demonstration / early commercial
	Greater and better scrap recycling		demonstration
	Scrap-based EAF		demonstration / early commercial

Other Sectors

Other Sectors	Topic summary	demo	TRL assessment low: R&D; medium: towards a pilot; high: demonstration; TRL 9: early commercial plant deployment
Electrification of production and processes	Heat Pump technology: Pulp & Paper, Wood & Fibre	existing demo (e.g. AT)	towards a pilot / demonstration
	new drying processes: Pulp & Paper, Wood & Fibre		towards a pilot
	Electrification of Pulp & Paper making 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
	Electrical Furnaces: Glass, Ceramics	existing demo (e.g. AT)	towards a pilot / demonstration

Other Sectors	Topic summary	demo	TRL assessment low: R&D; medium: towards a pilot; high: demonstration; TRL 9: early commercial plant deployment
Use of clean hydrogen	Hydrogen in float glass making	existing demo (e.g. UK)	towards a pilot / demonstration
	(Green) Hydrogen use in calcination of alumina	potential demo (e.g. AUS)	demonstration
Carbon capture and storage (CCS)[5]	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

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

Cross-Sectoral Topics / Innovation Needs

Cross Sectoral	Topic summary	demo	TRL assessment by pathway (low/medium/high) Highlighted in **bold** means that in this technology pathway most topics are in this/these TRLs
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		

Cross Sectoral	Topic summary	demo	TRL assessment by pathway (low/medium/high) Highlighted in **bold** means that in this technology pathway most topics are in this/these TRLs
Use of clean hydrogen	Use of blue/green H2 across all EII sectors (as fuel and feedstock)		R&D/**towards a pilot/demonstration**
	Use of green H2 in CCU		
	H2 integration through sector coupling		
Carbon capture and storage (CCS)[6]	Capture of CO2 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**

[6] 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	Topic summary	demo	TRL assessment by pathway (low/medium/high) Highlighted in **bold** means that in this technology pathway most topics are in this/these TRLs
	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		
	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		

Timeline and pathways to develop and deploy technologies

To be added (action plan)

(4) Barriers and enabling framework conditions and measures

Barriers

There are key barriers that presently prevent the uptake of renewable energy and other low-carbon and/or 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.

Technical barriers: commercial scale technologies able to deliver energy or fuel and the required technical performance at competitive costs are currently not yet available. Further RD&D is necessary to advance the performance of technologies. Technologies for the provision of net-zero high-temperature heat 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 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. Such enabling factors and framework conditions can be characterised 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
- 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 a long 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 Co2/CBAM revenues to innovation / technology development and transfer & 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: reduce direct biomass burning
- 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

- 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 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 EU nations and regions essential
- Training and safety are big issues with implementing new technologies AB

Others

- SMEs requirements are different
- Place-based approach / industrial clusters: regional authorities can play a role in setting up the symbiosis between different stakeholders
- Education: more technicians are necessary
- Workforce development with specialized skills and knowledge
- Affordability

- COST - enable investment by addressing key cost drivers
- Harmonized software development for Co2 reporting / data compatibility
- Engage with consumers - public awareness