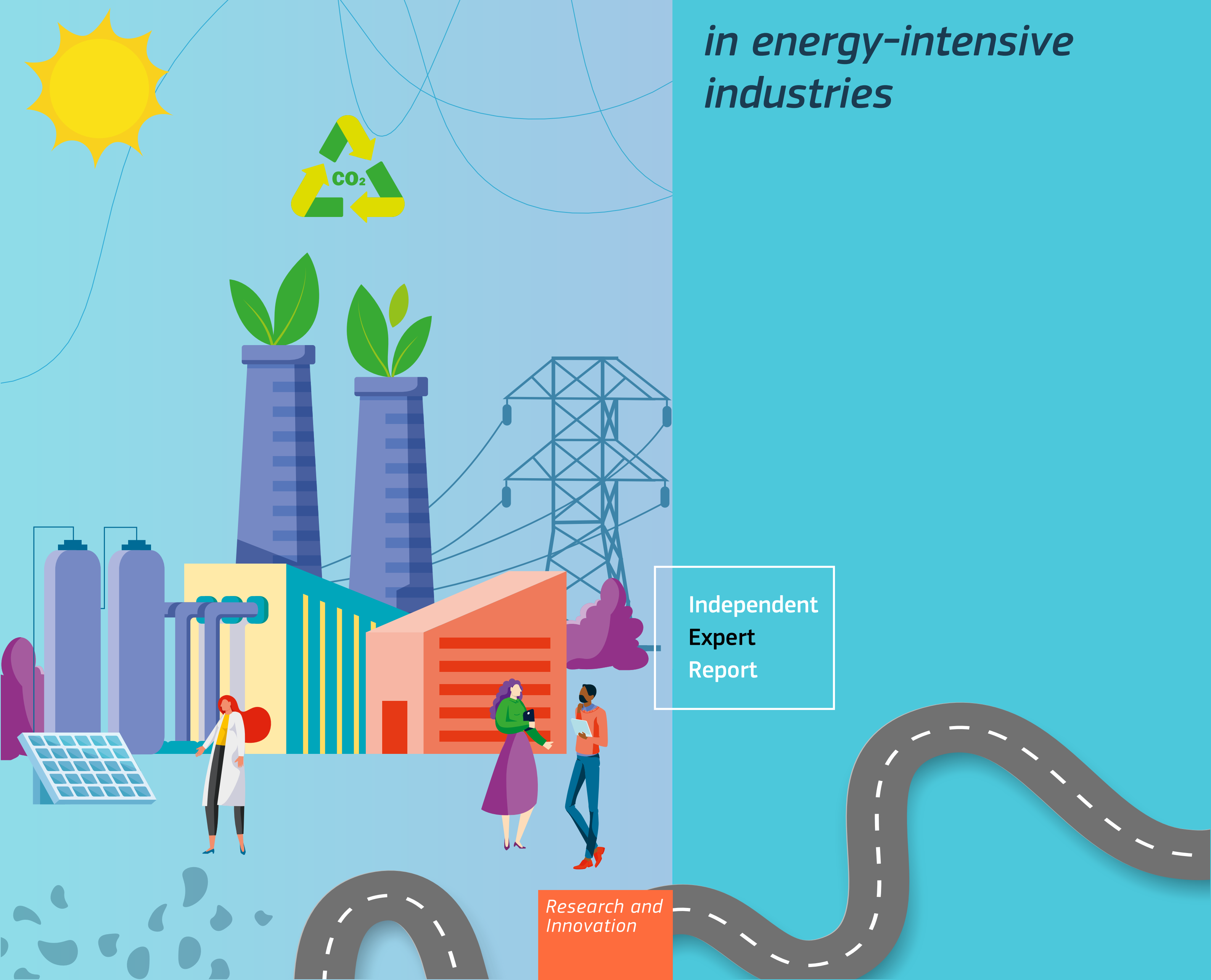
European Commission

ANNEXES

ERA
Industrial technology roadmap for low-carbon technologies

in energy-intensive industries



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Annexes: ERA industrial technology roadmap for low-carbon technologies in energy-intensive industries

European Commission
Directorate-General for Research and Innovation
Directorate E — Prosperity
Unit E.1 — Industrial research, innovation and investment agendas

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Annexes

ERA INDUSTRIAL TECHNOLOGY ROADMAP FOR LOW-CARBON TECHNOLOGIES

in energy-intensive industries

Prepared by the Austrian Institute of Technology GmbH, for the consortium

2022 Directorate-General for Research and Innovation EUR 2022.1824 EN

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ANNEX 1
Summary of SMEs surveys

As small and medium-sized enterprises face specific challenges in the decarbonisation of industrial processes[1], DG R&I ran specific surveys dedicated to SMEs, in relation to their experience and challenges in developing or adopting new environmental technologies. Specific challenges have been identified by both the more traditional small manufacturers, with limited financial resources to develop and invest in new technologies, and start-up companies involved in developing new low-carbon technologies and solutions.

For both of these types of business, a survey was conducted from November 2021 to January 2022 to collect empirical data about the challenges posed by decarbonisation of manufacturing and strategies used to deal with them.

The first survey was conducted among the general SME population in collaboration with Enterprise Europe Network (EEN). In total, 261 SMEs, most with fewer than 250 employees, participated in the cross-sectoral survey (manufacturing, services, construction) covering 14 EU Member States. The sample is balanced between Member States from western/northern, central/eastern and southern Europe, making it possible to address the question of whether there are difference between different regions when low-carbon technologies are adopted.

The second survey was conducted among small highly innovative firms involved in developing low-carbon technologies, i.e. technology startups, which often play an important role in technological and industrial transformation. This survey was targeted at SMEs that develop low carbon or circular industrial technologies sourced from Eutopia and Crunchbase data sources. In total, 178 companies from 17 countries participated, providing information about their innovation and funding strategies and barriers regarding the development of environmental technologies and solutions. Most of these firms have fewer than 40 employees and were founded less than 10 years ago. Out of the 175 respondents, 79% claimed they develop environmental technologies or solutions aimed at reducing GHG emissions.

The findings of these surveys were included in the roadmap, as it follows:

- Chapter 2 - Key Technological Pathways for Decarbonisation of Energy-Intensive Industries: pages 20-21; 33-34;
- Chapter 3 - R&I Investments: pages 45-46;
- Chapter 4 - Framework Conditions: pages 80-81; 94-95.

1 See also European Commission (2018), Final Report of the High-level Panel of the European Decarbonisation Pathways Initiative, https://ec.europa.eu/info/publications/final-report-high-level-panel-european-decarbonisation-pathways-initiative_en

ANNEX 2

Workshop Report: ERA common industrial technology roadmap on low-carbon industrial technologies for energy-intensive industries - Online Workshop, 24.11.2021, 14:00-17:00

Background and aims of the workshop

The European Commission is currently developing a common industrial technology roadmap for the decarbonisation of the industry which is co-created with Member States, industry, research and technology organisations, universities and other stakeholders laying out investment agendas from basic research to deployment.

In the course of this project a stakeholder workshop was organised to discuss the barriers and enablers for the development and deployment of decarbonisation technologies. In total about 40 experts from industry (large and small companies), research organisations, universities, industry associations, NGOs and policy participated from across Europe (see Appendix A for the list of participants).

The following report describes the results of this workshop which was organised as online event on 24 November 2021.

Agenda

14:00 Welcome and Introduction

14:20 Status-quo of the analysis

14:45 Q&A

15:00 Break-out sessions in subgroups

16:30 Wrap up from the Break-out sessions

16:45 Summary and next steps

17:00 End of the workshop

Welcome, Introduction and Status-quo of the analysis

The workshop was opened by Peter Dröll, Director Prosperity of DG RTD, who explained the background for developing ERA common industrial technology roadmaps.

Next, Doris Schröcker, Head of Unit Industrial Research, Innovation & Investment Agendas explained the specific goals and expectations for the technology roadmap on low-carbon technologies stressing the importance of involving various stakeholders in a co-creation process.

Angelo Wille, Deputy Head of Unit Industrial Research, Innovation & Investment Agendas, presented the outline of the roadmap.

After the welcome and introduction, Karl-Heinz Leiter and Wolfram Rhomberg, both from AIT, who support the EC in developing the roadmap and organising the workshop, presented some selected findings from their analysis. Karl-Heinz Leitner gave an overview of the sectoral and regional differences in relation to Greenhouse Gas (GHG) emissions and introduced the findings from a stakeholder survey organised by the EC in September about the assessment of technologies and barriers. Wolfram Rhomberg talked about decarbonization pathways and investment needs summarizing the findings from ongoing projects and roadmaps which have been already published in the past, e.g. for different industries.

The slides of the presentations from DG RTD and AIT can be found in Appendix B.

Q&A

After the presentation in a Q&A some questions were raised by the participants addressing the following topics:

- It was argued that waste heat management to reduce energy consumption and footprint will be crucial and is missed in the presentation;
- To a very large extent, EU polluters do not pay for the environmental damage that they cause, imposing health and clean-up costs on the whole society instead;
- The figures which have been presented referring to the SPIRE/P4P roadmap relate only to the amounts of investments for a first of a kind (FOAK) plants but not yet the full deployment;
- In all the roadmaps and studies which have been published so far there is hardly a discussion which activities and investment have the highest impact for achieving the climate goals, which should be tackled in a better way in the future;
- Currently, the EC works on a second industrial tech roadmap on circular industrial technologies. That roadmap will address several ecosystems, namely EII, construction and textiles. The work on the two roadmaps could contribute to an even wider, integrated approach;
- From the industry perspective, particular in relation to chemicals, the perception is that the industry (many large enterprises) is much more innovative as the statistical R&D figures reveal;
- The location of the industry sites will also have an impact in the future as many sites will be located near the coastline, how to avoid in this context stranded assets is important, and it will require also to rebuild some assets at the cost line, e.g. to use renewables. So the question is whether this additional investments (e.g. relocation) are considered within the estimation of the total investment needs in the future;
- When making investment decisions, the impact on the society have to be taken into account as well, for instance, in order to assess the best options (e.g. electrification);
- A prioritisation of actions and investment is important with the risk that end-of-pipe technologies might be favored over measures that address the real source of the problem, e.g. the products. Such topics are not addressed within the most roadmaps and net-zero pathways which are very technology-focused but hardly about behaviour of society, hence an integrated approach is needed;
- The definition of energy-intensive industries (EEI) for the roadmap and in relation to statistical analysis has to be made clear

Compilation from the four breakout sessions

After the Q&A the participants split up into four group discussing in two rounds the following questions:

Round 1: Challenges & Barriers

- What are the key barriers for the development and deployment of decarbonisation technologies?
- What are specific challenges for widening countries?
- What are specific challenges for SMEs?

Round 2: Enablers & Measures

- How to overcome these obstacles & barriers?
- What is needed to mobilize private investments?
- What is needed at EU level and at national level?
- The main interactive part of the workshop

The participants jointly worked on a whiteboard (via the online tool conceptboard) and posted their comments. See Appendix C for the copies of the four whiteboard (conceptboard).

The main results of the four groups which were presented after the parallel session along the different dimensions in the plenary can be summarised as follows:

R&D (from development to first deployment)

Barriers and obstacles:

- Lack of access to finance for 1st of a kind innovation (FOAK)
- Hard to select the most promising technologies as proof of technology, clear tech profile requirements and tech performance requests are missing
- Lack of preliminary impact assessments (e.g., resource use on a large scale etc.)
- Weak and unclear regulatory framework (weak ETS design, free allowances, and little to no product policy, not enough GPP elements - also for existing techs), insecurity with regards to regulation and anti-innovation regulation (REACH, weak ETS)
- Value Chain approach not yet established: materials, supplier, manufacturing, use, etc.
- Uncertainty about future industrial value chains
- Decision on funding to de-risk fast movers takes too long
- Failure to internalise external costs: consider the other externalities beyond climate e.g. air quality, resource use, soil, toxic free environment goal, etc
- Co-funding of pilot/demo units by the industry (high risk funding)
- High risks especially for SMEs, in addition: Regulatory approvals/permits
- specific for widening countries (but maybe also EU wide): differences in funding schemes, national support makes unlevel playing field

Measures and enablers:

- Keep focusing on reducing the value of death for scale-up and commercialization (innovation = creating actual sales and a return)
- Develop intra-sectoral and cross-sectoral collaboration
- Collaboration of industry in comparable R&D&I fields
- Foster cross sector material development from zero-carbon loss perspective
- Holistic collaboration within the value chain/eco system: Process Industry, Manufacturing Industry, RTOs, universities, and start-ups/SMEs
- Industrial projects covering the new value chains along the lifecycle of materials/products (supported by regional/national/EU funding and cooperation)
- Access to the technology gate keeper within large corporations
- Provision of sustainable technological solutions assessment/selection, on most promising pathways and solutions (as orientation for R&D funding and companies for uptake and scale up)
- Pooling European focus around most relevant/impactful solutions to combine sometimes varying different national focus
- Generation of more awareness on financial opportunities; Creation of synergies to communicate funding opportunities (centralized)
- de-risk the fast movers; Attractive co-investment opportunities to de-risk projects
- de-risking both on short- and long-term aspects
- Widening countries: Attractive funding programs and programmes dedicated to widening countries
- Stability in the regulatory environment
- Binding EU target on reduced resource use
- Avoid unfair competition
- Avoid stranded assets
- R&D for the production/storage and distribution of H2 (also related to modelling)
- Education and training of the workforce on the relevant technological solutions
- Introduce a pre-qualification round for EU funding applications so that not all the application effort has to be made even without good chances for a successful application (two step approach)
- Less bureaucracy & higher funding quotas urgently needed

Financing and uptake of solutions beyond R&D (TRL9plus)

Barriers and obstacles:

- No subsidies available to get a Prototype in the market
- Technologies/processes related to the energy- and feedstock transition need an extra push to reduce costs by multiplication (First of A Kind - FOAK) always high costs and often not able to compete with incumbent (fossil) processes without support)
- Need of high investments to test the solutions at high TRL

- Financial market does not take risks
- Lack of transfer to the others once a FOAK is installed and on processes/measures to support that
- No relevant financial payback from decarb investments; Market for technology deployment is not yet there
- No green steel market, moving ETS prices, no hydrogen available yet= no bankable business case
- Lack of risk sharing possibilities throughout upscaling and integration into existing systems and value chains
- Weak business case, through e.g. regulatory gaps, and market tools weakness;
- Excessive operational cost, e.g. levies on electricity
- SME: Lack of access to financial markets for SMEs
- SME: Complexity of procedures and financial mechanisms for SMEs (bureaucracy, amount of paperwork, complexity and dynamic of large EU consortia)
- SME: Lack of orientation and lack of problem ownership (this is not for me; the big companies should do it)
- Widening countries: limited capacity in public authorities and agencies
- Continued funding of fossil fuels
- Regulatory approvals/permits

Measures and enablers:

- Stakeholder Engagement (already at the R&D stage)
- Provide certainty to the grant support (therefore support capex decisions)
- Incorporate "EU Sustainable Finance Taxonomy Technical Screening Criteria" into State Aid guidelines and use them to determine what can be eligible for state aid under the CEEAG
- Public support needed until the very pre-commercialization phase
- Financing the steps after the pilots i.e., the combination of R&D, solution, and transition period
- Subsidies for R&D, investments, and operations (capex and opex)
- Change EU ETS benchmark design: cover the entire sector / activities life cycle impact & not differentiate by process or technology options e.g. as is the case for cement production (limited to clinker) or like for iron & steel (differentiated by process route & also output grades)
- Make a list of recognized technologies which are automatically eligible for capex support
- Provide warranties through EIB for short listed TRL 9 's (to accelerate roll out)
- Need for "Best value for common interest test" / clarify what the options / techniques are supposed to deliver and therefore the R&D priorities / options considered (this should also look at the business models);
- More data sharing on environmental performance of industry (environmental performance / scale of investments in pollution prevention etc.)

- More sharing of best practice.
- Awareness rising on already implemented verification processes for market uptake (such as the ETV process)
- Simplification of funding schemes; accessible through a simple "one-stop shop" principle.
- Simple instruments for private investments in creating tax advantages.
- Taylor-made financial instruments for high potential - high impact solutions
- Involvement of capital representatives in innovation systems already during the research and development phase.
- Have a good business cases (for infrastructure) to get private investments in
- Provision of a solid, 'gold standard' for sustainable investments, based on full environmental impacts
- Setting up temporary application Centers for SMEs to test and develop new processes
- Extending patents for innovative projects
- Training of Employees
- Demand side instruments, e.g. product design standards that promote "green" products (e.g. steel) / product passports (labelling etc.), Sustainable Product Initiative
- Effort sharing clause for downstream users to make up for the price premium
- Requirements & standards should adopt a functional + sustainability
- Carbon Border Adjustment Mechanism (CBAM) + : evolve to robust mechanism for global environmental level playing field (CBAM+) so to not harm zero pollution ambition frontrunners in the EU
- Strong TRADE defense in terms of environmental level playing field
- Temporary focused subsidies to compensate for initial higher costs compared to incumbents due to lower economy of scale
- Establish an EU-wide Standard for IoT-interfaces in order to allow systemic synergies in the operation of energy devices from different manufacturers (IoT=Internet of Things)

Provision of green (electric) energy

Barriers and obstacles:

- Sufficient deployment of additional renewable electricity generation
- Energy grid: storage and access and cost of green energy
- Need for big powerlines
- Competition for the resources/energy
- Time frame of availability/price
- Infrastructure needs if switched to green energy sources
- Lack a real sector integration approach (energy system must be balanced to be resilient)

- Lack of availability of green electrons/electricity
- Access to large scale green H2 at competitive costs
- Lack of public acceptance for wind and PV parks
- Increase in primary production and cost competitiveness is a prerequisite for most solutions. Other side of the coin is that this is a no regret option from all perspectives
- availability of affordable green electricity
- The current pipeline network for hydrogen in Europe is insufficient and the gas pipeline system will need to be adapted to receive hydrogen.
- Pipe/cable connections and storage facilities for heat, electricity, CO2 and hydrogen(carriers): connection between sea ports and industrial clusters needed
- Provide freedom in the regulation for energy grid operators so that they have the possibility to invest in innovative technology that makes their operation more flexible and leaves room to anticipate extensions needed in the future (otherwise the grids will be a serious bottleneck for decarbonization)
- Regulation and legislation is not really supporting collaboration among competitors, while the collaboration among competitors provides huge opportunities for synergies

Measures and enablers:

- Large scale energy efficiency as priority
- Balanced approach/Energy system Integration; take the best of each solution
- EU-based low CO2 emission power generation in combination with a suitable power grid can be complemented with import of green energy carriers/feedstocks such as (e- and bio) methanol/ethanol and green ammonia from ex-EU regions that have access to abundant renewable or low-carbon power.
- Need for multiple energy sources to ensure sustainable and affordable transition
- Stable pricing to allow financing
- Regulate CO2 prices; at least till 2030 - avoid speculation on CO2 prices
- A predictable CO2 pricing towards 2030 and 2050 including a Carbon Border Adjustment Mechanism (CBAM) would facilitate investors to de-risk their investments and anticipate on tipping points for more sustainable technologies/processes to economically outperform the incumbent high emission processes
- Prioritize use of electrons/electricity following CO2 abatement efficiency considerations (electrification only for highly efficient solutions)
- Ensure that entire EU intermediate product technology chain is available in Europe to achieve the targeted green technology pathways
- Enable use of alternative energy vectors such as hydrogen or ammonia by dedicated infrastructure
- Produce H2 wherever possible on the site where it is needed

- Even individual FOAK cases are not financial disaster, the visibility to not declining market needs to exist in order to have a driver to take the (lowered) technological risk

Materials and feedstock supply

Barriers and obstacles:

- Availability of feedstock
- No cost truth in the individual sectors. Many environmental costs are socialized.
- New limitations for the use of forest raw material limits the potential
- Export of waste outside Europe limits the potential
- No legally binding EU target on reduced resource use limits the potential
- Decrease time for granting permits and installing supportive regulations to accelerate the feedstock transition (e.g. waste becomes feedstock)
- Critical raw materials can be a showstopper for market deployment of certain solutions and can significantly hinder market interest once faced with challenges;

Measures and enablers:

- Fossil carbon carriers/materials should be regulated in their new use so that the use of secondary raw materials is promoted. EU target on reduced primary resource use necessary
- True price must be made visible – raw materials or fossil fuels are far too cheap
- Process and manufacturing industries need to integrate for synergies and burden sharing
- Innovation: better performing materials towards sustainable products and services
- A regional approach to industrial decarbonization, based on the resources available (e.g., access to renewables, or CO2 transport and storage networks)
- Enabling high grade mines and enabling more technology providers by patent regulation of "core technologies"

Carbon capture & storage (Infrastructure)

Barriers and obstacles:

- High Cost of implementation and Cost competitiveness
- High energy demand
- No policy clarity on the role of CCS and CCU technologies in climate action (framing & limiting/defining their use)
- Lack of public acceptance of geologic storage; permanence of the capture is not clear
- End-of-pipe focus of CCS threatens GHG source reductions
- Very little room for SME's with respect to very large investments and deliveries
- None-technological barriers (public acceptance, huge infra project implementation etc.)
- CCS is end of pipe, limited role for thisNo NGO-acceptance

Measures and enablers:

- More Focus on CCU and its Integration in processes to avoid end of pipe approaches
- Priority on processes that deliver already clean CO2 with no/few purification needs
- If industry is fan of CCS/CCU then they should compete for finding via the EU ETS innovation fund only / own resources

Circularity and recycling

Barriers and obstacles:

- No legally binding EU target on reduced resource use
- Lack of standards for recycled materials
- Regulation and perception of recycled feedstock
- Design for circularity not yet rewarded in markets (esp. manufactured products; cradle to cradle approach)
- Little focus and innovation on CE business models which can influence both product design (manufacturing) & demand for sustainable products
- Accumulation of impurities and lack of separation
- Regulations and cross border implementation. The same product/material can be waste in one country and by-product in another.
- Legal issue to operate recycling & reuse and production of new product on one site, e.g. processing of primary and secondary raw materials in one facility is not allowed
- Weak business case for CE and weak existing market tools; Lack of Business Models
- Energy consumption to close cycles
- Cheap waste exports and resources are still left
- Very scattered field of solutions and approaches. Difficulty to pool efforts.
- Promote industrial symbiosis (this means upstream and downstream considerations): possible indicators to require / more transparency and better access to data notably
- Availability of pure high quality scrap

Measures and enablers:

- Support of physical environments/infrastructure, Hubs for circularity and industrial symbiosis (e.g. testbeds for an integrated approach)
- Good examples how tech and regulation can collaborate needed, e.g. paper recycling
- Allow the primary and secondary raw materials to be processed in the same facility
- Support for the deployment of new CE business models and the R&D&I for it
- Increased involvement of society, everyone should be aware of their own contribution/influence.
- Real costs calculation needed
- Labelling of products with regards to origin of materials and CE design

- Explicit support for solutions that foster resilient supply chains and circular economy solutions
- Value chain approaches from processes, manufacturing, use and re-use/recycling as solution to overcome barriers
- Quantification and modelling of the impact of circularity and recycling
- Industry network modelling in a sector-overarching manner (suppliers, processing, manufacturing, distribution, recycling, etc.)

Regulatory barriers

See also in the other categories

Barriers and obstacles:

- Policy barriers for incentives for CO_2 transport and storage networks (e.g., TEN-E)
- Lack of harmonized EU regulation; CO_2 value is not harmonized, ETS should be the common approach
- Regulatory gaps hinder business cases
- Long permitting processes for new technologies; Operation License for new things
- Retrofit often means no more permission to operate
- European state-aid legislation prevents large scale demonstrators
- Electricity grid regulation is tailored to cost-efficiency that there is not sufficient space for investments in innovative technology.

Measures and enablers:

- Enabling regulatory framework (e.g., TEN-E allowing for multiple transport modalities for CO_2 networks)
- Adoption of regulations so companies (feedstock suppliers, process- and manufacturing industries) can move faster towards zero emissions
- Phase out of free allocation and a parallel introduction of the CBAM
- Art 26 of the EU ETS to be scrapped / Free allocations and bad EU ETS benchmark designs / IED to provide for forward looking BAT
- Electricity grid regulation: Exceptions, otherwise the grids will be a serious bottleneck for decarbonization
- Existing regulations should be regularly evaluated by law for their barrier effect in relation to climate targets and in order to prevent rigidity (e.g. H_2 production/use).
- Uniform framework conditions on climate targets, CO_2 price, calculation of climate footprints, etc.
- Stability for long term planning and investments, esp. CO_2 price developments
- We need am EU-wide Standard for IoT-interfaces in order to allow systemic synergies in the operation of energy devices from different manufacturers (IoT=Internet of Things)
- Flexible and pragmatic policies ("enabling" State aids, secondary legislation, taxonomy); Agile governments

Next Steps

At the end of the workshop Doris Schröcker (DG RTD) gave an outlook of the next steps:

- Results report of the workshop will be circulated by beginning of December (the report in hand)
- Workshop participants are invited to provide comments by 8 December
- Participants are asked to provide comments to the list of technologies that was circulated before the meeting also by 8 December
- The business associations are being consulted in parallel also on the list of technologies and how to overcome barriers to development and deployment

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ANNEX 3

Technological options for decarbonisation of energy-intensive industries by pathways

Explanation

The list below gives a basic overview of the main technology pathways for decarbonisation in energy-intensive industries, including different technological options. The application potential of the technologies is not always cumulative and in some cases one technological pathway might exclude another.

The elaboration of the list is based on a detailed deep-dive analysis of single technological options for industrial decarbonisation, including available information on TRLs, range of R&D topics, emission reduction potential and application potential; based on current key studies and roadmaps, in particular considering analysis by the relevant Horizon Europe partnerships (see below).[2]

Focus is on R&D Topics TRL 1-9 (TRL low: 1-3, medium: 4-6, high: 7-9) in the Industrial sectors Cement & Lime, Chemicals, Iron & Streel, Ferro-Alloys & Silicon, Pulp & Paper, Non-ferrous metals, Ceramics and Glass.

Not included are technologies for the production of clean energy, such as H2 as a large-scale fuel/feedstock and its storage or technologies for the sectors refineries and water.

Definition Application Potential (from the Masterplan of the High-Level Group on Energy-Intensive Industries):

High (xxx)
Medium (xx)
Low, not wide scale (x)
Not significant (o)

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

2 This detailed analysis is available to the European Commission

- International Energy Agency Technology Outlook & NetZero 2050
- Written input/feedback from various business associations with regard to draft document

Electrification of Production and Processes

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 (Cement & Lime)

- from up to 35% ER to max. 50%[3] ER
  TRL low/(medium)

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) (Chemicals)

- up to 100% ER
  TRL low/(medium/high)

Electrified primary steel: electrochemical reduction of iron ore and use of green electricity for EAF or for ore reduction (iron ore electrolysis); Generation of oxygen by electrolysis for combustion processes; Electrification of process steps e.g. sintering or reheating of furnaces (Iron & Steel)

- from up to 87% ER to max. 100% ER
  TRL (low)/medium

Electrolysis (Ferro-Alloys & Silicon)

- ER n.a.
  TRL high

Electrification of paper making process (e.g. steam supply, drying) (Pulp & Paper)

- up to 100% ER
  TRL low/medium/high

Innovative approaches to non-ferrous electrolysis, low temperature electrolysis and electric heating for heating purposes in production (e.g. regenerative and high-temperature burners) (Aluminium & Non-ferrous metals)

- up to 100% ER
  TRL low/medium/high

Electrification of (large-scale) tunnel kilns, hybrid kilns and Heat pump technology, electric cracking (Ceramics)

- from up to 73% ER to max. 80% ER
  TRL low/medium/(high)

Electrification of the furnace and all (100%) electric melting in large furnaces (Glass)

- from up to 75% ER to max. 85% ER
  TRL low/medium/high

3 According to CEMBUREAU the emission reduction potential of even 100% electrification would lead theoretical to a maximum of overall 30% emission reduction as the percentage of the combustion emissions in the cement production is always below 35%.

Crosscutting for (some) sectors: Electrification of thermal processes (furnaces) and process steps; heat pumps for low/medium and high temperature processes; electrically driven separation; electrochemical processes and liquid electrolyte high temperature processes

TRL range[4] "Electrification": **low**/**medium**/high

Application Potential by sectors (from HLG EII):

High (xxx): Chemicals, Iron & Steel (heat and mechanical*), Non-ferrous metals*, Ceramics (heat and mechanical), Glass (heat and mechanical)
Medium (xx): Cement (heat and mechanical), Iron & Steel (electrochemistry excl. H2), Pulp & Paper (heat and mechanical)
Low, not wide scale (x): Lime (heat and mechanical)
Not significant (o): Cement & Lime, Pulp & Paper, Ceramics, Glass (all electrochemistry excl. H2)

* (partly) established, can be extended

Use of green (renewable and low carbon) hydrogen

Use of low-carbon hydrogen for chemical production (e.g. ammonia, methanol, polymers), hybrid ammonia production; Water electrolysis and methane pyrolysis for integrated production of low-carbon H2 (Chemicals)

- up to 100% ER
  TRL medium/high

Use of green Hydrogen in direct ore reduction, and plasma reduction (smelting reduction); Blending of H2 into commercial production routes (combustion) (Iron & Steel)

- from up to 95% ER to max. 100% ER
  TRL medium/(high)

Use of H2 for the production of hydrocarbons (Ferro-Alloys & Silicon)

- n.a.
  TRL (medium)/high

Hydrogen combustion for heating purposes and as a reducting agent; substitution of natural gas by "green" H2 (Aluminium & Non-ferrous metals)

- from up to 95% to max. 100% ER
  TRL low/(medium)

Use of (at least two thirds) green hydrogen in hybrid systems, e.g. kilns (Ceramics)

- from 65%+ ER
  TRL medium/high

Use of Hydrogen in production/combustion processes (Glass)

- from up to 15% ER to max. 85% ER
  TRL medium/high

Crosscutting for (some) sectors: Use of Hydrogen for better combustion in furnaces of high temperature process industries

TRL range "Use of Hydrogen": low/**medium**/high

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4 Highlighted in **bold** means that in this technology pathway most topics are in this/these TRLs

Application Potential by sectors (from HLG EII):

High (xxx): Chemicals, Iron & Steel, Non-ferrous metals***
Medium (xx): Ceramics, Glass*, Cement & Lime**
Low, not wide scale (x):
Not significant (o): Pulp & Paper

* from GAE
** from EuLA and CEMBUREAU; application potential is at least medium. No significant R&D topics found in existing studies/roadmaps, but according to CEMBUREAU and EuLA, H2 related projects exist (Hynex, CEMEX) that indicate potential for use of H2 in cement/lime production and (combustion) processes.
*** from European Aluminium; regarding "Calcination"

Carbon capture & storage (CCS)

Direct capture/separation and adsorption/absorption of process emissions; Carbonate/CO2 looping (using limestone, with oxyfuel, through mineralization); Oxy-fuel combustion; Post-combustion technologies (Cement & Lime)

- up to max. 95% ER
  TRL (low)/medium/high

Capture of CO2 from process and combustion emissions (amine based, adsorption, absorption, direct separation) (Chemicals)

- from up to 90% to max. 97% ER
  TRL medium/high

Generation of CO2-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 (Iron & Steel)

- from up to 60% ER to max. 90% ER
  TRL medium/high

Separation of CO2 from other gases and store in the ground (Ferro-Alloys & Silicon)

- ER n.a.
  TRL medium/high

CCS from aluminium electrolysis process (Aluminium & Non-ferrous metals)

- ER n.a.
  TRL low/medium

CCS from exhaust gases (post-combustion), pre-combustion or oxy-fuel combustion (Ceramics)

- from up to 50% ER to max. 79% ER
  TRL medium/(high)

CCS Glass Furnace (Glass)

- up to 90% ER
  TRL medium

Crosscutting for (some) sectors: Capture and storage of CO2 from process emissions and combustion emissions

TRL range "CCS": low/**medium**/**high**

Application Potential by sectors (from HLG EII):

High (xxx): Cement & Lime, Chemicals, Iron & Steel
Medium (xx): Non-ferrous metals***
Low, not wide scale (x): Glass*
Not significant (o): Pulp & Paper, Ceramics**

* from GAE
** identified R&D topics might indicate higher potential
*** from European Aluminium

Carbon capture & utilisation (CCU)

CCU in Cement Production and on process emissions; CCU on cement and lime kilns; Carbonisation of solid raw material/curing with CO2; Mineral CO2 and CO2 scrubbing (Cement & Lime)

- up to 90% ER
  TRL (low)/medium/high

Utilisation of captured CO2 (and CO from 'industrial waste gases') for the production of chemicals (including basic and fine chemicals) and polymers through various processes (Chemicals)

- from up to 30% ER to max. 100% ER
  TRL low/medium/high

Reuse and valorization of waste and gases esp. from the BF/BOF into chemicals/products/raw materials. Synergies with chemical industry (Iron & Steel)

- from up to 20 % ER to max. 85% ER
  TRL medium/(high)

Valorization of CO2/CO and slag (Ferro-Alloys & Silicon)

- ER n.a.
  TRL (low)/medium/(high)

Concentrate, capture & purification of CO2 from alumina refineries and use it for other purposes (Aluminium & Non-ferrous metals)

- ER n.a.
  TRL medium

CCU from exhaust gases to use in other processes (Ceramics)

- up to 90% ER
  TRL medium

CO2 capture and purification technologies for CO2 valorisation (Glass)

- ER n.a.
  TRL (low)/medium

Crosscutting for (some) sectors: (Flexible) CO2 capture and purification technologies for CO2 valorisation

TRL range "CCU": low/**medium**/high

Application Potential by sectors (from HLG EII):

High (xxx): Cement & Lime*, Chemicals, Iron & Steel
Medium (xx): Non-ferrous metals***
Low, not wide scale (x): Ceramics, Glass**
Not significant (o): Pulp & Paper

* According to CEMBUREAU, the prerequisite for realizing a high application potential is that the recognition of emission reductions through CCU processes is made possible by the EU.
** from GAE
*** from European Aluminium

Alternative fuels and feedstocks (excluding H2), bio-based resources, and integration of renewable energy

Use of concentrated solar heat and PV, alternative fuel mix (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 (Cement & Lime)

- from up to 28% ER to max. 50% ER
  TRL (low)/medium/high

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 (Chemicals)

- from up to 25% ER to max. 100% ER
  TRL medium/high

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 (Iron & Steel)

- from up to 28% ER to max. 100% ER
  TRL (low)/medium/high

Use of natural gas and bio-carbon; switch to alternative reductants (Ferro-Alloys & Silicon)

- ER n.a.
  TRL low/medium/high

Biomass gasification and combining paper production and drying with solar thermal (Pulp & Paper)

- ER n.a. TRL medium/(high)

Use of low-carbon fuels/energy and renewable electricity in aluminium production process steps; Green carbon sourcing for anodes; Use of biofuels and low carbon fuels in copper and nickel production (Aluminium & Non-ferrous metals)

- ER n.a./up to 25% Energy Savings
  TRL low/medium/high

Upscaling and integration of hybrid technologies; Use of biogas and syngas/biomethane firing; Biomass Gasification (Ceramics)

- from up to 30% ER to max. 100% ER
  TRL medium/high

Oxy-fuel and biomass combustion; Use of liquid biofuel and carbon neutral gas; integration of renewables (esp. for electric melting) (Glass)

- from up to 50% ER to max. 85% ER
  TRL medium/high

Crosscutting for (some) sectors: Integration of alternative fuel (mixes) and renewables (solar/wind); Processing of (non-recyclable) waste and biomass in high temperature furnaces; Direct use of bio-based resources as feedstock in industrial applications/processes; hybrid systems, e.g. hybrid kilns

TRL range "Fuel switch": low/**medium**/**high**

Application Potential by sectors (from HLG EII):

High (xxx): Cement (biomass already well established*), Chemicals (biomass already well established for some chemicals*), Pulp & Paper (biomass already well established*), Non-ferrous metals, Glass
Medium (xx): -
Low, not wide scale (x): Lime, Iron & Steel (biomass/biofuels), Ceramics
Not significant (o): -

* can be extended in some cases

Alternative materials and more energy efficient processes

"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, energy recovery and optimal combustion process; Dry kilns, multistage cyclone heaters (Cement & Lime)

- from up to 10% ER to max. 90% ER[5]
  TRL medium/high

Membrane reactor technologies and other breakthrough technologies alternative to distillation; Process intensification, including reactor design/equipment, new catalysts and improvements in monomer production; separation technologies, e.g. advanced technologies for thermal separation (Chemicals)

- from up to 10% ER to max. 90% ER
  TRL (medium)/high

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; Heat reuse by heat exchangers; Coke dry quenching (Iron & Steel)

- from up to 20% ER to max. 35% ER
  TRL medium/high

5 According CEMBUREAU feedback

Pre-treatment, pre-heating and pre-reduction of raw materials; new ferro-chrome-nickel process; New hydrometallurgical process for purity silicon production; waste heat recovery (Ferro-Alloys & Silicon)

- ER n.a.
  TRL low/high

Extraction of lignin from wood pulp for industrial products, or as biofuel; New drying techniques: use of Steam in Flash Condensing and Paper Drying; Dry-Pulp for Cure-Formed Paper; Supercritical CO2: substitution of steam-heated cylinders; Deep eutectic Solvent pulping; Enzymatic pre-treatment (Pulp & Paper)

- from up to 20% ER to max. 55% ER
  TRL low/medium/(high)

Technologies complementary to Bayer Process; Carbo-thermic Alumina Reduction and Kaolinite Reduction; Bauxite: Red mud treatment; Biomass as raw material in anode production; use of inert anodes; Recuperative or regenerative burners; Heat reuse (from off-gases, by heat exchangers); Novel design approaches: wetted anodes and multipolar cells; Reduced electricity with carbon anodes (Aluminium & Non-ferrous metals)

- significant ER/up to 46% ER
  TRL (low)/medium/high

On-site CHP plant; Design for energy efficient Kiln; Vacuum drying technologies; Heat recovery technologies (heat exchangers) (Ceramics)

- up to 73% ER
  TRL medium/high

Batch pelletisation, Raw materials pre-heating and Glass batch reformulation; Waste heat recovery, vacuum drying technologies (Glass)

- from up to 5% ER to max. 20% ER
  TRL medium/high

Crosscutting for (some) sectors: New kiln technologies, installing heat exchangers; energy/waste heat recovery (also between sectors) and optimal combustion processes; Drying technologies; Process intensification, e.g. through next-gen catalysis;

TRL range “Alternative materials and more energy efficient processes”:
low/**medium**/**high**

Application Potential by sectors (from HLG EII):

High (xxx): Cement & Lime, Chemicals***, Iron & Steel, Pulp & Paper (if focus on efficiency**), Non-ferrous metals (esp. inert anodes and if focus is on efficiency**), Ceramics (if focus on efficiency**)
Medium (xx): -
Low, not wide scale (x): Glass*
Not significant (o): -

* Glass: no explicit information available, derived from GAE feedback: rather low
** can be extended in some cases
*** from CEFIC; particularly with regards to membrane reactor technologies

Materials efficiency, secondary resources, and waste valorisation (incl. recycling/CE and industrial symbiosis)

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)

- up to 34% ER
  TRL medium/high

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)

- from up to 11% ER to max. 56% ER
  TRL medium/high

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 materials efficiency and circularity; Utilization of residues from steel production internally (e.g. BF/BOF top gas recycling) or in other sectors (mineralization of slags for the cement industry) (Iron & Steel)

- from up to 38% ER to max. 100% ER
  TRL high

Use and valorisation of slag (Ferro-Alloys & Silicon)

- ER n.a.
  TRL high

Lignin extraction; Black liquor recovery/gasification; Valorisation of pulp/paper waste streams; New recycling technologies without wetting and drying, upgrading recovered fibres (Pulp & Paper)

- from up to 10% ER
  TRL medium/high

Efficient physical scrap collection and sorting of aluminum and other non-ferrous metals; melt purification technologies & re-melting of scrap aluminium, new de-coating equipment; Aluminium Mini Mills (Aluminium & Non-ferrous metals)

- ER n.a./up to 84% Energy Savings
  TRL medium/high

Raw material development for Circular Economy, material recovery and ceramic recycling (Ceramics)

- ER n.a.
  TRL medium/high

More efficient/effective Glass recycling: better collection and sorting (Glass)

- from up to 5% ER to max. 20% ER
  TRL high

Crosscutting for (some) sectors: Industrial and Industrial-urban symbiosis and reuse; Innovative materials for better life cycle performance; Inherent recyclability of materials; Upgrading of secondary resources; Better separation and sorting technologies

TRL range "Materials Efficiency": low/**medium/high**

Application Potential by sectors (from HLG EII):

High (xxx): Cement & Lime (cement: use of waste streams well established*), Chemicals, Iron & Steel, Pulp & Paper ("efficiency" already well established*), Non-ferrous metals ("efficiency" already well established*), Ceramics ("efficiency" already well established*), Glass** ("Recycling" already well established*)
Medium (xx):
Low, not wide scale (x): -
Not significant (o): -

* can be extended in some cases
** from GAE

Enablers: Digitalisation

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

E-commerce

Internet of Things

5G mobile networks

Blockchain

Enablers: Eco Systems and support actions for Non-technical innovations/drivers

INTEGRATING non-technological aspects in Research and Innovation activities to improve the technological solution's effectiveness

CREATION of European 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 EU industries.

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This document includes the annexes to the ERA industrial technology roadmap for low-carbon technologies in energy-intensive industries. It contains three documents prepared by the Austrian Institute of Technology: a summary of the SMEs surveys conducted for the roadmap, a report of an online workshop that took place on 24 November 2021 and a list of technological options for decarbonisation of energy-intensive industries by pathways.)

Research and Innovation policy

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