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Technologies to be supported to achieve a 95% reduction in GHG emissions by 2050 in the European Union

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PREFACE

The **CARISMA** project ("**C**oordination and **A**ssessment of **R**esearch and **I**nnovation in **S**upport of climate **M**itigation **O**ptions") intends, through effective stakeholder consultation and communication leading to improved coordination and assessment of climate change mitigation options, to benefit research and innovation efficiency, as well as international cooperation on research and innovation and technology transfer.
Additionally, it aims to assess policy and governance questions that shape the prospects of climate change mitigation options and discuss the results with representatives from the target audiences to incorporate what can be learned for the benefit of climate change mitigation.
Knowledge gaps will be identified for a range priority issues related to climate change mitigation options and climate policy making in consultation with stakeholders.

PROJECT PARTNERS

No	Participant Name	Short Name	Country Code
CO1	Radboud University	RU	NL
CB2	University of Piraeus Research Center	UPRC	EL
CB3	JIN Climate and Sustainability	JIN	NL
CB4	Institute for Climate Economics	I4CE	FR
CB5	University of Graz	UNI Graz	AT
CB6	Stockholm Environment Institute	SEI	SE
CB7	Centre for European Economic Research	ZEW	DE
CB8	Centre for European Policy Studies	CEPS	BE
CB9	ENVIROS S.R.O.	ENVIROS	CZ
CB10	Technical University of Denmark	DTU	DK

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Abstract

This report reviews those technologies that have the highest mitigation potential to enable a greenhouse gas emissions reductions target of 95% or more across the EU economy. Such a climate policy target requires transformational technology changes well beyond efficiency improvements in all sectors of the economy. Developing technologies with the highest mitigation potential in all major sectors of the economy should be prioritised for future research. Information on mitigation potential of technologies in sectors is contrasted with data on how funding for mitigation technology development has been distributed across different sectors so far. According to one account, 70% of public innovation funding in the past ten years went to the electricity sector and transport fuels, while the industrial, buildings and agriculture sectors are responsible for 60% of GHG emissions in the EU. Energy-intensive industrial sectors, in particular the steel, cement, refining and chemicals sectors, are characterised by numerous production processes and types of energy use, as well as process emissions that require bespoke technological solutions. Besides sector-specific technologies, several cross-cutting technologies could reduce emissions significantly across the board. Hydrogen-based production processes and carbon capture and storage offer high potential for emissions reductions in industry, while electrification can play a major role in every sector, with the exception of agriculture and waste. Because of the importance of electrification, electricity storage and grid management become key. These cross-cutting technologies require significant investments to manage an electricity system with a high penetration of renewables, but also from a small part of innovation budgets.

1 Introduction

This report addresses the issue of which technologies would be required to achieve the mid-century climate objectives of the EU across the economy. In particular, we aim to investigate what needs to be done from an R&D and innovation funding perspective to increase the likelihood that emission reductions consistent with the Paris Agreement will be achieved in the EU. Amid the various sectors and myriad technological options, this decarbonisation effort requires prioritisation of technologies, as public funding is limited and competes with other objectives. Given that many sectors require breakthrough technologies and given various market and non-market barriers to private investment in such technologies, public funding support will play an important role.

1.1 Context

The current long-term climate policy target for the EU is to achieve an 80-95% reduction in greenhouse gas emissions from 1990 levels by 2050. As a consequence of the Paris Agreement, which has more ambitious temperature goals, this target is likely to be made more stringent in the coming year with the European Commission working on a updated 2050 strategy likely including a net-zero target[1]. The policy framework that is in place, and the policies that are planned for the 2030 horizon are predicated on a pathway to achieve 80%, with the intermediate reduction targets of (at least) 40% for 2030 and 60% by 2040[2]. At the same time, the collective commitments (Nationally Determined Contributions – NDCs) made under the Paris Agreement are not sufficient to achieve the goal of limiting warming to 'well below' 2°C, let alone the preferred limit of 1.5°C. Therefore, as part of the review mechanism, all Parties to the Paris Agreement, including the EU, will be under (political, if not legal) pressure to increase their ambition over time.

For the EU, this would probably mean that policies should be geared towards the upper end of the 80-95% range, or beyond. The IPCC's Special Report on the 1.5C temperature goal may even imply that net-negative emissions before 2050 are needed. The purpose of this report is to review which technologies would enable the achievement of climate policy targets of reducing GHG emissions by 95% or more. Such a scenario requires that all sectors of the economy need to practically eliminate their emissions, and that some that have that possibility, will have to go negative. While the EU explores potential options for new technologies that could remove carbon dioxide from the atmosphere ('carbon dioxide removal' (IPCC, 2014) or 'negative emission technologies', e.g. EPRS 2016), this document discusses the types of technologies that could directly reduce GHG emissions from major sources to very low or zero emissions, including a limited focus on Carbon Capture and Storage (CCS) in combination with biomass as a potential carbon dioxide removal option.

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[1] See: https://www.euractiv.com/section/climate-environment/news/eu-to-aim-for-100-emission-cuts-in-new-mid-century-roadmap/

[2] See: European Commission (2018). 2050 low-carbon economy https://ec.europa.eu/clima/policies/strategies/2050_en

1.2 Defining potentials

This document focuses on a set of technologies that could collectively contribute to significant emissions reductions across the entire economy. In light of a 95% emissions reduction target for 2050, "decarbonising" thus means achieving close to zero GHG emissions in most, if not all (sub)-sectors, and negative emissions in as many sectors as possible. The first step to achieve this is to identify those technologies with the highest mitigation potential. While there may be many technologies, practices, and other innovations that could lead to significant efficiency improvements, even a comprehensive list of such measures would still be insufficient to achieve the EU's emissions reduction targets, particularly if underlying emissions-intensive practices and industrial processes are not fundamentally changed. Such an absence of transformational change, essentially leading to continued use of CO_2-emtting processes (albeit more efficient ones), would be incompatible with a target of reducing emissions by 95% or more.

Hence, this document focuses on those technologies and measures that will have the highest potential from a technological, not an economic or social perspective. This means that the upper end of the potential is defined as being equal to the current emissions in a given sub-sector (while there may be cases where technologies allow for negative emissions, these are not the main focus in this report). This would be the case if a single technology enables emissions in a sector to be reduced in full. For example, if it is accepted that all electricity generation could be based on a combination of renewables and electricity storage, then the potential for this combination is at least equal to current electricity sector emissions (and may be higher if other sectors electrify their processes). Where different sources of emissions, such as various stages of industrial production processes or different modes of transport, can be clearly identified, the maximum potential is equal to the emissions of these sub-sectors/processes.

1.3 Sources: Greenhouse gas emissions data

GHG emissions data are collected using two sources, the EU Transaction Log (EUTL)[3] for sectors covered by the EU ETS, and data from the European Environment Agency (EEA) for the non-ETS sectors. The EUTL data is released on an annual basis by the European Commission based on compulsory reporting by individual installations[4]. The accuracy of this data is therefore high. To aggregate and better analyse this data, CEPS, with the University of Graz, has developed an in-house database, where installation-level data from the EUTL is aggregated on sector level using the NACE-4 classification. NACE classification is the same system as used by the European Commission in drafting EU ETS implementing legislation which requires economic classification. An alternative, the EEA's EU ETS Data Viewer[5], is less attractive as emissions are reported under their "Activity Code", which is based on the process of emitting GHGs (e.g. combustion of fuels). If a

[3]http://ec.europa.eu/environment/ets/
[4]https://ec.europa.eu/clima/policies/ets/registry_en#tab-0-1
[5]http://www.eea.europa.eu/data-and-maps/data/data-viewers/emissions-trading-viewer

breakdown into economic sectors is desired, as adopted in the current document, certain processes may occur in multiple sectors, but it does allow for aggregation according to sector, not process.

For the non-ETS sectors, EU member states are required to gather GHG emissions data, and report them to the EEA, which in turn releases annual reports. Due to unavoidable lags in reporting and measurement, this data is at best two years old (2015 in the case of this document).

1.4 Product substitution

By focusing on the specific sources of emissions in sectors, the approach this document takes inherently looks at current practices and production processes, and what could enable these same products to be produced with as little emissions as possible. However, substituting current practices and products with other products, services, and practices – possibly in other sectors – that would produce far fewer GHG emissions is always an option that should be considered. A substitution approach, however, could from the perspective of the incumbent industry, be summarised as reducing demand for current emission-intensive products, such as cement or certain chemicals.

While such substitution and demand reduction arguably should be considered beneficial in so far as it is environmentally, economically and technically feasible, it is reasonable to assume that not all energy-intensive products can be substituted or displaced. The residual emissions may still be incompatible with the very ambitious targets requiring more than 95% reductions which this analysis assumes. As such, investigating and supporting means of reducing emissions in currently used products remains important, notwithstanding the merits of substituting these products with lower or zero-emission alternatives.

1.5 Outline

The remainder of this report consists of an overview of how public funding for emissions reductions projects has so far been distributed across the economy in section 2, and, in section 3, a detailed examination of the technological options available in the main-emitting sectors of the economy: the power sector, the largest energy-intensive industries, transport, buildings, agriculture, and waste. Section 4 provides some conclusions.

2 How has research funding for GHG mitigation been distributed so far?

Beyond technological potential, prioritisation of future public innovation investments should also take into account which sectors have been the recipient of funding in the past. Ideally, funding would be spread out across sectors, as emissions reductions are required in all sectors. While the challenge of reducing emissions in some sectors may not be purely technological, but rather economical or societal (e.g. split incentives in the buildings sector)

The table below (Table 1) shows a preliminary and approximate indication of total research funding by the European Commission framework programmes targeting emissions reductions between 2008 and 2014 and how this funding has been distributed across different sectors so far. The electricity sector is treated separately from energy, given the importance of electricity generation, but also because in funding terms, some projects have been focused on the exploration and generation side of energy production. The right column in Table 1 shows the shares of GHG emissions, based on data from the EU Transaction Log and from the EEA. While this breakdown in emissions is different from the standard IPCC methodology, it allows for a sectoral breakdown that corresponds to the main EU climate policy frameworks. It ensures, for example, that there is not a major grouping called 'emissions from energy use' where the emissions from the power sector and energy use in energy-intensive industry are combined.

Table 1: Indicative EU research funding across major emitting sectors between 2008 and 2014 vs GHG emissions shares (2015/16 – latest year available)[6]

	EUR mil.	Share of funding	Share of GHG emissions
Power/Electricity[7]	558	30%	21%
Transport	747	40%	21%
Manufacturing/industry[8]	153	8%	30%
AFOLU	25	1,5%	10%
Energy production	188	10%	n/a (part of others)
Buildings	210	11%	15%
Waste	1,5	0,1%	3%

Source(s): Funding data from Radboud University data (2017). Zahar Koretsky & Heleen de Coninck. GHG data from EUTL and EEA.

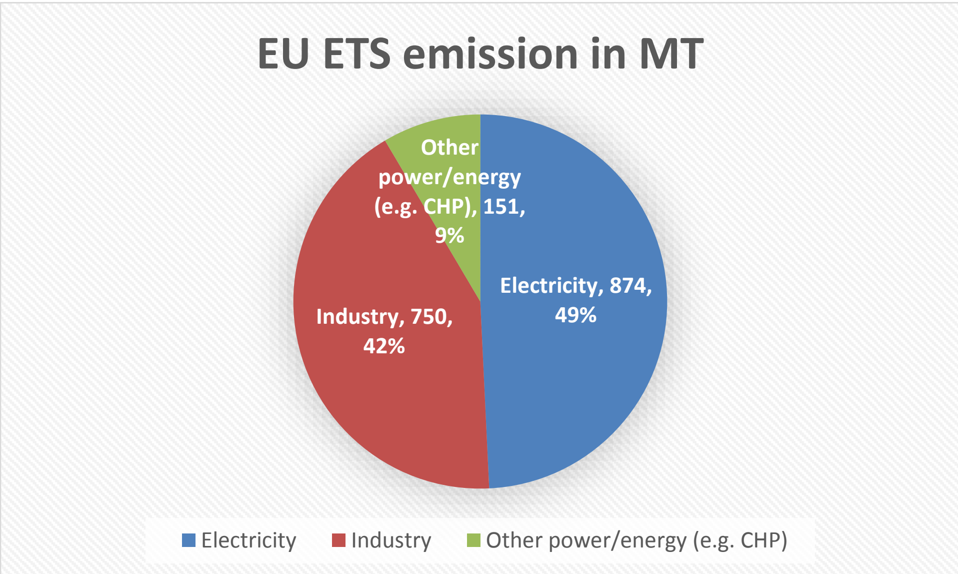
[6] Disclaimer: this data is an approximation and should be treated with caution. While the numbers may change somewhat with additional data, the data corresponds to other trends in climate and energy policy, where the power sector and transport sectors have received relatively more attention than industrial sectors, although the latter is changing during the last year in particular.
[7] Power and electricity sector emissions have been collected through the EU Transaction Log (NACE classification used for aggregation); overall EU GHG emissions calculated by EEA
[8] This category contains both energy-intensive industries (most of which are covered by the EU ETS) as well as manufacturing sectors which are often non-ETS sectors.

This comparison between funding received, and shares of emissions shows that certain sectors have clearly been favourites for financial support in the past. The electricity and transport sectors in particular, have received just under 70% of research funding between 2008 and 2014. While clearly some of the most significant sectors in terms of GHG emissions, this leaves only 30% of funding for sectors covering 60% of emissions in the EU's economy. The discrepancy between the figures on funding and emissions for the (combined) manufacturing and industrial sectors is especially stark, given that emissions in these sectors come from a wide variety of sectors significantly varying in size (some included in the EU ETS), energy intensity and type of energy used, as well as production processes more broadly – many of which require tailored technological solutions to significantly reduce GHG emissions.

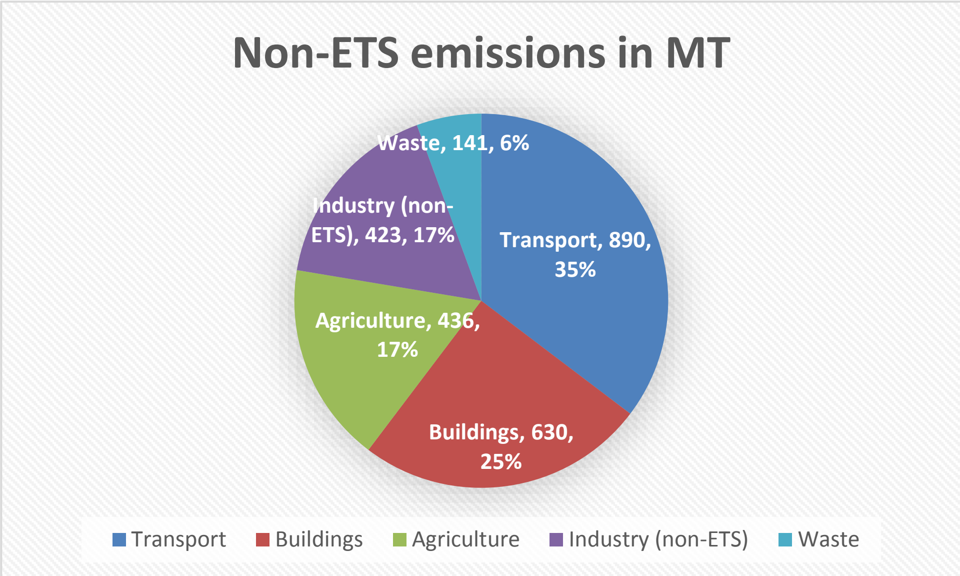
Figure 1 below shows the most recent greenhouse gas emissions data (in Mt CO_2 equivalent) available in the major sectors of the economy. It provides the absolute quantity of GHG emissions, corresponding to the shares listed in Table 1 above. These sectors will be examined below, with special focus on the biggest energy-intensive industrial sectors, with regard to how emissions are generated in these sectors and which technology could potentially address these emissions sources.

Figure 1: Most recent GHG emissions data EU[9]

Total EU GHG emissions in 2015: 4295 Mt CO2e



[9] EU ETS emission data from EUTL (2016); non-ETS data from EEA (2015).


Non-ETS emissions in MT
Waste, 141, 6%
Industry (non-ETS), 423, 17%
Transport, 890, 35%
Agriculture, 436, 17%
Buildings, 630, 25%
Transport
Buildings
Agriculture
Industry (non-ETS)
Waste

3 Main economic sectors and technologies for deep decarbonisation

The most promising technologies that would enable reductions in GHG emissions across all sectors of the economy, consistent with a target of more than 95% GHG emissions reductions in the EU, are listed below. The concept of 'deep decarbonisation' has been introduced to convey what is necessary on a global scale to limit emissions to the extent that the UNFCCC's temperature targets (as expressed in the Paris Agreement) are feasible.

Specifically, deep decarbonisation means that global emissions should reach net-zero between 2050 and 2075 (DDPP, 2015), but also that steps taken to address GHG emissions allow and prepare for deeper steps beyond that. Technology deployment is intrinsically linked to this step by step decarbonisation, as technologies that wholly transform processes have a higher potential to contribute to deep decarbonisation than incremental efficiency improvements to existing processes.

Likewise, the technologies discussed here are equally about what technologies not to prioritise, i.e. those technologies were the potential is limited and represents an improvement in current technology or process while still resulting in residual emissions.

This list is not a ranking but lists technologies per major sector of the economy. This list is derived from the assessment made in the subsequent sections of this document, which zoom into the specific sectors and technologies, summarising the key technologies at the end.

- Electricity storage (power sector)
- Carbon Capture and Storage (CCS) (all energy-intensive sectors)
- Hydrogen (multiple energy-intensive sectors, including Refining)
- Direct Reduced Iron (Steel – enables more Electric Arc Furnace use, and CCS)
- Catalytic reactors (Refineries, Chemicals)
- CCS for Cement
- Renewable Heat (Buildings)
- More efficient envelopes (Buildings)
- Batteries (Transport)
- Fuel Cells (Transport)
- Biofuels for aviation
- Reduced emissions from fertilisers and livestock (agriculture)
- Lining land-fills, reducing waste (waste sector)

3.1 Power sector

The electricity sector accounts for approximately 21% of total EU GHG emissions in 2016 and 55% of EU ETS emissions (EUTL, Table 1). GHG emissions in the power sector are primarily resulting from the combustion of fuels for the production of electricity. Combined Heat and Power plants (CHP) make up the rest of the emissions. While electricity is a homogenous product, one can differentiate between baseload electricity generation and peak load. In general, peak load is provided by more flexible energy sources such as gas. Renewable energy (RE) technologies to decarbonize the power sector have made significant advances throughout recent years so that their future deployment depends more on further cost reductions than on new RE technologies as such. This is also reflected in the combined R&D spending in the 2008-2014 period, where photovoltaics, wind turbines, and solar energy still received over 60 million in funding, but without reaching the top-10 of most supported technology groups.[10]

Choosing between supporting different RE technologies is also not easy, as all could in theory contribute equally to decarbonizing the power sector, and many face similar constraints in terms of intermittency. As an exception biomass is not affected by variability, but it faces different problems of supply by competing with food production. This does not mean that increased market uptake and deployment of renewable energy in electricity generation is not essential to reach (near) zero emissions, but rather that other measures than innovation support are required to reach such deployment levels, e.g. support for deployment through contracts for differences or similar instruments.

All RE electricity generation, however, benefits from increased storage capacity, as well as improvements in grids so that electricity can be supplied more readily when it is required at peak demand times (Denholm & Hand, 2011). Therefore, innovation support should focus on storage in particular, so that all forms of RE electricity can be used more effectively in a decarbonized power mix. Technologies that can countervail periods of low generation by variable and intermittent sources are essential for this. Increased electricity storage would also lower the capacity of renewable energy sources required.

Technology support in the power sector should focus on electricity storage and distribution grids, as together these would enable a high degree of penetration of renewables that from a technology perspective are already at more advanced stages of maturity. This also brings positive spill-overs for sectors looking at increased electrification as a means to reduce their emissions. Electricity storage can be provided in many different ways. While ideally the support is kept as technology-neutral as possible, it is imperative to support modes of electricity storage with different purposes: i.e. short-term as well as seasonal storage.

3.2 Industrial/manufacturing sector

The industrial and/or manufacturing sectors currently account for approximately 30% of total EU GHG emissions (two-thirds of these emissions are from sectors under the EU ETS). GHG emissions in energy-intensive industries arise from a large number of sectors, both large and small in terms of turnover, with widely varying production processes. The four biggest industrial sectors (steel, refining, cement and chemicals) are responsible for

[10] Combined these three groups would end up in the 8th spot, behind Hydrogen fuel cells (CARISMA Work Package 3 data, available on http://carisma-project.eu/Results)

about 75% of industrial (non-power) emissions under the EU ETS. Glass, paper and pulp, lime, aluminium, oil and gas extraction and ceramics, make up the majority of the remaining 25%, with dozens of smaller sectors responsible for only a few percentage points of the residual EU ETS emissions. For the technology options analysis of this document, we focus on the four biggest emitting sectors.

Innovation support for the iron and steel, refineries, cement and chemicals sectors ideally should address each of these sectors, in so far as they have not developed technologies that, if deployed at scale, could reach net-zero emissions. For some sectors, this may require multiple technologies as their emissions arise from different sources, e.g. energetic emissions, feedstock use as well as process emissions.

Research and development seeking breakthroughs in cross-cutting technologies such as CCS (IEA, 2011) and hydrogen would benefit multiple industrial sectors, which could be an argument for preferential support and encouragement through increased innovation support. The storage and transport parts of CCS in any case requires public support due to the infrastructure nature.

While CCS has long been part of climate mitigation policy discourse, it has also attracted controversy due to liability and public acceptance issues. Additionally, efforts to support CCS have not been successful, as evidenced for example by the absence of completed CCS projects (none which were planned in industry sectors) in the EU ETS' NER300 fund. But by and large, CCS in the past was seen as a mitigation technology for the power sector, where many alternative mitigation pathways have always been possible.

3.2.1 Iron and Steel production

Technologies to reduce GHG emissions:

- Increased Electric Arc Furnace (EAF) use through scrap metal use (currently constrained by scrap availability)
- Direct reduced iron (DRI) (also enables CCS)
- Blast Furnace with top gas recycling
- CCS
- Hydrogen-based steel-making

The steel sector accounts for approximately 4% of total EU GHG emissions in 2016 (EUTL). There are a number of technologies that can enable significant emission reductions in iron and steel-making. Some of these are already widely in use (EAF) but are only responsible for a small share of total steel production, due to the limited availability of inputs (scraps), and constraints on the types of final products that can be produced through EAF. Additionally, the use of EAFs still results in a certain amount of direct emissions through the oxidization of inputs in the EAF. While the emissions in EAF are only a fraction compared to other steel making processes (BF-Basic Oxygen Furnace), the residual emissions may nevertheless be incompatible with a 95% target scenario. Indirect emissions can also be highly significant, although this depends on the mode of electricity production such as when electricity is produced from coal. While the indirect emissions are from a technology perspective more a matter for the power sector itself, CCS may contribute to a solution in cases where the electricity is generated by using waste gases generated during traditional steel-making.

Even if EAFs may not be an industry-wide long-term solution, its increased use could help achieve emissions reductions in the short and medium term. EAFs are also compatible with DRI, which can serve as an input into EAF steel-making. DRI in itself enables further emission reductions, as it is a pre-condition for hydrogen-based methods of steel production, and enables CCS relatively easily as carbon dioxide is already captured to improve flu gases (IETD, 2017).

The biggest potential comes from basing steel production as much as possible on hydrogen. Older studies (Ranzani da Costa et al, 2013) already showed potentials of 80% emission reductions from hydrogen-based steel production. A new pilot plan in Linz, Austria has demonstrated the potential for full CO2 neutral steel production (Voestalpine, 2017). According to a steel sector roadmap (Eurofer, 2013), 60% reduction in GHG emissions by 2050 is achievable with increased scrap EAF, DRI, and CCS. Hydrogen-based methods in principle enables near zero-carbon steel production but are still far from being a mature technology.

An alternative hydrogen-based steelmaking approach is 'hydrogen plasma smelting reduction', which has the potential to fully reduce emissions from steel-making, but which is at a far lower level of development than other hydrogen methods. (Soni & Thakkar, 2017). Nevertheless, this also makes it a good candidate for innovation support. A similar point can be made about iron ore production through bulk electrolysis (which also links to hydrogen if the hydrogen is produced with electrolysis), which equally enables zero-carbon steel making, but is lacking in research and development so far (Allanore et al., 2008).

In summary, hydrogen use would be compatible with DRI, which also enables CCS relatively easily. Thus, these three technologies could help the sector achieve deep decarbonisation. Increased use of EAF is highly beneficial too but might be constrained by availability. Increased DRI availability would provide an alternative solution. Ensuring that EAF can be more widely used also requires policies in addition to innovation support; i.e. policies that would result in a higher availability of inputs to the EAF process. Circular economy policies can play an important role here (Material Economics, 2018).

Technology support should focus on enabling higher uptake of DRI (including hydrogen use) and CCS considering positive potential spill-overs to other sectors that could also make use of hydrogen and CCS. DRI itself would also enable more EAF steel production.

3.2.2 Refineries

The refining sector accounts for approximately 3.5% of total GHG emissions in the EU (EUTL, table 1). GHG emissions from refining activities arise from the following sources[11]:

- Direct combustion (85% of emissions)
    - Fluid Catalytic Cracking (FCC) Coke on Catalyst
    - Other fuels
- Indirect energy
- Hydrogen generation
- Flare loss
- Methane

The vast majority of emissions arise from fuel combustion. As such, focusing on replacing these fuel combustion emissions represents the primary challenge. While there are various efficiency improvements envisioned that could reduce emissions, the potential of such measures (which include electrification of rotating machines, recovery of low-grade heat, improved energy management systems) is limited (FuelsEurope, 2018).

Some of these emissions are process emissions which are hard to avoid. Improvements to catalytic convertors (the main source of process emissions) and CCS enable deeper decarbonisation. Hydrogen produced through electrolysis could serve as an alternative feedstock, as would bio-feedstocks which could moreover allow for negative emissions (an example of BECCS).

Even if demand for refined oil products (fuels) may come under pressure in Europe due to the strong expected growth of electric vehicles there, fuel demand in other parts of the world will remain high, as well as demand for fuels used in aviation and maritime transport.

It is noteworthy that catalytic reactors have been the beneficiary of public R&D investment totalling 13 million euros in the 2008-2014 period.

Technologies to be supported thus include CCS and hydrogen, which have potential positive spill-over effects and should be prioritized for technology support in the future. Additionally, further catalytic reactor improvements can address the process emissions which are otherwise difficult to tackle and may have positive spill-overs for the chemical industry.

3.2.3 Cement production

The cement sector accounts for approximately 3% of total GHG emissions in the EU in 2016 (EUTL, Table 1). Unlike with many other industrial sectors, GHG emissions in the cement sectors arise to a significant degree from process chemistry – which accounts for 64% of (Portland) cement production, and a minority from fuel combustion (Hills et al,

[11] https://ec.europa.eu/clima/sites/clima/files/ets/allowances/docs/bm_study-refineries_en.pdf

2015). GHG emission reductions in the cement sector so far have been incremental and driven by energy efficiency and clinker substitution. With economically viable technologies, the cement sector can achieve about 50% reduction in emissions. Innovation focus should therefore be on the other 50%. On a long-time horizon towards 2050, the cement sector estimates its abatement need to be 136MtCO_2 reduction based on the 2050 target at 34MtCO_2, 80% reduction from the 1990 level at 170MtCO_2 (CEMBUREAU, 2013). The cement sector roadmap identifies five routes to emissions reductions:

- Resource efficiency
- Energy efficiency
- Carbon capture and reuse or storage (CCUS)
- Product efficiency
- Downstream

The latter two, while beneficial on shorter time-scales are outside the scope of this report. The cement sector roadmap also estimates the potential of CO_2 savings per technology (CEMBUREAU, 2013:11):

- Kiln efficiency and fuel mix[12] -34MtCO_2;
- Clinker substitution and novel cements -11MtCO_2;
- Transport efficiency -2MtCO_2;
- Decarbonisation power -10MtCO_2;
- Breakthrough technologies, such as CC(US) -79MtCO_2

According to CEMBUREAU (2013), a reduction of 79 MtCO_2 still requires breakthrough technologies to address. CCS is frequently mentioned as such a technology. Innovation support should focus on this, or novel technologies such as the novel cements described below, as CCS is eventually not a sustainable option and is limited in areas without geological storage capacity.

While current cement production is focused on Portland cement, there have also been attempts at substituting Portland clinker with new, low-carbon clinker types; some of which have yet to be developed. Examples include geopolymers and alkali-activated binders, which allows for emissions reductions of 90% in the full production process but is currently constrained by the production of sodium silicate, and magnesium-based cements, which could be wholly carbon free but which are still in an early research phase (Lehne & Preston, 2018).

While there has been some R&D investment focused on low carbon cement, at 4 million Euro this investment is negligible in light of the significant share that the cement industry contributes to total EU GHG emissions and the specific need for breakthrough technology in the sector.

Technology support should focus specifically on novel technologies or clinker types as well as CCS and CCU for cement. Of the latter two, CCS is the more important one as geological storage less likely to be constrained than demand for the captured CO_2. For

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[12] See also Ecofys 2017.

CCU to be feasible, it may be necessary to ensure sufficient demand by having integrated industrial facilities; this would have further positive spill-overs for energy-intensive industry in general.

3.2.4 Chemicals (including fertiliser production)

The chemicals sector comprises organic basic chemicals, inorganic basic chemicals, and the production of fertilisers. Together, these three subsectors account for approximately 2.8% of total GHG emissions in the EU (EUTL, Table 1).

In 2010, emissions[13] in the chemicals sector can be broken down as follows:

- Combustion (heat generation) 132Mt;
- Process emissions including N_2O emissions from nitric acid and other chemicals 43Mt;
- Indirect CO_2 emissions and associated with power consumption 59Mt;

The chemicals sector roadmap towards 2050 (CEFIC, 2013) estimates the potential of CO_2 savings per technology in different scenarios. However, this roadmap is clearly predicated on emissions reductions arising from efficiency improvements primarily. It assumes a 2050 target where the sector needs to reduce emissions by 50%. Under this "level playing field" scenario, emissions reductions could be achieved as follows:

- Ambitious energy efficiency improvements, -35% from 2010;
- Changes in the fuel mix for heat generation used to meet the heat demand for chemical processes, i.e. further shift to natural gas or biomass, -10%;
- N_2O emission abatement, -10%;

This adds up to a 55% reduction compared to 2010. To go beyond this, fully decarbonised electricity generation (which seems achievable in a 2050 timeframe) is necessary, but more importantly CCS is required.

Energy efficiency improvements can only contribute to intermediate climate targets (about 35%). Alternative fuels can also reduce emissions, but this is limited by the amount of heat required in certain processes. Process emissions can also be reduced by improvements to catalytic reactors.

The chemicals sector roadmap identified important research areas with advanced biomass conversion processes, process improvements, and the utilisation of carbon dioxide as raw material (Carbon Capture and Utilisation, CCU). No quantitative estimates were made for the potential of CCU, which is still in very early stage of development (CEFIC 2013).

[13] Source: Figure 2-12 'Overview of GHG emissions from the European chemical industry in 2010' by Ecofys, quoted on p.19, CEFIC 2013.

A new roadmap for the chemicals industry (Bazzanella and Ausfelder 2017) examines key technologies (energy efficiency, the utilisation of alternative carbon feedstock (renewable raw materials (biomass) and CO_2) and low-carbon electricity-based processes) under four scenarios with different levels of ambition. The potential for CO_2 emission reductions is estimated up to 210MtCO_2 annually (representing virtually all of the sector's EU emissions) under the Maximum (Max) scenario followed by 101MtCO_2 annually under the Ambitious (Amb) scenario and 70MtCO_2 annually under the Intermediate (Interm) scenario.[14] If the production of the fuels is added, the CO_2 abatement potential will increase to 117MtCO_2 (Interm) and 216MtCO_2 (Amb) respectively (Bazzanella and Ausfelder 2017). Based on the quantification of the demands for the above technology options as well as the demand for investments, the industry regards the high production cost of the target building blocks (i.e. the key technologies) as a main hurdle. For research and innovation priorities, the chemicals industry identifies low-carbon hydrogen production, CO_2 utilisation, lignocellulosic biomass-use for chemical and biochemical synthesis and advanced concepts for waste heat recovery as important areas.

Certain chemicals can also be produced using hydrogen as a feedstock. These include chlorine, ammonia, methanol, olefins, and BTX. Together these chemicals are responsible for two thirds of the sector's GHG emissions (Dechema, 2017). This adds further arguments to scaling-up research in hydrogen applications, as hydrogen also is a technology that can decarbonise other major energy-intensive sectors.

Technology support should focus on CCS and hydrogen-based processes, which is important for additional deeper reductions beyond the more incremental improvements listed above. Equally important is the need to support research on CO_2 utilisation depending on the status of deployment[15] for different CO_2-based products.

[14] The Maximum scenario is based on 175% of BAU emissions, the Ambitious scenario on 84% of BAU emissions, and the Intermediate scenario on 59% of BAU emissions (Bazzanella and Ausfelder 2017).

[15] The status has been categorised into lab-scale, deployment, or commercial. See Figure 11, 'Target products of chemical CO_2 utilisation routes and status of deployment', (Bazzanella and Ausfelder 2017).

3.3 Non-ETS industry

Identification of key technologies and their potential significance is challenging in the non-ETS industry sector, as, unlike installations covered by the EU ETS, the absence of an installation-based reporting system makes reporting less transparent. However, some installations in EU ETS sectors might have been included in non-ETS emission statistics as their emissions are too low in number to be considered for the emissions trading scheme[16]. If they are nevertheless part of industries which normally have bigger installations (and are thus included in the EU ETS), innovations that benefit these ETS sectors will also help these smaller installations decarbonise. Where this is not the case, special attention should be given to these industries as they are together responsible for over a quarter of total EU industrial GHG emissions. 2% of these emissions are F-gases.[17]

The industry sector covered by the Effort Sharing Decision(ESD) is certainly made up of a large number of small and medium-sized enterprises (SMEs), which have particular characteristics, but also features larger companies which have thousands of employees but are less energy-intensive compared to the major industrial sectors reviewed above, such as those in the engineering and transport equipment sectors (AEA et al. 2012a, p1). These sectors include manufacturers of automobile/railway and associated infrastructure, wind turbines, power plants etc. Most importantly, they include technology providers.

There are three main types of industrial energy use in non-ETS industry (AEA et al. 2012a, p2):

- Industrial cross-cutting technologies (such as electric motors and electric motor systems: pumps, ventilation, compressed air, industrial steam generators etc.) which are used in many industrial branches;
- Cross-cutting technologies with specific branch characteristics (in particular industrial dryers and furnaces). These can be applied in different industrial branches but are not exactly identical and need to be adapted to the sector's specifications;
- Process technologies (e.g. chemical or metallurgical reactors, etc.) which are specifically adapted for a particular industrial branch.

As industry belonging to the field of ESD is a heterogeneous group of companies, policy instruments targeting at these different groups need to be tailored to address their specific barriers along the product cycle, as well as the barriers for other actors to the diffusion of low-carbon technologies (technology suppliers, intermediaries such as wholesalers etc.).

This sector is not presently given priority for technology support partly because energy efficiency improvements for SMEs are considered to be an important but incremental approach and partly because the technologies targeting at a specific industrial branch are

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[16] The EU ETS Directive sets a minimum threshold of 20 MW for installations in most sectors
[17]https://ec.europa.eu/clima/policies/f-gas_en

estimated to deliver smaller mitigation potential than those discussed in the ETS industry context. Since many technologies are cross-cutting, developments in larger industrial sectors can have beneficial impacts on non-ETS industries as well.

3.4 Buildings

GHG emissions from the buildings sector account for approximately 15% of total emissions in the EU in 2015 (EEA, Table 1). The vast majority of GHG emissions in the buildings sector are attributable to the heating of buildings. This includes both space heating (68% in 2014) and water heating. Energy (electricity) to power appliances is also normally included in the total energy use of buildings, but from an emission reduction perspective, this is already covered by the power sector itself. Energy for cooking and cooling make up the rest.

Heating of buildings can moreover be divided into two main categories: centralised district heating systems and decentralised systems with buildings having access to their own energy heating sources.

To reduce emissions from heat generation, the heat can be generated by renewable energy, or by reducing demand through better insulation and more energy efficient buildings. While the latter can go a long way in many places, only the former has the potential to ensure that zero-emissions are achieved in the sector, as completely passive buildings are not feasible under all circumstances.

While increased energy efficiency is essential to make low-carbon energy sources more cost-effective, it is the generation of heat that ultimately needs to become low-carbon if the building sector is to reduce its overall GHG emissions. Hence, innovation support should focus on making heat generation less carbon-intensive.

According to the IEA, progress on renewable heat is lagging behind (IEA, 2017). Any form of innovation support that could lead to significant cost reductions in solar heat, heat pumps, and district heating would help the buildings sector to decarbonise the energy use fully.

In the case of district heating, this implies replacing fossil fuel generation which currently provides heating. Given the scale requirements, biomass, for instance from waste incineration, is an obvious option that can make use of existing infrastructure. While waste incineration in combination with heat grids is mature, its potential might decrease in the future because of reduction of the production of non-biogenic waste. Centralised solar collectors or geothermal provide an alternative source of renewable heat.

For decentralised heating, a way to achieve zero-carbon heating is through heat pumps, which run on electricity and could thus be powered by renewables. This is an example of market coupling and would move buildings emissions to the power sector.

Renewable gas is an option that would allow the use of existing infrastructure both for centralised and decentralised heating systems (Pieblags & Olczak, 2018). Beyond biogas, syngas and power-to-gas (using hydrogen and synthetic methane) are options here, with the main constraint being the production of these gases at scale. With power-to-gas, an additional requirement is the concomitant production of hydrogen through electrolysis which adds significant electricity demand.

Many, if not all, of the technologies described here already exist. The challenge for renewable heating, therefore, isn't a question of developing new technology per se, but enabling its proliferation at scale. In the case of biomass, production at scale requires significant resources and landmass to grow relevant crops. In the case of heat pumps, if these are to be adopted at scale the electricity requirements (from renewables) are equally significant. This is a particularly acute issue in the case of peak demand during cold spells, when electricity demand for heating would be orders of magnitude higher than average demand, just as is the case already with gas demand during such periods.[18]

This is not to say that (radical) improvements in building envelopes are not required to reduce energy demand. In fact, more efficient buildings may be a necessary condition for the uptake of renewable heat generation, both from practical (installation) and economic perspectives, as energy demand from zero-carbon sources would otherwise grow by a too large extent.

The non-market barriers that such energy efficiency and insulation improvements face require policies beyond just innovation support. Nevertheless, the potential of reducing energy demand through improvements in building envelopes is highly significant. With far more efficient buildings, the residual energy needs can be met more easily.

Technology support in the 2008 – 2015 period has included various projects focused on the buildings sector, including building efficiency (estimated at 43 million euros), heat pumps (3 million) and CHP improvements. Eventually, however, the buildings sector will require heating and cooling sources that do not generate any emissions in the first place.

Technology support should focus on renewable heat technologies (Solar heat or Heat Pumps), but also in particular on the energy infrastructure required to produce renewable heat (such as through syngas) at scale. Additional innovations in buildings envelops may be required to enable higher uptake of such renewable heat technologies.

3.5 Transport

The transport sector as a whole is responsible for approximately 25% of total GHG emissions in the EU in 2015 (EEA, Table 1). GHG emissions arise from lightweight vehicles (cars and vans), heavy duty vehicles, maritime and aviation. Road transport makes up the majority of transport GHG emissions, with 15% (of total EU GHG

[18] https://www.bloomberg.com/news/articles/2018-03-01/cold-snap-triggering-gas-crisis-in-u-k-shows-rising-supply-risk

emissions) coming from cars and vans, and 6% from heavy-duty vehicles. The remaining emissions come from maritime (1%) and aviation (3%) (EU Transport GHG, 2011).

Much progress has been made in recent years with electric vehicles, while internal combustion engine (ICE) vehicles continue to improve their efficiency as well. However, compared to lightweight vehicles, heavy-duty vehicles receive far less attention, in spite of such vehicles being responsible for a significant chunk of GHG emissions.

All modes of transportation mentioned here contribute significantly to total EU GHG emissions, although maritime emissions are by far the smallest. While light-duty vehicles are the biggest contributor, heavy-duty vehicles and aviation both contribute in about as many emissions as major industrial sectors such as steel and cement. As such, all of these transportation modes should receive attention in the context of a 95% target.

In the case of vehicles, both batteries for electric vehicles and fuel cells enable a 100% reduction in GHG emissions in theory, provided that the electricity and hydrogen are produced in a zero-carbon way. While electric vehicles have so far more focussed on lightweight vehicles, the technology could also be applied to heavy-duty vehicles as the energy density of batteries continues to improve. The same goes for heavy-duty vehicles, where hydrogen and fuel cells are being investigated as a long-term solution, but hydrogen could also be used to power regular cars as well.

The road transport sector has indeed already been the beneficiary of public financial support. Initially, this support was tilted towards biofuels, but after 2011 such funding disappeared, likely reflecting concerns of the impact of biofuel production on land-use and food security. Nevertheless, of all technologies supported, biofuels remain the biggest individual category supported in the 2008-2014 period. Electric vehicles themselves, are the second biggest, with 136 million (only 1 million less than biofuels). Furthermore, fuel cells in combination with hydrogen have also received slightly over 100 million in support though various projects.

For aviation, biofuels would be a primary way to enable emissions reductions in the sector. Hydrogen also provides a (currently unproven at scale) potential alternative (Yilmaz & Tarhan, 2012). While there have also been investigations into electricity-powered aircraft, the ranges would limit the applicability to shorter range flights.[19] Long-haul flights powered by something other than fuels seem well out of reach before 2050. While improvements in battery technology may yet benefit potential electric aircraft, biofuels would enable emissions reductions across all ranges of air travel. Biofuel production comes with its own set of challenges related to potentials, land use and land-use change, but innovation support could focus on those advanced biofuels for which sustainability concerns are minimised as much as possible.

[19] https://www.economist.com/science-and-technology/2017/11/30/small-hybrid-electric-airliners-ready-for-take-off

This leaves the maritime transport sector, which at 1% of total EU GHG emissions represents a small but not insignificant share of total emissions. While some radical solutions have been proposed, such as small-scale nuclear propulsion, or using wind (kite-sails) or solar power, most (if not all[20]) technologies are aimed at increasing efficiency. In the absence of technologies that would clearly enable zero-emission shipping, efficiency improvements seem advisable. Technologies that are investigated in other sectors, such as hydrogen, biofuels and batteries could create positive spill-overs for maritime transport as well, and increased efficiency would help with the uptake of such solutions then. Marine propulsion research is estimated at 11 million euros in financial support over the 2008-2014 period (source: CARISMA 3.1 data).

For the transport sector, a range of technologies should be further supported so that all modes of transport are covered. For lightweight transport this should be batteries for electric vehicles. For heavy-duty vehicles, hydrogen and fuel cells may be more suitable. There may also be positive spill-overs between light- and heavyweight vehicle technologies. For low-carbon aviation, biofuels would aid emissions reductions for all types of flights, while battery technology also has the potential to enable shorter range electric aircraft.

3.6 Agriculture

The agricultural sector accounts for approximately 10% of total GHG emissions. In contrast to other sectors of the economy, CO_2 emissions from energy use do not play a major role; it is rather other sources and greenhouse gases that account for the vast majority of emissions in this sector.

GHG emissions from agriculture are dominated by two sources[21]:

- N_2O from agricultural soils (use of fertilisers) (51%)
- CH_4 from livestock (31%)

Though the vast majority of agricultural GHG emissions do not come from CO_2, but from other greenhouse gases, the importance of agriculture in attaining food security[22], has led to the sector being less subject to stringent climate policies up to the adoption of the Paris Agreement (CGIAR, 2016). The Paris Agreement still makes reference to the importance of food production but nevertheless, “all sectors of the economy” are covered by the Paris Agreement. Current agricultural sector GHG emissions would wholly consume (and exceed) the annual remaining post-2050 carbon budget under a 95%

[20] https://cleantechnica.com/2017/12/02/china-launches-worlds-first-electric-cargo-ship-will-use-haul-coal/
[21] http://ec.europa.eu/eurostat/statistics-explained/index.php/Agriculture_-_greenhouse_gas_emission_statistics
[22] Article 2(1b) of the Paris Agreement highlights the importance of food production, and that low GHG emissions development should not threaten it

target (which would be roughly 280 Mt CO2e). Therefore, there is an increasing attention to climate-smart agriculture[23].

Since large-scale technological breakthroughs cannot yet be foreseen (with the exceptions of Bio-energy and CCS – or BECCS[24] – which is outside the scope of this document), GHG emissions reductions in the agricultural sector require a focus on the incremental efficiency improvements, as well as demand reduction (e.g. through artificial meats), in contrast to the other sectors reviewed in this document. This is an inherent consequence of the manner in which emissions arise in the sector, even if it is dominated by two major sources.

Technology support should focus on technologies or practices that would reduce emissions in these subsectors. Increased efficiency of fertiliser use, and demand reduction both in the case of fertiliser use and livestock can contribute to intermediate climate goals but does not in itself enable deeper decarbonisation. To go beyond incremental improvements, a move towards BECCS would be required.

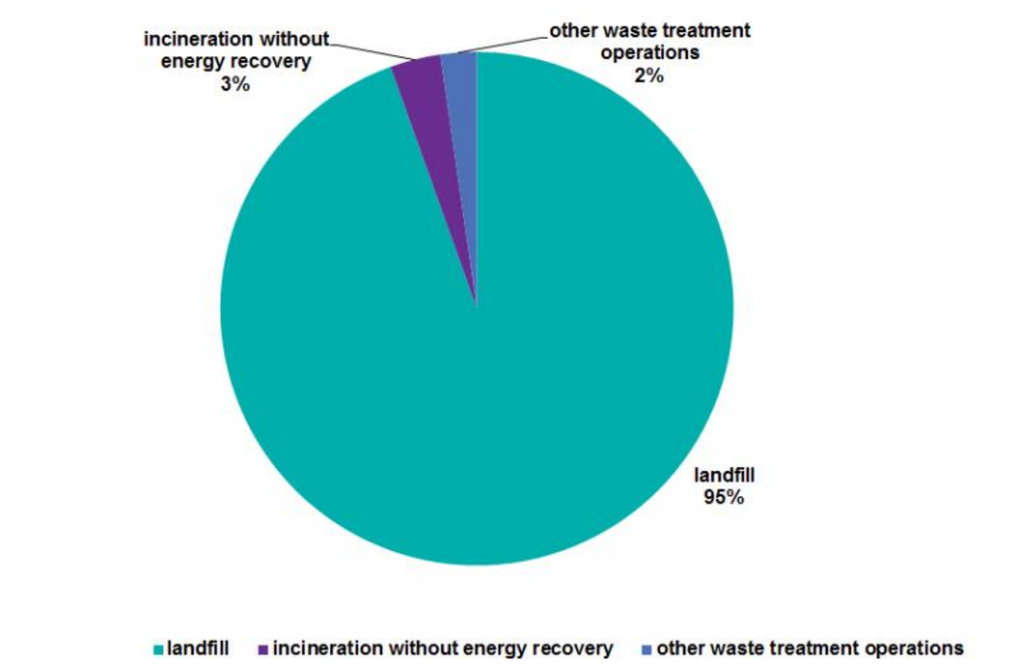
3.7 Waste

The waste sector accounts for approximately 3% of total GHG emissions in the EU in 2015 (EEA, Table 1). The waste sector should also receive innovation support but has not received this so far other than through projects aimed at creating biofuels from waste (source: CARISMA D3.1 data). Three percent of total GHG emissions represents a significant enough share (comparable to the chemical industry) to warrant more attention.

Figure 1 presents the estimated proportions of GHG emissions from the three types of disposal/treatment operation in 2011 and shows that 95 % of the GHG emissions from waste management come from the landfill sector, while the other two types of operation contribute only 5 %. Energy recovery is not included, as it is statistically attributed to the energy sector emissions.

Figure 2: Estimated share of the three waste disposal operations in GHG emissions (2011)

[23] https://ec.europa.eu/clima/news/climate-smart-agriculture-and-forestry-projects-help-turn-eu-policies-action_en
[24] See EP study, p.4 http://www.europarl.europa.eu/RegData/etudes/BRIE/2015/559498/EPRS_BRI(2015)559498_EN.pdf



Source: EEA Greenhouse gas data viewer, March 2014

It is therefore reasonable to focus on reducing emissions from landfills, while also focusing on replacing them with technologies to recycle or dispose of waste with low emission solutions.

Technology support should focus on reducing the need for landfills, through waste reduction and improvements in recycling and waste-to-energy. Lining remaining land-fills would allow up to 90% GHG emission reductions[25]

[25] http://www.ghgonline.org/methanelandfill.htm

4 Concluding remarks

This document aims to give an overview of what kind of technologies, with current information, are projected to enable emissions reductions compatible with ambitious long-term (2050) EU targets of 95% or more. Such an approach inevitably requires a focus on those technologies that, in theory, have the highest technical potential. As such, it seeks to move beyond efficiency improvements, which may be more economically efficient for shorter time horizons. In a hypothetical scenario where all the technologies in this report would be developed, ambitious mid-century climate targets would be achievable.

When compared to what technologies have been funded in the 2008-2014 period, it becomes evident that industrial sectors in particular have not seen significant levels of public innovation support, even if just under one third of total EU GHG emissions can be attributed to industry in some way. What's more, due to the high number of heterogeneous sectors in industry, emissions arise due to vastly different production processes. This increases the number of technologies that need to be developed for deep decarbonisation scenarios. Having said that, there are a number of cross-cutting technologies, that could benefit multiple industrial sectors and, in some cases, sectors outside of industry as well. These technologies include CCS, hydrogen and syngas for example.

Beyond pure technological potential, there are myriad economic factors affecting whether certain technologies can be brought to the market in a time frame that is desirable from a climate policy point of view. Additionally, even if they can be brought to the market, it is still necessary that they can compete with more carbon-intensive alternatives already available. Another element that should factor into prioritisation decisions is that of sequencing: are there technologies that need to be developed first because other technologies depend on them? Some technologies require the availability of other technologies before they can be deployed at scale, such as abundant renewable electricity for hydrogen production based on electrolysis. In some cases, certain technologies (or markets based on these technologies) need to develop first before other technologies can proliferate.

The technologies mentioned, and summarised at the beginning of this document, should be seen in light of potential policies and programmes that aim to provide public support for innovation and research and development. A concrete example is the Innovation Fund under the EU ETS for the 2021-2030 period, which will be expressly targeted at industrial innovation, and consist of about half a billion ETS allowances to be monetised. More generally, the successor to the Horizon 2020 programme, as well as any Research, Development and Innovation elements of the next Multi-annual Financial Framework of the EU, would be relevant as well to enable support for technological innovation projects. Finally, EU member states have the autonomy to decide how to spend revenues raised by auctioning EU ETS allowances. This may become more pertinent in light of the increasingly higher share of industrial GHG emissions as a share of total emissions.

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