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## A green COVID-19 recovery of the EU basic materials sector: Identifying potentials, barriers and policy solutions

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## Discussion Papers

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#### IMPRESSUM

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# A green COVID-19 recovery of the EU basic materials sector: identifying potentials, barriers and policy solutions<sup>1</sup>

Olga Chiappinelli<sup>1\*</sup>, Timo Gerres<sup>2</sup>, Karsten Neuhoff<sup>1</sup>, Frederik Lettow<sup>1</sup>, Heleen de Coninck<sup>3,4</sup>, Balázs Felsmann<sup>5</sup>, Eugénie Joltreau<sup>6</sup>, Gauri Khandekar<sup>7</sup>, Pedro Linares<sup>2</sup>, Jörn Richstein<sup>1</sup>, Aleksander Śniegocki<sup>8</sup>, Jan Stede<sup>1</sup>, Tomas Wyns<sup>7</sup>, Cornelis Zandt<sup>9</sup>, Lars Zetterberg<sup>10</sup>

**Abstract:** This paper explores which climate-friendly projects could be part of the COVID-19 recovery while jump-starting the transition of the European basic materials industry. Findings from a literature review on technology options in advanced development stages for climate-friendly production and enhanced sorting and recycling of steel, cement, aluminium and plastics are combined with insights from interviews with 31 European industry stakeholders about the practical and economic feasibility of these technology options. Results indicate that with an estimated investment of 28.9 billion Euro, about 20% of EU's basic materials could be produced through low-emission processes or additional recycling by 2025 with technologies that are commercially available or at pilot scale today. However, our stakeholder consultation also shows that in order to make these short-term investments viable in the long term, six main barriers need to be addressed, namely i) the lack of effective and predictable carbon pricing, ii) the limited availability of affordable green electricity, iii) the lack of a regulatory framework for circularity, iv) low technology readiness and funding, v) the lack of infrastructure for hydrogen, CO<sub>2</sub> and power, and vi) the lack of demand for climate-friendly and recycled materials. Based on these insights, the paper proposes elements of a policy package that can create a long-term framework favourable for investments in these technologies and should ideally accompany the recovery package to give credibility to investors that the business case will last beyond the recovery timeframe.

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<sup>1</sup> This paper extends the analysis contained in the report by Neuhoff et al. "Investments in climate-friendly materials to strengthen the recovery package", Climate Strategies Report, June 2020

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## **Key policy insights**

1. Technologies for climate-friendly materials production, sorting and recycling can be supported as part of the recovery package, but require a long-term policy framework
2. Combining continued free allocation with a Climate Contribution within the EU ETS can ensure economic viability of climate-friendly materials
3. Project-based Carbon Contracts for Difference can eliminate carbon price uncertainty for climate-friendly processes
4. Auctions for publicly backed Contracts for Difference and Power Purchasing Agreements can guarantee the availability of low-emission electricity at stable prices
5. Green public procurement and public-private partnerships can provide infrastructure for hydrogen, CO<sub>2</sub> and power supply
6. A revision of regulations on product design and end-of-life emissions can improve incentives for enhanced sorting and recycling.

**Keywords:** Green COVID-19 Recovery; Industrial Decarbonisation; Policy Package; EU Green Deal; Technology Readiness.

# 1 Introduction

In response to the 2020 COVID-19 health crisis, the European Union and its member states are launching a wide range of economic stimulus measures. These recovery packages should not only achieve the short-term objective of boosting the economy and creating jobs, but additionally deliver climate and long-term economic benefits [1]. Supporting climate-friendly investments in the basic material sector can have the potential to be a key element of the recovery package. However, this is challenging as it would require public funding to fulfil three conditions [2]: first, to *target* novel production processes, sorting and recycling technologies, to trigger investments with high economic returns. Second, the implementation of many of the projects needs to be *timely*, meaning that technologies are “shovel-ready”, i.e., in an advanced development stage. Lastly, recovery support needs to be *temporary*, i.e. sufficient to leverage private investments to replace public funding after the recovery timeframe. This means that the regulatory environment must provide long-term incentives and risk-hedging instruments, which ensures that business cases for new investments are robust beyond the recovery package.

At a first glance, the characteristics of the basic material sector do not seem to be a good fit for a timely and temporary recovery policy. Production processes are technologically mature and highly standardized, while process equipment is capital intensive and has a long design life of 15 to 50 years [3]. Energy consumption is a key cost component, ranging from 24% of the gross operating surplus in refineries to 79% in the steel industry, making basic material production (steel, cement, chemicals, and aluminium) highly emission intensive, accounting for 57% of all emissions covered by the European Emission Trading System EU ETS [4]. Furthermore, basic materials are internationally traded commodities with little differentiation in product characteristics, which makes it difficult to develop business cases for competitive climate-friendly production processes with increased capital and operational expenditures [5].

The high emissions of basic materials have brought this sector in the spotlight of policymakers. Long-term net-zero emissions objectives within the EU require a deep transformation of the basic material production until 2050 and have triggered industrial stakeholders to increase R&D and envision climate-friendly sectoral strategies [6]–[9]. The recovery package represents an opportunity for climate-friendly investments to ensure that the EU basic materials sector is on track to reach the climate targets.

In this context, this paper explores whether and to which extent low-emission options are shovel-ready, such that investments in these technologies could become a part of the recovery while jump-starting the transition of the European basic materials industry. The focus is solely on options with high technological readiness that are available for near-time implementation. Options identified in the literature are compared to stakeholder feedback about practical and economic feasibility and the potential scale of investment costs is quantified. For this purpose, we conducted 31 interviews with industrial experts about climate-friendly production process alternatives, enhanced sorting and recycling and the barriers hindering their deployment in the steel, cement, aluminium, and plastics industry. We then review elements of a policy package, which could help to overcome these barriers. Some policies are suitable to be included in the recovery package while others could accompany it to establish a robust investments framework beyond the recovery timeframe. Our analysis thereby enhances the currently limited scientific knowledge on opportunities and barriers about the near-term implementation of low-emission technologies in the basic material sector.

Unlike previous studies, e.g. on the Dutch concrete sector [10] and chemical industry [11] or the German industry [12], this work analyses the multinational cross-sectorial dimension of industrial transition, taking into consideration technological barriers and the industrial stakeholder perspective to evaluate feasible policy actions in response to the COVID-19 pandemic and beyond.

The paper is structured as follows: Section 2 describes the methodologies adopted for the analysis. Section 3 identifies technology options, which could be supported through the recovery package. Section 4 discusses perceived barriers to investments in these technologies. Section 5 identifies the policy needs based on the findings in section 3 and 4.

## 2 Methods

We conducted 31 semi-structured interviews with industry experts across 6 European countries, i.e., Germany, Netherlands, Belgium, Spain, Hungary, and Poland (see Table 1 in Annex 9.1 for categorization of interviews). The interviews were conducted by phone or video-call from 11th of May until 23rd of September 2020. Using a standardized questionnaire (Annex 9.1), we asked our interviewees about the most promising climate-friendly technology options for the transition of their sector, how their accelerated deployment could contribute to an economic recovery and what barriers they see for their implementation. Interviews were conducted in the national language of the interviewee, recorded, transcribed or summarised, and upon request sent to interviewees for review. Coding of all interviews was implemented by one researcher, based on an English translation of a summarized version of the transcripts. The researcher then peer-reviewed results together with the researchers conducting the interviews. To respect confidentiality, this paper does not refer to individual interviews.

Section 3 compares findings from these interviews with information provided in the literature about available technologies options, focusing on the best available processes used commercially, today, and compares them with low-emission process and recycling alternatives with high technological readiness level (TRL)<sup>2</sup> and options mentioned by interviewees. Existing reviews focus primarily on technology options for deep decarbonisation [13], [14]. Advancements in material efficiency and improved repair and reuse are beyond the scope of this analysis. The technical feasibility and investment costs of adjacent new infrastructure, e.g. for the supply of hydrogen or CO<sub>2</sub> transport, is out of the scope of this analysis. Nevertheless, the access to such infrastructures is analysed as a possible barrier for technological implementation.

Interviewees were asked an open question on perceived barriers. For the analysis in Section 4 the barriers were ranked in a stepwise approach. First, barriers were categorized by identifying similar responses across interviewees. Second, an interviewee-specific ranking of barriers was determined based on the emphasis on specific barriers, whether it was mentioned first or only later on, how often it was mentioned and how important it was regarded to be. Third, the share of interviewees that mentioned a specific barrier as one of the main three was determined for each category. The

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<sup>2</sup> TRL as used by the European Commission (Annex G of the General Annexes to the EC Work Programme 2016/17), ranging from TRL 1 – basic principle observed to TRL 9 –actual system proven in operational environment. This review focuses on technologies of TRL 6 –technology demonstrated in relevant environment, and higher.

final ranking reflects how often the respective barrier was one of the three main barriers for the interviewees.

### **3 Technology options for investment through the recovery package**

Investments in the basic material sector need to be *timely* if included in the economic recovery package. This limits the support to those technology options which are or can be commercially available within the next years. In the following we present a techno-economic overview of the best available processes in use on commercial scale, today, and compare them with climate-friendly process and recycling alternatives with high TRL. Special emphasis is placed on their energy consumption since all basic materials production processes have in common that fossil fuels and feedstock is the main operation cost driver.

#### **3.1 Steel**

Primary steel is produced by reducing iron ore with coal in blast furnaces–basic oxygen furnaces (BF-BOF). Modern installations require about 16.7 GJ/t, of which 95% is thermal energy [15] with on average 1.9 tCO<sub>2</sub> emitted per ton of steel slab in Europe [16]. Steel recycling, which accounted for 40% of EU production in 2018 [17], is about 75% less energy and emission intensive [15]. While smelting in electric arc furnaces (EAF) is electrified, natural gas is normally used for hot rolling processes. Primary steel can also be produced in EAFs when combined with direct reduction of iron ore with natural gas (DRI-EAF). This technology is commercially available with only small capacities in operation in the EU, but widely used in regions with access to cheap natural gas (Iran, Russia, and Saudi Arabia) [18], [19].

Adopting and advancing direct reduction processes, so that hydrogen could be used instead of natural gas, is the most advanced decarbonisation option for primary steel. While energy demand might increase slightly compared to DRI with natural gas, the use of hydrogen could reduce the emission intensity to less than 0.4 tCO<sub>2</sub> per ton of steel [20], [21]. While the process using purely hydrogen is still in pilot phase (TRL = 5) [22] and the most advanced European project HYBRIT produces 1 t/hour [23], some interviewees stated that a transitional approach using both natural gas and hydrogen is feasible [20], [24]. One technology provider suggested that already 2-8 Mt of such DRI capacity could be added per year from 2021 onwards, but that installation projects of at least 28-30 months could delay the technology implementation. Recent literature estimates investment costs for hydrogen-based DRI-EAF could be at 574 € per ton of annual capacity including hydrogen electrolysis [25]. Interviewees stated costs for such integrated sites to be closer to 900 € per ton, more than double the greenfield construction of new BF-BOF plants. Access to low-cost climate-friendly hydrogen is the principal operational cost uncertainty.

Some interviewees would prefer financing for efficiency measures and carbon capture and storage (CCS) applied to existing processes until long-term solutions are fully developed and cost competitive. Top gas recycling (BF-BOF+TGR) could help to reduce emissions by 60% [26], [27] and coal could be partially substituted with climate-friendly hydrogen or biomass [28]. Although the emission reduction potential of these options is limited [29], some interviewees consider a



combination of these options as efficient for reducing emissions on the short term and where green hydrogen is unavailable, even when considering concerns about biomass availability and social acceptance of onshore geological storage of carbon dioxide [30]. Over the next years investments in these options are considered likely, but public support directed towards these areas should not preclude the required shift towards carbon neutral production technologies.

Enhanced recycling of steel has been mentioned by two interviewees. The availability of scrap is projected to grow significantly reflecting the increased construction and manufacturing volumes in recent decades [31]. A major barrier for more recycling is steel alloys with elements like nickel and chrome, used to improve the physical characteristics of steel. Additionally, steel scrap is contaminated, for example with residual copper from wires. Consequently, scrap is usually downcycled to lower quality steel. Today, sorting processes for end-of-life products to separate scrap into different alloys are not sufficiently used [31]. Better technologies for sorting, separating, or processing scrap may be able to mitigate this issue, but need additional financial support [32]. Indirect emissions of EAFs could be reduced by contracting low-emission electricity.

## 3.2 Cement

With an annual production of 179.8 Mt (2018), cement is the most produced basic material in Europe [33]. Highly standardized multistage dry kiln designs account for almost all EU production. The clinkering process requires temperatures of more than 1400°C and best practice installations have a thermal energy demand of 2.8 GJ/t [15], resulting in fuel and process-based emissions of about 0.67 tCO<sub>2</sub> per ton of cement [34]. Various energy sources can be used, like petroleum coke, coal, natural gas, domestic waste, non-toxic industrial waste, or biomass. Since energy consumption is the main cost driver for cement making, sourcing differs substantially in EU member states and is driven by the local availability and cost [35]. Most emissions from cement production originate from calcination of limestone in the kiln, which means that deep decarbonisation cannot be achieved by only switching to low-emission fuels [36].

Short-term improvements in the cement industry are based on using more biomass and waste, low-carbon clinker, and additives to substitute clinker [7]. All these options can be realized with today's kiln technology and do not require major investments. Interviewees highlighted that the development of alternative binders, e.g. Celitement [37], is promising, but still in early development phases. Increasing the biomass share is difficult due to the quality of available bio-based feedstock, since dust, nitrogen oxides (NO<sub>x</sub>) and sulphur dioxide (SO<sub>2</sub>) emissions are to be avoided [34]. Carbon capture will be needed to reduce emissions further and major pilots are in operation or planned in Europe [22]. Interviewees confirmed that end-of-pipe measures, such as amine scrubbing (MEA), require an investment of about 76 million Euros per plant of 1 Mt/a capacity [38], which could potentially be combined with direct solidification of CO<sub>2</sub> using residual concrete [39]. This is significantly cheaper than the investment needed for the LEILAC pilot project, which can capture 95% of process related emissions with a new calciner design without significantly increasing the energy demand [40]. Oxyfuel combustion is another technology which has been implemented in industrial pilots and could be installed during major refurbishment campaigns [41]. Energy consumption increases slightly, but remains significantly lower than for MEA, making it one of the most economic capture alternatives [38]. Interviewees highlighted that capture technologies are ready for implementation, but the usage of captured emissions is one of the main

barriers for implementation. Some applications of CO<sub>2</sub> as feedstock are explored in the chemical industry, but its suitability to produce synthetic e-fuels is limited since fossil emissions would be released to atmosphere during the subsequent combustion of e-fuels. Furthermore, storage options continue to face high uncertainties regarding cost and social acceptance [42].

Secondary production of cement by recycling construction waste remains negligible and residuals are used in landfills or as filling material for new construction sites [43]. Recovered cementitious materials could be re-used and, with current best practices, up to 30% of limestone feed could be replaced [44]. One interviewee indicated that enhanced sorting solutions are available and could be implemented in about 25% of Germany's stationary recycling sites at investment costs of 0.5-10 M€ per plant by 2025, making such solutions a potentially cost competitive alternative to primary production. Innovative separation processes include the SmartCrusher, which was implemented in an industrial scale pilot in 2013 and could recover higher shares of clinker from construction waste [45], thereby replacing some primary cement production [44].

### 3.3 Chemicals

The chemical industry is a multifaceted sector with a wide range of different process routes and final products. However, most emissions are caused by processing fossil hydrocarbons. About 60% of direct and indirect emissions are linked to steam cracking and distillation of ethane and naphtha into its derivatives (ethylene, propylene, and other aromatics). Natural gas conversion to ammonia and methanol (via hydrogen) is responsible for another 10% of emissions, while the remaining emissions are related to process heat provision [9].

According to the IEA [46], best available technology for naphtha steam cracking between 750-950°C requires 13.6 GJ/t of thermal energy, of which 1.4 GJ/t can be recovered as process steam. In case of ethylene, building block for polymers and exemplary for other high value chemicals (HVC), an estimated 1.26 tCO<sub>2</sub>/t of product are released [47]. Ammonia and methanol are produced by combining catalytic steam reforming with high pressure reactions. During this process, natural gas is used to obtain hydrogen. Best available technologies for ammonia production are slightly less energy intensive allowing for a net energy consumption of 9.0 GJ/t [46]. Based on study data from Dutch ammonia plants, emission intensity is assumed to be 1.90 tCO<sub>2</sub>/t of product and due to the relatively pure CO<sub>2</sub> waste streams 60% of it can be captured without significant additional investments [48].

Interviewees opted for technology options which would allow the production of high value chemicals without steam cracking. Methanol-to-olefin (MtO) technologies have been implemented on commercial scale to produce fuels from natural gas via methanol [49] and could also be used to produce olefins from bio-based feedstock [50]. The main barrier for the introduction of this technology is the availability of low-emission methanol, produced from biomass or climate-friendly hydrogen and captured CO<sub>2</sub> [51]. Relative installation costs per ton of product for the MtO process is expected to be comparable to ammonia plants [46]. Current pilot projects, such as Carbon2Chem [52] and Carbon4PUR [53] focus on the use of captured industrial CO<sub>2</sub> emissions as feedstock for high value chemicals.

Plastic causes about 4 tCO<sub>2</sub> emissions per ton of final product, while on average 0.5 tCO<sub>2</sub> per ton is released when incinerated at the end of its life [54]. Although close to 30% of plastic waste is

collected for recycling in the EU, recycled plastics only account for about 6% of today's material use in Europe [55]. The main barrier for increasing recycling rates and thereby reducing the demand of primary chemical production is the ability to sort and decompose polymers into different components.

Interviewees stated that improved mechanical recycling of plastic debris is technologically feasible but requires investments in state-of-the-art facilities with improved sensor-based sorting capabilities. According to literature, such installations consume between 2.7 and 4.6 GJ/t of mostly electric energy and are available for 400-700 €/t of capacity [56]. Interviewees envisaged that by mechanical recycling 50-75% of packaging waste can be recovered. This is equivalent to 30%-50% of all plastic waste in the EU [55], [57].

Mechanical recycling is a well-known and cost-effective but challenging for composite materials and raises concern of thermal-mechanical degradation [68]. By means of chemical recycling molecules can be deconstructed into their initial components, which can be re-fed as feedstock into the primary production route. Different process alternatives exist. Pyrolysis is commercially available but requires pre-sorting of recycling streams. Hydrocracking is less feedstock sensitive, but still under development and requires external hydrogen supply [58]. According to interviewees about 50M€ per plant with an annual capacity between 20.000 and 30.000 t is needed, making the technology more expensive than mechanical recycling. Commercial installations are currently under construction [59] or in advanced piloting or realization phase [60]. The interviewees pointed to the emergence of a healthy competition between mechanical and different chemical recycling approaches. This expectation is also stated in the literature [61].

Enzymatic biorecycling is another option mentioned by interviewees. This technology is being researched but not available at commercial scale, yet [62]. Like chemical recycling, depolymerization can be achieved. The advantages over chemical solutions are that process temperatures are relatively low and no organic solvents are used [63].

### **3.4 Aluminium**

The production of aluminium is the most energy intensive process of the industries under investigation. Best available commercial processes consume about 65.5 GJ/t of aluminium, plus an additional 14 GJ/t if carbon-based anodes are seen as an energy source [64]. Aluminium is produced from Bauxite with Alumina as an intermediate product. Thermal energy used to refine Bauxite to Alumina is commonly supplied by using natural gas but it can be electrified, given the low temperatures of the Bayer process (180°C) [65]. Alumina is processed to aluminium via electrolysis, making aluminium production highly electricity intensive (46.5 GJ/t). Carbon anode consumption is the main source of emissions, so that even in case of decarbonized electricity supply, emissions of about 3-4 tCO<sub>2</sub> per ton of aluminium remain [18], [66].

Emissions can be limited by using carbon-free anodes, which would avoid (direct) CO<sub>2</sub> emissions during aluminium smelting. So far, industrial-scale demonstration projects have not been implemented [67], though interviewees mentioned that a joint-venture of Rio Tinto and Alcoa plans to commercialize carbon-free electrodes using the ELYSIS technology by 2024 [68]. Another producer stated that this technology might not be market-ready until 2030 and expects that research and development costs for reaching TRL 8 will require funding of 50 to 100 M€.

Optimized electrolysis technologies, which reduce energy demand by 15% have been implemented on an industrial scale in a Norwegian plant [69].

Primary production accounts for less than 25% of EU aluminium production [66]. For secondary production, the distinction must be made between the recycling of “new scrap” and “old scrap”. Resmelting of relatively pure industrial aluminium scrap consumes 1.4 GJ/t and emits 0.15 tCO<sub>2</sub>/t of product. Recycling of composites and the wide range of alloying elements in processed aluminium require pre-treatment and often limit secondary production to downcycling, resulting in higher energy consumption (2.2 GJ/t) and emission intensity (0.25 tCO<sub>2</sub>/t). One interviewee stated that the cost for a new large scale recycling facility is about 270 M€, which roughly corresponds to the cost of a state-of-the-art facility that entered operation in Germany in 2014 [70]. Smaller specialized modular designs are available off-the-shelf from different technology providers [71].

Recycling is limited by the availability and purity of scrap. While between 90-95% of aluminium in automotive and buildings is recovered for recycling, more significant potential for increased recycling exists for packaging and beverage cans with current recycling rates of 60% and 75%, respectively [66], [72]. The availability of post-consumer scrap is expected to grow significantly as increased per capita consumption over the past decades will be available in form of scrap. A significantly higher share of demand could be covered by recycled materials, but public support might be needed for the implementation of enhanced sorting technologies (e.g. Laser-Induced Breakdown Spectroscopy (LIBS), X-ray fluorescence spectroscopy, 3D detection) [31].

### **3.5 Investment needs for climate-friendly materials**

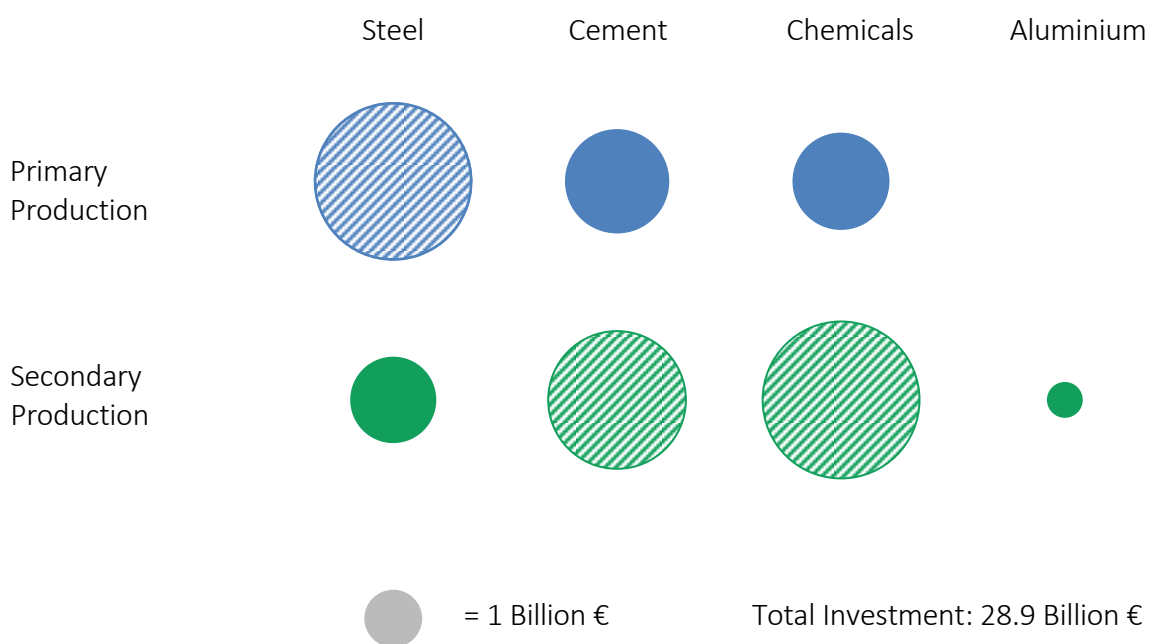
The review of alternatives for currently used primary production processes shows that alternative, climate-friendly technologies exist for all basic materials. Support for possibly shovel-ready alternative process technologies can help to kick-start the transition of the basic materials sector, even though operation of these alternatives might rely on non-renewable energy and feedstock during the first years of operation, given that adjacent technology and infrastructure are not available yet (e.g. climate-friendly hydrogen or carbon transport and storage). The improvement and optimization of recycling technologies shows great potential for the intensification of secondary production routes and reducing the need for emission- and energy-intensive primary production. Except for the cement sector, recycling processes are well-established, but the purity of waste streams needs to be improved to increase circularity and avoid downcycling.

Figure 1 summarizes investment needs in Europe if approximately 10 % of today’s primary production (base year: 2018) is replaced by low-emission technologies and an additional 5 to 10% of primary production (base year: 2018) is replaced by enhanced sorting and recycling options mentioned in this section until 2025.<sup>3</sup>

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<sup>3</sup> Data and methodology used for this estimation is detailed in Annexes 9.2 and 9.3.

Figure 1: Estimation of investment volumes until 2025 to replace existing production with new climate-friendly production processes (primary production and recycling, relative to 2018 data). Cost data based on literature or (indicated as cross-hatched) estimates from interviewees.

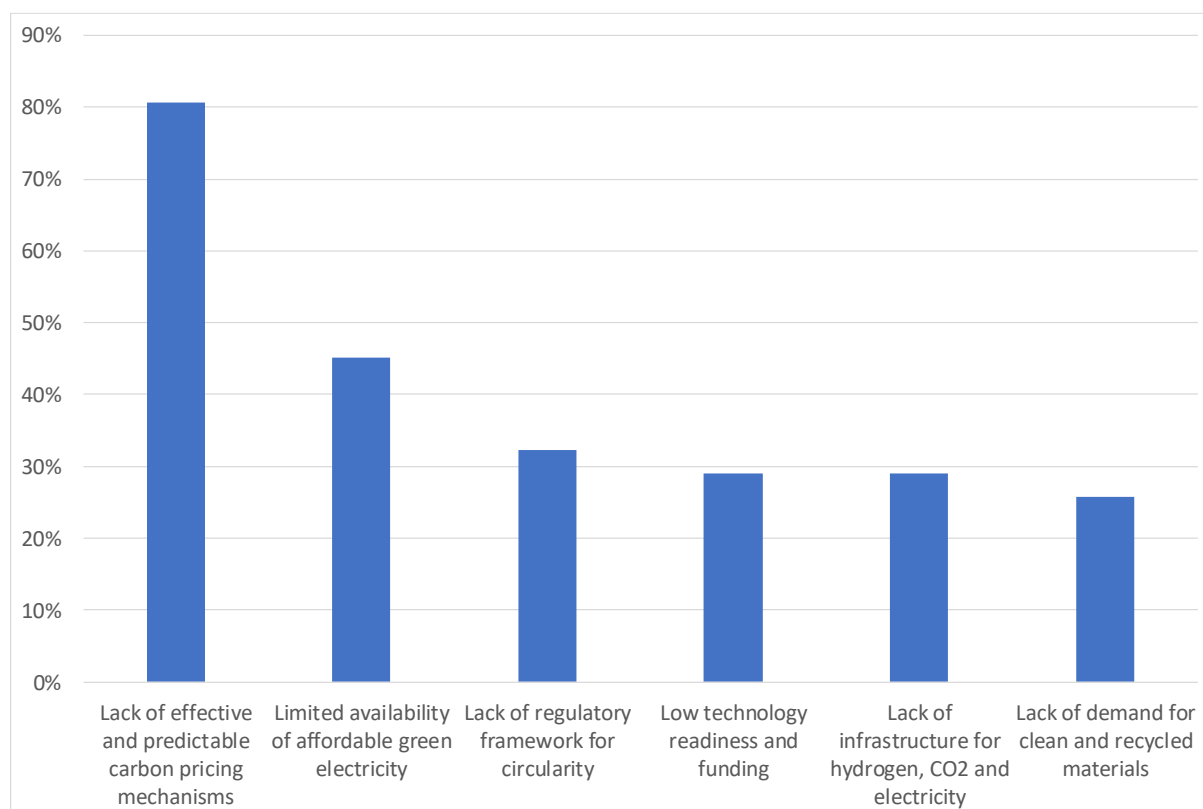


	Capacity replacements by <b>new low-emission primary processes</b> relative to 2018 production		Capacity additions <b>new low-emission secondary processes</b> relative to 2018 production	
Steel	10%	replaces EU primary production	10%	replaces EU primary production
Cement	10%	replaces EU primary production retrofitted	5%	replaces EU primary production
Chemicals	10%	replaces EU primary ethylene production	10%	of EU plastic demand met with recycling (additionally)
	20%	CCS retrofit for ammonia production		
Aluminium			10%	additional EU secondary production

## 4 Investment barriers

The previous section has identified a set of technology options for climate-friendly production, enhanced sorting and recycling processes that can be supported as part of the recovery package. However, the interviews disclosed that barriers for implementing these technologies exist. Six main barriers were identified and ranked in order of importance, as visualized in Figure 2 and presented in the following.

Figure 2: Ranking of barriers based on interviewee responses



### 4.1 Lack of effective and predictable carbon pricing mechanisms

A major barrier for four out of five of the interviewees was that climate-friendly options are not competitive with conventional technologies due to ineffectiveness and uncertainty of current carbon pricing mechanisms. Interviewees, especially from the steel industry, stated that elevated and stable carbon prices are crucial for investing in technologies with long design life, while operating using hydrogen or other low emission energy feedstock and energy carrier. In case of carbon capture, elevated carbon prices are needed to recover both investment and operational costs of the technology.

The confidence of investors is limited that the carbon price will reach a level which compensates for the additional costs of clean production processes. In this context, carbon leakage concerns were emphasized by almost two thirds of the interviewees. Increasing carbon prices and declining

levels of free allowance allocation could cause an asymmetric cost increase for EU producers. Economic survival of the domestic industry could be prioritized over a more stringent EU ETS cap, lowering the credibility of high carbon prices. Due to the ongoing free allowance allocation only a small and uncertain share of EU ETS carbon costs is passed on into the supply chain with a negligible impact on end-consumer prices [73]. As a result, only limited incentives for material efficiency, material substitution and use of recycled materials are created over the value chain.

Furthermore, uncertainty regarding future carbon prices is considered to be a major project risk, which increases the option value of current assets and incentivizes to postpone investment decisions and wait for regulatory changes [74].

## **4.2 Limited availability of affordable green electricity**

Almost half of the interviewees stated that the limited access to cheap low-emission electricity is a major barrier for the deployment of climate-friendly material production processes. As most of the latter imply a switch from fossil energy carriers to electricity, companies would be more exposed to electricity price uncertainty. Electricity markets are expected to be more volatile due to increasing shares of intermittent solar and wind generation [75], while long term renewable power purchase agreements (PPA) require contractual stipulations addressing supply volatility of renewables [76]. A lack of predictability of future prices for low-carbon electricity contributes to uncertainty about the operational costs of low-carbon technologies and additional project risk.

## **4.3 Lack of regulatory framework for circularity**

One third of interviewees highlighted the lack of a policy framework to support circularity. One issue is the missing focus on lifecycle emissions of basic materials, which is perceived as an important barrier for the competitiveness of enhanced sorting and recycling. Some interviewees stated that insufficient accounting of emissions from the incineration of plastic waste hinders investments in enhanced sorting and recycling. In case of cement, one interviewee indicated that the lack of effective landfill fees for construction waste disincentives increased sorting and recycling efforts.

Some interviewees considered the regulatory framework for the use of biomass and captured industrial CO<sub>2</sub> to be underdeveloped. Others, and in particular all interviewed sorting and recycling companies emphasized barriers for closed-loop recycling, mentioning that the feasibility of the latter declines with an increasing variety of composites, alloys and additives [55]. Current regulation, such as the Ecodesign Directive (2009/125/EC), and in-service collection systems were considered insufficient to provide a sufficiently homogenous content and consistent quality of recoverable materials within waste streams. Interviewees also mentioned a lack of coordination between recyclers and potential consumers regarding standards and quality requirements for recycled materials.

#### **4.4 Low technology readiness and funding**

Almost one third of all interviewees and the majority of those from the chemical industry indicated that climate-friendly technologies have not reached the technology readiness level for investment in large-scale pilots or commercial projects. Some interviewees mentioned difficulties in scaling up alternative processes. While individual components and sub-processes might have a high TRL, process integration has not been done on industrial scale, so far, which results in a significant project risk and possible cost driver.

Sizeable funding is required to bring innovation from market readiness to industrial scale implementation [77], but so far few public funding options exist at national and EU level. Private firms are reluctant to invest if the break-even period for profitability is highly uncertain, the investment volumes are relatively large, process integration has not been done before, patents offer limited protection and profitable lead-markets for green commodities are not available. Failure of construction projects represents a major risk for private sector companies, as can be observed for investments in the latest generation of nuclear power plants in the US and France [78], [79]. Additionally, the current crisis creates uncertainty about the timeline and scale of the recovery, forcing companies to reduce expenditures, including innovation funding.

#### **4.5 Lack of infrastructure for hydrogen, CO<sub>2</sub> and electricity**

Almost one third of interviewees referred to the unavailability of transport infrastructure for hydrogen, power and CO<sub>2</sub> as a major barrier. The transition towards climate-friendly basic materials is perceived as a classic "chicken and egg" problem. Without certainty about the development of the needed infrastructure, companies will not invest in changing processes.

#### **4.6 Lack of demand for clean and recycled materials**

Similarly, as mentioned by about one quarter of the interviewees, including all those active in sorting and recycling, without sufficient demand for climate-friendly products, there are scarce investment incentives for climate-friendly production processes and enhanced sorting and recycling [55].



## 5 How to unlock investments with a recovery package?

The previous sections highlighted that barriers of technological, economic, and regulatory nature hinder investments in climate-friendly technologies. In this section we present the elements of a policy package that could help overcoming these barriers. Only policies with a temporary nature could be implemented as part of the recovery package. Other policies are needed to ensure a long-term framework favourable for investments in these technologies and should ideally accompany the recovery package to give credibility to investors that the business case will last beyond the recovery timeframe.

### 5.1 Ensuring effective and predictable carbon pricing

The most important perceived barrier by interviewees is the lack of an effective and stable carbon pricing mechanism that ensures the long-term competitiveness of climate-friendly production and closed-loop recycling both domestically and abroad. This can be addressed by the following policies that should accompany the recovery package.

#### 5.1.1 Full carbon cost internalization and carbon leakage protection

For climate-friendly production processes to be cost-competitive, a carbon pricing mechanism is needed that meets two main requirements. First, it should be robust to carbon leakage risk, so that carbon price levels can credibly reach the level of incremental costs of climate-friendly production processes. Second, the carbon cost of conventional processes needs to be reflected in product prices so that consumers of materials pay for emissions and climate-friendly producers can recover incremental decarbonisation costs. Full carbon cost internalization along the value chain is needed to create the full incentives for climate-friendly options [73].

Past reforms of the EU ETS reduced the level of free allocation to cut emissions while securing carbon leakage protection by awarding free allowances. Achieving these two objectives with one instrument alone has not been possible [80]. A new reform of the EU ETS is urgent, and one of the priorities of the new European Commission. Two options are currently being discussed [81]:

*A trade-based approach* would introduce border carbon adjustments (BCAs) to address carbon leakage risks in combination with a shift to full auctioning of emission allowances to achieve full carbon cost internalization. A variety of design options exist for the implementation. BCAs could only cover imports, which might trigger concerns for export-oriented industries since they would face higher costs than their international competitors. Continued free allocation for export-oriented industries could, in turn, result in a limited carbon cost pass-through and persistent regulatory uncertainty. As a border-related approach, it may also trigger international retaliations and challenges under WTO [82]. Alternatively, a symmetric BCA could reimburse the carbon costs for goods exported to other jurisdictions, thereby providing a better carbon leakage protection for the domestic industry without continued free allocation. The implementation would require a high level of international coordination with WTO-type agreements to secure robustness to appeals by individual countries.

*A consumption-based approach*, by adding a Climate Contribution to the EU ETS, might be more suitable in the short term to create the necessary investment framework [83]. Benchmark-based

free allowance allocation for the industry would be continued, but combined with a Climate Contribution, i.e. an excise charge on basic materials and material-intensive end-products (e.g., cars). Such extra charge would be passed along the value chain and paid upon final consumption (regardless whether produced domestically or abroad). The charge would be tied to the weight of the material at the same benchmark used for free allowance allocation. Such approach would combine full carbon leakage protection with an effective carbon price signal to all actors along the value chain. Building on experiences with other consumption charges, a WTO-compatible and administratively feasible implementation is viable in the short-term [84].

### **5.1.2 Hedging against carbon price uncertainty**

Regulatory risks, and in particular carbon price uncertainty, are perceived investment barriers. Carbon Contracts for Differences (CCfDs) issued by governmental financial institutions can help investors in climate-friendly production and recycling processes to hedge against regulatory and carbon market risks, thereby covering increased operational costs of climate-friendly processes [85]. Based on a contractually agreed strike price for emission reductions relative to benchmark emissions from reference technologies, investors are guaranteed a fixed revenue per ton of non-emitted CO<sub>2</sub>. As long as EU ETS prices are below the strike price, the difference between strike price and market price is reimbursed. If CO<sub>2</sub> prices exceed the strike price investors must return additional earnings to avoid windfall profits. Besides improving the financial security of climate-friendly investments, CCfDs reduce financing costs and companies are incentivized to not delay investments until EU ETS prices stabilize at higher level. CCfDs may reduce the need for public funding since government expenditures might be partially or fully recuperated if CO<sub>2</sub> prices rise [86].

## **5.2 Securing availability of affordable green electricity**

The lack of sufficient affordable green electricity is a major barrier and points to the importance of a continued policy focus on renewable deployment also as part of a recovery strategy. Public auctions for renewable Contracts for Differences (CfDs) are an option to eliminate regulatory uncertainties and allow project developers to secure low-cost financing and thus reduce power generation costs. With lower electricity costs, lower carbon price levels are required for climate-friendly technologies for basic materials production to compete with conventional ones [25]. Auctions for public renewable CfDs or for publicly backed Power Purchasing Agreements (PPAs) also help to accelerate investments in wind and solar energy by eliminating the option value of delaying investments due to electricity market uncertainties [87]. This is particularly relevant during the recovery period with increased demand uncertainty and declining credit rating of signing parties in private PPAs.

## **5.3 Increasing regulatory focus on circularity**

Closing the loop and upcycling waste streams require targeted policy measures that should be implemented together with the recovery package. First, feedstock availability for recycling processes could be improved by pricing the carbon emissions of waste incineration and disposal as landfill, creating incentives for implementing enhanced sorting technologies. An Advanced

Disposal Fee on materials could ensure the internalization of such cost. This fee could be partially returned in case of closed-loop recycling, thereby changing material choices within the production and packaging industry as well as increase recycling efforts for plastic [88].

Second, existing environmental legislation like the Ecodesign Directive (2009/125/EC) needs to be revised and aligned with policy objectives of closed-loop recycling and enhanced repair and reuse. This encompasses tighter rules on product lifetime, reparability, and material use. By homologizing material use for certain applications, e.g. alloys used for beverage cans, sorting can be facilitated, while avoiding downcycling. In case of plastic packaging the use and need of additives should be carefully re-evaluated to ensure that functionality does not come at the expenses of further recyclability [55]. To be effective, these measures need to be aligned with clearly defined recycling targets as well as transparent metrics for tracking material streams within the recycling loop.

## **5.4 Reaching technology readiness**

Recovery package funding, 750 billion Euros proposed by the EU Commission for the period from 2021 to 2024<sup>4</sup>, could support firms in unblocking investments in near-market ready technologies and first-of-a-kind industrial implementation. At the EU level, the budget increase of the Investment Plan by 30 billion Euros could be suited to support larger-scale demonstration plants and first-of-its-kind projects with high technological readiness, but without any experience in their industrial scale implementation and operation. Funds can therefore also be directed to the digitalization of sorting and recycling plants, which would allow for a better monitoring and optimization of material flows. The increased budget of Horizon Europe by 13 billion Euros could be used for bringing technologies towards market readiness, which are currently in pilot phase, possibly in combination with member states funding windows (including as part of the Recovery and Resilience Facility and Just Transition Fund).<sup>5</sup>

In order to help low-emission technologies overcome the valley of death and, at the same time, allow for a timely implementation of projects, regulatory hurdles such as complex requirements and lengthy approval processes need to be addressed via a coordinated effort by relevant regulatory bodies [89].

## **5.5 Providing infrastructure**

Countering the “chicken-and-egg” problem which holds back the climate transition requires sufficient infrastructure to be put in place to meet the potential demand for climate-friendly options. Large-scale infrastructure projects could possibly be developed in Public-Private Partnerships [90]. Commissioning and financing these projects as part of the national and EU recovery packages (e.g. through the enhanced Just Transition Mechanism [91]) and ensuring a low carbon footprint of projects would not only create jobs and demand for climate-friendly materials but also give a credible signal to investors.

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<sup>4</sup>European Parliament resolution of 23 July 2020 on the conclusions of the extraordinary European Council meeting of 17-21 July 2020 (2020/2732(RSP))

<sup>5</sup> The majority of the EU recovery funding will be dedicated to the Recovery and Resilience Facility (560 billion Euros) and made available to member states which can determine the allocation of these funds with their national recovery and resilience plans.

## 5.6 Creating demand for climate-friendly and recycled material

As carbon prices will only increase gradually, it is important to create short-term demand and lead markets for climate-friendly and recycled materials already as part of the recovery strategy.

*Labels* can nudge climate-aware private consumers into low-carbon choices [92]. *Standards* on product design can also play an important role to enhance demand of climate-friendly options [93]. However, so far most European labelling and standardization requirements are not aligned with climate goals, since their focus lies primarily on safety and functionality rather than environmental considerations [94]. A timely revision of product design regulation as discussed in Section 5.3 can support enhanced recycling as part of a climate-friendly recovery strategy.

*Quotas* may oblige companies to use an increasing share of recycled materials (recyclates) in their production processes. This could help to address uncertainty about future demand for services from sorting and recycling companies, which is seen as a main barrier by interviewees (Section 4.6). Quotas have already been adopted for recycled content in plastic beverage bottles by Directive (EU) 2019/904 and additional recycling requirements are envisaged for other plastic packaging, construction materials and vehicles [95]. At the same time, some companies have already committed to such quotas on a voluntary basis ( see e.g. [96]).

*Green Public Procurement* practices that take into account the carbon footprint of products can allow governments and other public bodies to leverage their purchasing decisions to create demand for climate-friendly and recycled materials and incentivize material efficiency in product design, construction and manufacturing [97]. This can be of high relevance for a green recovery. Not just infrastructure projects, but also measures to reduce the impact of climate change, such as coastal protection, are often material- and labour-intensive. Procuring these projects under the recovery package could boost the economy and the demand for low-carbon and recycled materials. The same applies for climate-friendly private or public-private construction projects, such as wind farms and recycling plants, or the transport infrastructure for hydrogen, power and CO<sub>2</sub>, which, as mentioned, are potentially in the scope of the recovery package.

## 6 Discussion on research methodology

The research presented in this work is of timely relevance in light of the COVID-19 recovery and bridges the latest academic contributions with insights from industrial stakeholders. Nevertheless due to the timely nature, our analysis is subject to some limitations.

First, the geographic spread of interviews was not balanced, with about half of interviewees based in Germany. This implies that the analysis cannot reflect relevant cross-country differences, e.g. with regard to availability of carbon storage options or low-cost renewable electricity, which to some extent emerged from the interviews. As such, results might be biased towards the German context and perspective.

Second, slightly different interview approaches were adopted by different research teams in different countries. Despite the coding being peer-reviewed with the researchers conducting the interviews, fully uniform information handling across interviews in different countries cannot be guaranteed.

Third, many of the interviewees did not answer the questions concerning expected investments until 2025 and relative costs. Therefore, the quantification of costs relies primarily on figures reported in literature and only partially on information provided by interviewees, as detailed in Annexes 9.2 and 9.3. Thus, the economic figures stated should be considered rough estimates.

These issues shall be addressed in a follow-up analysis. A repetition of the survey involving a larger and more uniform sample size per country could allow to reflect country-specific characteristics across the EU. In addition, an interview design more tailored to extract information on investment potential and costs might allow to improve the robustness and comprehensiveness of the quantification exercise. Updated cost figures should additionally include required infrastructure investments which, while excluded from the current analysis, are seen as an important area of recovery funding. Nevertheless, current results do identify the most important areas of sector-specific funding needs for the basic material sector and can therefore provide valuable insights for both academia and policy makers to further detail, the design of targeted – recovery and post-recovery - policy measures.

## **7 Conclusion**

The EU recovery package in response to the COVID-19 health crisis represents a unique opportunity for investments in a climate-friendly transition of the EU basic materials to reach Paris targets.

Based on interviews with industrial experts across Europe, this paper has identified a portfolio of technologies for climate-friendly materials production, sorting and recycling that are shovel-ready within the time frame relevant for the recovery package.

However, clearly defined economic and regulatory barriers currently hinder the deployment of such technologies. Recovery funding by itself will not be effective and needs to be complemented with policies that address these barriers and thus also ensure the business cases for new investments is robust beyond the recovery period. This work highlights elements of such a policy package.

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## 9 Annex

### 9.1 Interviews

We are considering the additional investment volume that climate neutral technologies in the basic material sectors could contribute to a recovery package. We have seen in recent years that there is a great dynamic in the development of these technologies in your sector and various options are being discussed.

- Which technologies would you think are ready for demonstration plants and could soon start playing a role in decarbonising your sector?
- For which of these technologies do you see a greater investment potential in the short term (within the next 5 years)?
- If we were to focus on the technologies that are at demonstration level, is there a risk that we ignore more promising options that are still in development or at pilot stage?

In the course of the Corona crisis, an economic stimulus package is being discussed and many actors are pushing for it to become a green stimulus package.

- Do you think that this stimulus package could help to support the implementation of investments in climate-friendly technologies in your sector?
- What challenges do you see currently in implementing climate-friendly technologies in your sector?
- What contribution could be made by the public/government side to solving the respective challenges?

Let's assume a scenario in which there is a broad public support to address these challenges, so among others a stimulus package provides support for investments into climate friendly technologies.

- How many plants could be invested in by 2030 (company level, national, EU)?
- What proportion of this could be implemented by 2025?
- Have expectations regarding investment costs developed relative to literature values?

In the past, one obstacle that was mentioned for the implementation of new technologies was bottlenecks in machinery and plant construction. It was argued that capacities to build these plants are limited in the short term.

- Do you agree with the assessment that this will be less the case as a result of the crisis?
- Which plant manufacturers do you see as central for your sector and for the technologies discussed?

Table 1: Categorization of interviewees by industry, type of company and country

<b>Number of interviewees by</b>	
<b>Industry</b>	
Steel	9
Cement	5
Chemicals	12
Aluminium	2
Sorting and recycling	3
<b>Type of company</b>	
Material producer	20
Technology provider	6
Other (e.g. associations)	5
<b>Country</b>	
Belgium	6
Germany	14
Hungary	2
Netherlands	3
Poland	2
Spain	3
United Kingdom	1
<b>Total</b>	<b>31</b>

## 9.2 Overview of reviewed technologies

Table 2: Technology options for the steel industry with advanced TRL.

	BF-BOF (BAT)		DRI-EAF (NG) (BAT)		DRI-EAF (H <sub>2</sub> )		BF-BOF+ TGR (CCS)		EAF BAT	
Production	Primary						Secondary			
TRL	9	Source: [16]	9	Source: [16]	5-6	Source: [22]	5-6	Source: [22]	9	Source: [16]
Energy Demand (GJ/t of crude steel)										
Total	16.7	[15]	13.0	[98]	12.5	[25]	15.6	[26]	4.3	[15]
Electric	0.8	[15]	2.5	[98]	> 10.6	[25], [98]	1.2	[26]	1.8	[15]
Thermal	15.9	[15]	10.5	[98]	< 1.9	[98]	14.4	[26]	2.5	[15]
Emissions (t/t of crude steel)										
CO <sub>2</sub>	1.89	[16]	0.63 -1.15	[21]	0.05 - 0.15	[24]	0.75 - 0.85	[26], [27]	0.46	[15]
Investments (€2018/t of annual capacity crude steel)										
Greenfield	491	[16]	460	[16]	418* 744*	[25] interviews	566	[21]	210	[98]
Retrofit	189	[16]								
Current EU production (MT / year of final product)										
Crude Steel	100.4	[17]	0.7	[17]	0.008	[23] HYBRIT Pilot	0.001	[99] ULCOS BF Pilot	67.4	[17]
Main barriers					Hydrogen availability		Carbon utilization		Scrap purity & alloys	

\*without H<sub>2</sub> electrolysis



Table 3: Technology options for the cement industry with advanced TRL (clinker/ cement ratio of 73.7%).

	Kiln BAT Multistage		Kiln BAT Multistage +80 % Coprocessing		CC-MEA		CC-Direct		CC-Oxy		Cement Crusher	
Production	Primary						Secondary					
TRL	9	Source: [34]	9	Source: [34], [35]	6 - 9	Source: [27]	5-6	Source: [22], [100]	6	Source: [22]	3-6	[45], [101]
Energy Demand (GJ/t of cement)												
Total	2.7	[38]	2.8	[34], [35]	5.2	[38]	4.2	[40]	3.1	[38]	0.04	[45]
Electric	0.3	[38]	0.3	[34], [35]	0.7	[38]	1.9	[22], [40]	0.7	[38]	0.04	[45]
Thermal	2.3	[38]	2.5	[34], [35]	4.6	[38]	2.3	[40]	2.3	[38]		
Emissions (t/t of cement)												
CO <sub>2</sub>	.67	[34]	0.47*	[34]	0.24	[38]	< 0.15	[22]	0.12	[38]	0	[101]
Investments (€2018/t of annual capacity cement production)												
Greenfield	199	[102]	No additional investments if BAT kiln		280	[103] interview confirmed			332	[103] interviews confirmed	630	Based on interviews no specific technology mentioned
Retrofit	174	[102]			76	[103] interview confirmed	Low, but for LEILAC Pilot: 250	[40]	174	[103] interviews confirmed		
Current EU production (MT / year of final product)												
Cement	179.8 with 41% co-processing rate		[33]	0.0016 NORCEM Pilot	[104]	0.08 LEILAC Pilot	[40]	0.02 CEMCAP Pilot	[105]	0.16 2013 Pilot	[45]	
Main barriers			* availability of carbon neutral (bio)waste	Carbon utilization						Scrap purity & recovered material quality		

Table 4: Technology options for the chemical industry with advanced TLR.

	Naphtha Cracking BAT		Methanol-to-X (MtO / MtA)		Mechanical Recycling BAT		Chemical Recycling (Pyrolysis)		Ammonia Production BAT (+CCS**/***)		H <sub>2</sub> to Ammonia Synthesis	
Production	Primary				Secondary				Primary			
TRL	9	Source: [46]	(MtO) 9 (MtA) 6	Source: [46]	9	Source: [56]	9	Source: [46]	9	Source: [46]	9	Source: [46]
Energy Demand (GJ/tC <sub>2</sub> H <sub>4</sub> )			(/t olefins / aromatics)		(/t of processed recycle)				(/t of ammonia)			
Total	12.0	[46]	9.5	[46]	2.7-4.6	[56]	1.8	[106], [107]	9.0 9.5** 11.2***	[46] [48] [48]	1.4	[46]
Electric	0.3	[46]	0.2	[46]	1.7-3.6	[56]	1.6	[106], [107]	0.3 + 0.5** + 0.3***	[46] [48] [48]	0.0	[46]
Thermal	13.1	[46]	11.4	[46]	1.0	[56]	0.2	[106], [107]	13.5 + 0** + 1.9***	[46] [48] [48]	1.4	[46]
Steam	-1.4	[46]	-2.1	[46]					-4.8	[46]		
Emissions (t/tC <sub>2</sub> H <sub>4</sub> )			(/t olefins / aromatics)		(/t of processed recycle)				(/t of ammonia)			
CO <sub>2</sub>	1.14	[108]	0*		based on steam source		0.14	[109]	1.90 0.09** 0.59***	[48] [48] [48]	0*	
Investments (€2018/t of annual capacity)												
Greenfield	1796	[46]	970 1330	[46] Interviews (MtO)	400-700	[56]	800 1.5k-2.5k	[59] Interviews	1796 + 43** + 283***	[46] [48] [48]	97 910	[46], [110] [46], [111] incl. H <sub>2</sub> production
Current EU production (MT / year of final product)												
Ethylene	19.8	[112]	pilots with carbon capture	[52], [53] Carbon4PUR and Carbon2Chem								
Plastics					2.9 (EU consumption of recycled plastics 2016)		[55]					
Ammonia									19.8		[113]	
Main barriers			Hydrogen availability to obtain low emission process feedstock		Recyclate purity / sorting efforts				Carbon utilization		Low-emission Hydrogen availability for Haber-Bosch Process	

\*emission intensities based on theoretical best case and require availability of climate-friendly green hydrogen and captured CO<sub>2</sub>.

\*\*/\*\* Additional energy demand and investment cost to fully reduce process\*\* and additional fuel based emissions by 98%\*\*\* by CCS for BAT ammonia production routes.

Table 5: Technology options for the aluminium industry with advanced TLR.

	BAT Bauxite to Aluminium		BAT New AL Scrap Resmelter		BAT Old AL Scrap Refiner	
Production	Primary		Secondary			
TRL	9	Source: [64], [114]	9	Source: [115]	9	Source: [115]
Energy Demand (GJ/t aluminium)						
Total	65.5 (79.5)*	[64], [114]	1.4	[115]	2.2	[115]
Electric	46.5	[64], [114]	0.1	[115]	0.2	[115]
Thermal	19.0 (+ 14.0)*	[64], [114]	1.3	[115]	2.0	[115]
Emissions (t/t of aluminium)						
CO <sub>2</sub>	3.50 4.5 EU mix	[18], [64], [66]	0.15 - 0.35	[115]	0.25 - 0.39	[115]
Investments (€2018/t of annual capacity)						
Greenfield	4200	[114]	970 1330	[46] Interviews (MtO)	400-700	[56]
Retrofit	720 (smelter)	[115]	364 – 520			[70], [71]
Current EU production (MT / year of aluminium)						
Aluminium	2.2	[18], [66]	3.9	[66], [116]	3.1	[66], [116]
Main barriers	Electricity price		Recyclate purity / sorting efforts			

\*values in brackets if anode consumption is considered as fuel

### **9.3 Detailed methodology for quantification of investment scale**

Figure 1 represents an estimation of investment volumes until 2025 to replace existing production with new low-emission production processes. The initial premise of the evaluation is a 20 % switch in production but based on the status of existing technologies assumptions slightly differ for each of the sectors. The provision of adjacent infrastructure, such as the hydrogen supply and both transport and storage of captured carbon emissions have been excluded. As consequence, cost estimations are significantly lower than numbers stated in literature.

#### **Steel**

Production data for the primary production in the EU is based on the statistics of the World Steel Association 2019 with an annual production volume of 101.1 Mt in the year 2018. Assuming an investment cost of 744 €/t (Table 2)<sup>6</sup> for primary production based on interviews, the replacement of 10% of the current production capacity is equivalent to 10.1 Mt of low emission primary steelmaking capacity with a total investment cost of 7,522 M€ if electrolyser costs are excluded from stated values by interviewees.

In case of secondary production, already accounting for 67.4 Mt of EU production in 2018, it is assumed that an additional 10% of primary production could be replaced with secondary production, meaning that secondary production would increase by 15%. Basis of this assumption is that secondary production processes are already well established so that this increase of production will be realized by the extension of existing production facilities and potential capacity additions of electric arc furnaces at an investment cost of 210 €/t annual capacity. An increased deployment of improved sorting technologies for steel at recycling sites may need to complement the extension of EAF capacities in order to enhance the potential for recycling of scrap and prevent downcycling.

As a result, 20% of the EU primary steel production in the year 2018 would be low-emission steel making by 2025.

#### **Cement**

In case of cement production, carbon capture solutions can be installed as retrofit. As such, it is assumed that 10% of the existing facilities could be equipped with carbon capture technology by 2025. The assumed investment cost of 128 € per tonne of annual clinker capacity, which corresponds to 174 €/t of cement capacity (Table 3) is based on Voldsund et al. (2019) for the oxyfuel technology and was validated through interviews. These costs, though, do not reflect any additional investments in infrastructure for carbon storage or carbon usage technologies.

Given that as of today, cement recycling rates are negligible it is assumed that only 5% of today's primary production could be replaced by recyclates by 2025. The investment cost of 630 € per

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<sup>6</sup> The assumed investment cost is based on the cost of 900 €/t for an integrated hydrogen direct reduction plant stated by interviewees minus the expected investment cost for the electrolyser of 156 €/t.

tonne of capacity is based on statements by interview partners and represents a preliminary estimate.

As a result, 15% of the 2018 cement production would be produced with low-emission processes by 2025.

## Chemicals

Two main products are studied to represent the chemical sector: ethylene and ammonia. In case of ethylene, building block for plastics, EU production in 2018 was 19.8 Mt. Based on interviews investment costs for a switch towards MtO/MtA technologies requires investments of 1330 € per tonne of annual capacity (Table 4). In case of ammonia, literature expects low-emission synthesis including climate-friendly hydrogen production to have similar installation costs compared to existing installations based on steam methane reforming, since hydrogen production technology has been excluded from this review only the investment cost for ammonia synthesis remain. Alternatively CCS for process exhaust stream for ammonia production can be implemented at relatively low costs.

Increased recycling of plastics is the key driver for secondary production in the chemical industry. Currently recycled material accounts for 6% of the 49 Mt of total annual plastic in the EE. For this evaluation, it is assumed that an additional 10% of the plastic demand could be covered by recycled plastics, which means that the share of recycled content in total plastic use increases to 16%. Investment costs are assumed to be 1500 €/t capacity based on interviews.

As a result, 20% of primary production of ethylene and ammonia production would be produced by low emission processes by 2025, while the quantity of recycled plastics increases from 2.9 Mt to 7.8 Mt per year.

## Aluminium

In case of aluminium, secondary production already accounts for the major share of EU production (6.975 Mt/a in 2018) (Table 5). Given the limited potential for changes in primary production in the short-term, investments would aim to increase secondary production by 10% or 0.7 Mt per year. Given that total production remains constant this represents 30% of today's domestic primary production. Investment costs of 500 €/t of annual capacity based on literature are assumed, resulting in a total investment of 349 M€.

As a result, 10% of additional secondary aluminium production could replace 30% of current primary production by 2025.

*Table 6: Investment scale estimation for primary production*

	EU Production in 2018	Capacity replacements with new production processes	Investment costs in technology options (€/t annual capacity)	Total investments until 2025 (Million €)
Steel	101.1	10%	744	7,522
Cement	179.8	10%	174	3,129
Ethylene	19.8	10%	1330	2,635
Ammonia	16.8	20%	43	163

Table 7: Investment scale estimation for secondary production

	EU Production in 2018	Capacity additions with new production processes	Investment costs in technology options (€/t annual capacity)	Total investments until 2025 (Million €)
Steel	67.4	10%	210.0	2,123
Cement	-	5%	630.0	5,664
Plastics	49 Mt plastic demand of which 6% is from recycled feedstock	additional 10% of today's demand covered by recycling	1500	7,350
Aluminium	7.0	10%	500	349

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