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Perspective

Assessing the potential of decarbonization options for industrial sectors

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SUMMARY

Industry emits around a quarter of global greenhouse gas (GHG) emissions. This paper presents the first comprehensive review to identify the main decarbonization options for this sector and their abatement potentials. First, we identify the important GHG emitting processes and establish a global average baseline for their current emissions intensity and energy use. We then quantify the energy and emissions reduction potential of the most significant abatement options, as well as their technology readiness level (TRL). We find that energy-intensive industries have a range of decarbonization technologies available with medium to high TRLs, and mature options also exist for decarbonizing low-temperature heat across a wide range of industrial sectors. However, electrification and novel process change options to reduce emissions from high-temperature and sector-specific processes have much lower TRLs in comparison. We conclude by highlighting important barriers to the deployment of industrial decarbonization options and identifying future research, development, and demonstration needs.

CONTEXT & SCALE

The industrial sector accounts for 38% and 25% of global final energy consumption and direct CO_2 emissions, respectively. To enable the design of comprehensive and evidence-based industrial decarbonization strategies, this paper assesses the technical potential of emission and energy savings of the most important abatement options for a wide range of industrial sectors and in a consistent way.

The results show that the decarbonization of industrial sectors is likely to require a combination of bespoke technologies that rely on electrification, fuel switching to hydrogen and biomass, carbon capture and storage (CCS) technologies, novel processes, and resources and energy efficiency options. Technologies with medium to high maturity (6–9 technology readiness level [TRL]) that involve CCS or fuel switching to hydrogen or biomass can save nearly 85% of emissions on average in most industrial sectors. Low-maturity electric technologies can theoretically decarbonize from 40% to 100% of direct sectoral emissions including from energy-intensive processes. Further research, development, and demonstration is therefore needed for low- and medium-maturity technologies

INTRODUCTION

Industrial products such as steel, chemicals, and cement are widely used across the global economy. The demand for, and production of, these materials has increased significantly over recent decades, leading to high energy consumption and greenhouse gas (GHG) emissions.[1] In 2022, the industrial sector (excluding refining) accounted for 38% and 25% of global final energy consumption and direct CO_2 emissions, respectively.[2] However, global industrial emissions will need to be almost eliminated to meet the Paris Agreement targets.[3] For instance, in the latest International Energy Agency (IEA) net-zero scenario, industrial combustion and process-related CO_2 emissions fall to near zero by 2050[4].

Decarbonizing industry is a significant challenge due to the heterogeneous range of processes and products meaning that decarbonization options are often sector and process specific.[5,6] These factors, combined with long investment cycles, high energy use, low profit margins, and trade exposure have led to the sector being characterized as "hard-to-abate."[7] However, with many countries adopting net-zero targets for GHG emissions, there is renewed focus on the technological and other options that can be used to decarbonize industry, with particular focus on large, energy-intensive sectors such as iron, steel, and cement.[8] Consequently, a number of countries and regions have been developing strategies, plans, and roadmaps for decarbonizing their industries, such as those seen for the United States, the European Union, and the United Kingdom.[9–11]

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However, focusing on the largest and most energy-intensive sectors will not enable countries to reduce industrial emissions sufficiently to be in line with their climate targets. For instance, in the UK, only around 50% of industrial emissions are from large, energy-intensive industrial clusters, with the remaining 50% arising from a wide range of sectors and sites that are dispersed across the country.[12] In the United States, up to 50% of industrial emissions are from sectors not covered by the current roadmap.[10]

accompanied by large-scale infrastructure development to accelerate the decarbonization of industrial sectors.

To enable the design of comprehensive, evidence-based, industrial decarbonization strategies and plans, it is vital to assess the potential emission and energy savings of the most important abatement options for a wide range of industrial sectors and in a consistent way. However, such a wide-ranging and inclusive assessment is currently missing from the literature.

Existing research has examined the potential of different options to decarbonize global industrial sectors, but with several limitations. Some studies[3,13] report emissions reductions for abatement options in a sector without being clear about the processes that are used as a baseline for the calculations, or they report aggregated emission savings on a sectoral level, without attributing these savings to particular processes.[14] Other studies explore the decarbonization options for a limited number of often energy-intensive sectors only,[15–19] report the potential of just one or two decarbonization options,[20,21] or the results are country and/or region specific.[22–24]

This paper fills a gap in the literature by providing the first extensive and consistent technical assessment of the emissions and energy saving options that can be used to decarbonize many industrial sectors. We calculate these savings at a sector level relative to the energy and emissions performance of a baseline commodity production route that is characterized using global average data where available. This provides a clear and consistent understanding of the contribution of mitigation options to industrial decarbonization efforts.

METHODS

We first categorize the industrial sector into 10 subsectors based on the relevant division, group, and class numbers of the International Standard Industrial Classification of All Economic Activities (ISIC) as shown in Table 1.[25] The disaggregation of the sectors allow more effective representation of the industrial sector for modelers and decision makers since the decarbonization options are usually process and sector specific.

For each sector in Table 1, we illustrate the production route of its commodities with specific energy and emission intensities to define the sector's system boundary and to serve as a baseline for comparison with alternative low-carbon routes. The most popular production route in a particular sector is considered; for instance, the blast furnace (BF)—basic oxygen furnace (BOF) route is used for iron and steel manufacturing. We focus on direct scope 1 emissions for all sectors except aluminum by assuming processes that use electricity will be decarbonized as electricity supply decarbonizes. The indirect scope 2 emissions for aluminum production are reported because electricity use is responsible for most of the sector emissions and to represent the different, on-site, electricity generation options available for aluminum sites and their technology readiness level (TRL).

We then review the literature to find the abatement options applicable for all sectors and their TRLs. Where the TRL for mitigation options are not explicitly available in

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Table 1. Industry sectors coverage in this paper based on ISIC codes

Sector	ISIC division description	Division number	Group number	Class number
Iron and steel	manufacture of basic metals	24	241,243	2,410, 2,431
Chemicals	manufacture of chemicals and chemical products	20	201–202	2,011, 2,012, 2,013, 2,021, 2,022, 2,023, 2,029
Cement and lime	manufacture of other non-metallic mineral products	23	239	2,394
Food and drink	manufacture of food products, manufacture of beverages	10–11	101–108	all
Pulp and paper	manufacture of paper and paper products	17	–	1,701
Glass	manufacture of other non-metallic mineral products	23	231	2,310
Aluminum	manufacture of basic metals	24	242	2,420
Refining	manufacture of coke and refined petroleum products	19	191–192	2,013, 2,021, 2,022, 2,023, 2,029
Ceramics	manufacture of other non-metallic mineral products	23	239	2,391, 2,392, 2,393, 2,396, 2,399

literature, the TRL is determined using the scale in Table 2 based on Kearns et al.[26] The key abatement options considered to decarbonize industrial processes are highlighted in Figure 1, which include the following:

- Switching to low-carbon fuel/energy supply: this includes using alternative low-carbon fuel for industries such as hydrogen (green and blue hydrogen, and bio-hydrogen), biomass (includes waste and virgin biomass, and biomass fuels), or low-carbon electricity.
- Carbon capture and storage (CCS): these are plants used to capture combustion- and process-related CO_2 emissions from industry. The captured emissions are then stored underground.
- Process modification or alternative low-carbon novel processes: some industrial commodities can be produced using alternative and novel production routes to save emissions (such as secondary aluminum production using microwave drying in paper production). Deploying novel processes is sometimes accompanied by fuel switching, depending on the nature of the industrial process.
- Resource and energy efficiency (REE): these refer to technologies or practices used to reduce emissions by using fewer raw materials (example: recycling), or enabling the use of emissions-free materials, or by using less energy to produce a product. Finding specific data about REE for each process is challenging. Therefore, we note the limitation of our paper regarding this.

Table 2. TRL status and category considered in this study

Category	TRL	Status
Demonstration	9	normal commercial operation
	8	full scale commercial demonstration
	7	demonstration, fully functional prototype
Development	6	pilot-scale
	5	sub-system validation in a relevant environment
	4	system validation in a laboratory environment
Research	3	proof of concept
	2	formulation
	1	concept

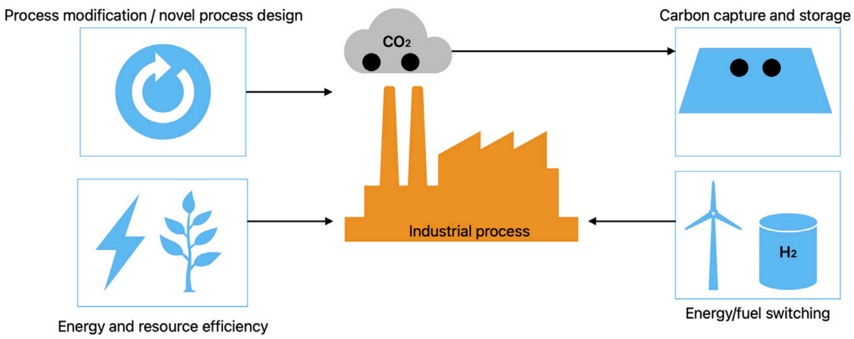

Figure 1. Overview of emission mitigation options applicable for industrial processes

RESULTS

Decarbonization of cross-sectoral industrial processes

Cross-sectoral technologies found in many industrial sectors include industrial combined heat and power (CHP) and steam boilers. CHP technology enables co-production of heat and power using one fuel source thus enabling energy savings of 30%–85% compared with separate production of heat and power, along with cost savings and emission reductions.[27,28] In applications where only heat production is needed, steam boilers are mostly used.

As electricity systems are expected to be one of the first sectors to be decarbonized in many world regions, there are concerns that increasing the role of fossil-fired CHP technologies would displace low-carbon electricity technologies and so increase total emissions.[29] Therefore, in a decarbonized energy system, CHP and boilers can only be used if they result in lower total emission during their lifetime compared with counterfactual options or if they can be retrofitted to use clean energy sources.

Table 3 presents the main decarbonization options for CHP and steam boilers. Fuel switching either technology to hydrogen or biomass has the potential to reduce direct emissions by up to 100% compared with counterfactual natural gas options, using technologies that have high TRLs and efficiencies. Current CHP plants working on biomass and 100% hydrogen have been demonstrated in several projects,[30,31] and some existing plants are expected to run on 100% hydrogen by 2030.[32] Further research and development (R&D) is needed to maintain and increase the efficiency and reliability of CHP technologies when working with different fuels, for instance, by enhancing prime movers and developing new working fluids.[10]

Using stationary fuel cell technologies for CHP generation in industrial applications can eliminate direct emissions (if powered by low-carbon hydrogen) and increase the overall efficiency when compared with CHP with internal combustion engines.[37] Fuel cells are most suitable for industrial applications in which electricity demand is higher than for heat. They can be used in food and drink to decarbonize the heat supply of combustion units. However, barriers to wide adoption of fuel cells include their high cost[42] and the current lack of hydrogen infrastructure.[43]

Heat pumps can be used to satisfy heat demand (up to 165°C) for many industries, such as food and drink, thus offering highly efficient alternatives to fossil-fired steam boilers.[44,45] Further R&D is needed to develop high-temperature heat pumps that can provide heat up to 200°C.[41] It is likely the cost of electricity, which in many

Table 3. Decarbonization options for CHP and steam boilers

Sectors	Technology	Decarbonization options	TRL	Maximum emission saving potential (%)[a]	Efficiency (%)[b]	Lifetime (years)	Source
All except cement and glass	CHP	fuel switching—biomass	9	100	63 (*T*) 22 (*E*)	20–25	BASIS Bioenergy[33] and SEAI[34]
		fuel switching—hydrogen	9	100	38–45 (*T*) 30–36 (*E*)	20–25	2G[35] and van Dam et al.[36]
		fuel cells[c]	9	100	25–30 (*T*) 35–60 (*E*)	9–15	Cigolotti et al.[37]
All except cement, lime, glass, other minerals, and non-ferrous metals	steam boiler	electric boiler	9	100	98–99	20–25	Danish Energy Agency[38]
		biomass boiler	9	100	90	15	Uslu[39]
		hydrogen boiler	9	100	90	25	Rutten[40]
		heat pump	4–9[d]	100	300	12–20	Danish Energy Agency[38] and Rademaker and Marsidi[41]

Keys: T, thermal; E, electrical,
[a]Compared to benchmark natural-gas CHP.
[b]May vary with different size/steam output pressure.
[c]There are different types of fuel cells for different industry needs (high vs. low temperature), solid oxide fuel cell (SOFC) is used here for stationary CHP applications.
[d]TRL is different based on the temperature level needed and the refrigerant type.

countries includes taxes and levies in addition to the underlying energy cost, will have a significant impact on the uptake of industrial heat pumps.[46]

Assessment of decarbonization options for industrial sectors

Iron and steel

Global iron and steel commodities are dominantly produced via the BF-BOF route with the key processes depicted in Figure 2. Iron ore, coke, and other minerals are fed into the BF where the oxygen is removed from iron ore to produce molten iron. It is then transferred into BOF where the impurities are removed to produce steel. The resultant gaseous by-products are utilized in a CHP plant on-site to produce electricity and heat. The use of these gases is vitally important to maintain the commercial viability of a steel plant, but they have significant emission factors (BF gas has nearly 4 times that of natural gas). This increases on-site emissions making producing 1 tonne of steel emits nearly 2 tonnes of CO_2e.

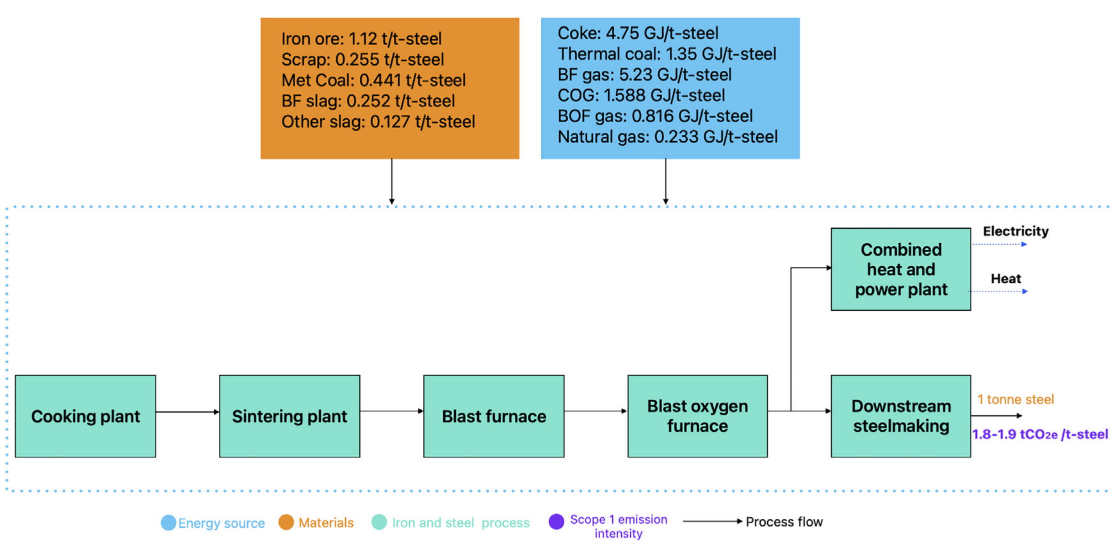

Figure 2. Main processes, energy use and emissions for iron and steel production via blast furnace
Produced based on the data from Mission Possible Partnership[47] and World Steel Association.[48]

Table 4. Decarbonization options for primary steelmaking

Production	Decarbonization option	TRL	Maximum emission saving potential (%)	Total energy consumption effects (%)	Source
Primary iron and steel (BF-BOF)	hydrogen direct reduction – shaft furnace + EAF	6–8	89	↓(0 – 1)	Keys et al.,[49] Berger,[50] and Draxler et al.[51]
	hydrogen direct reduction – fluidized bed + EAF	4–5	89	–	Berger[50]
	smelting reduction (HIsarna) + CCS	7	80	↓23	Keys et al.[49] and Richardson-Barlow et al.[52]
	top gas recycling blast furnace + CCS	5	78	↓35	Keys et al.[49]
	iron ore electrolysis + EAF	4–5	88 – 94	↓(21 – 25)	Keys et al.[49]
	natural gas direct reduction shaft furnace + EAF + CCS	9	86	↓28	Keys et al.[49]
	hydrogen-based flash reactor	4	89	↓60	Berger[50] and Sohn et al.[53]
	hydrogen-based plasma reduction	4–5	89	–	Berger,[50] Draxler et al.,[51] Voestalpine,[54] and Eberl[55]
	biomass fuel substitution to coal/coke use	7–9	40	–	Mandova et al.[56]
	electric arc furnace	9	90	↓72	Keys et al.[49]
	CCS	7	86	↑17	Mission Possible Partnership[47]

Table 4 provides an overview of the decarbonization options for iron and steel. The use of electric arc furnaces (secondary steelmaking) is an attractive option that can lead to 90% emissions reduction compared with BF-BOF route if steel scrap is available and product quality is maintained. However, if primary steel production is needed while keeping the BF-BOF assets, using CCS can result in 86%% emissions saving but with 17% higher energy consumption for the CCS plant. Alternatively, with some modifications to the BF and the use of CCS, smelting reduction (HIsarna), and top gas recycling furnace can result in nearly 80% emissions savings.

On the other hand, novel and less mature steelmaking can result in 89%–94% emissions saving via three routes. First, hydrogen-based direct reduced iron with an electric arc furnace (EAF) using shaft furnace and fluidized bed. Second, hydrogen-based direct steel production without the use of EAF by using flash and plasma reactors. Third, direct electrification of steelmaking using Electrowinning technology with EAF.

Chemicals

The chemical sector has heterogeneous processes and products making it difficult to represent entirely or report emission saving on a sectoral level. However, Figure 3 presents the key processes to produce emission-intensive products; ammonia, and hydrogen as ammonia products and high-value chemicals (ethylene, propylene, benzene, toluene, and xylene, etc.) as non-ammonia products. Ammonia is predominately produced via the Haber-Bosch process where 90% of its emissions associated with hydrogen production. Hydrogen is primarily produced using fossil fuels (mainly natural gas) through steam methane reforming (SMR) or autothermal reforming.

To produce a mixture of high-value chemicals, several feedstocks such as naphtha are diluted with steam in a steam cracker furnace at high temperature (~900°C). The furnace is mostly heated using self-produced fuel gas.

As shown in Table 5, ammonia production can be decarbonized when low-carbon hydrogen is used, which can be blue or green hydrogen or from methane pyrolysis and biomass gasification/digestion. If blue hydrogen is used, this can lead to a 2% increase in the energy consumption of the ammonia plant but will not result in a

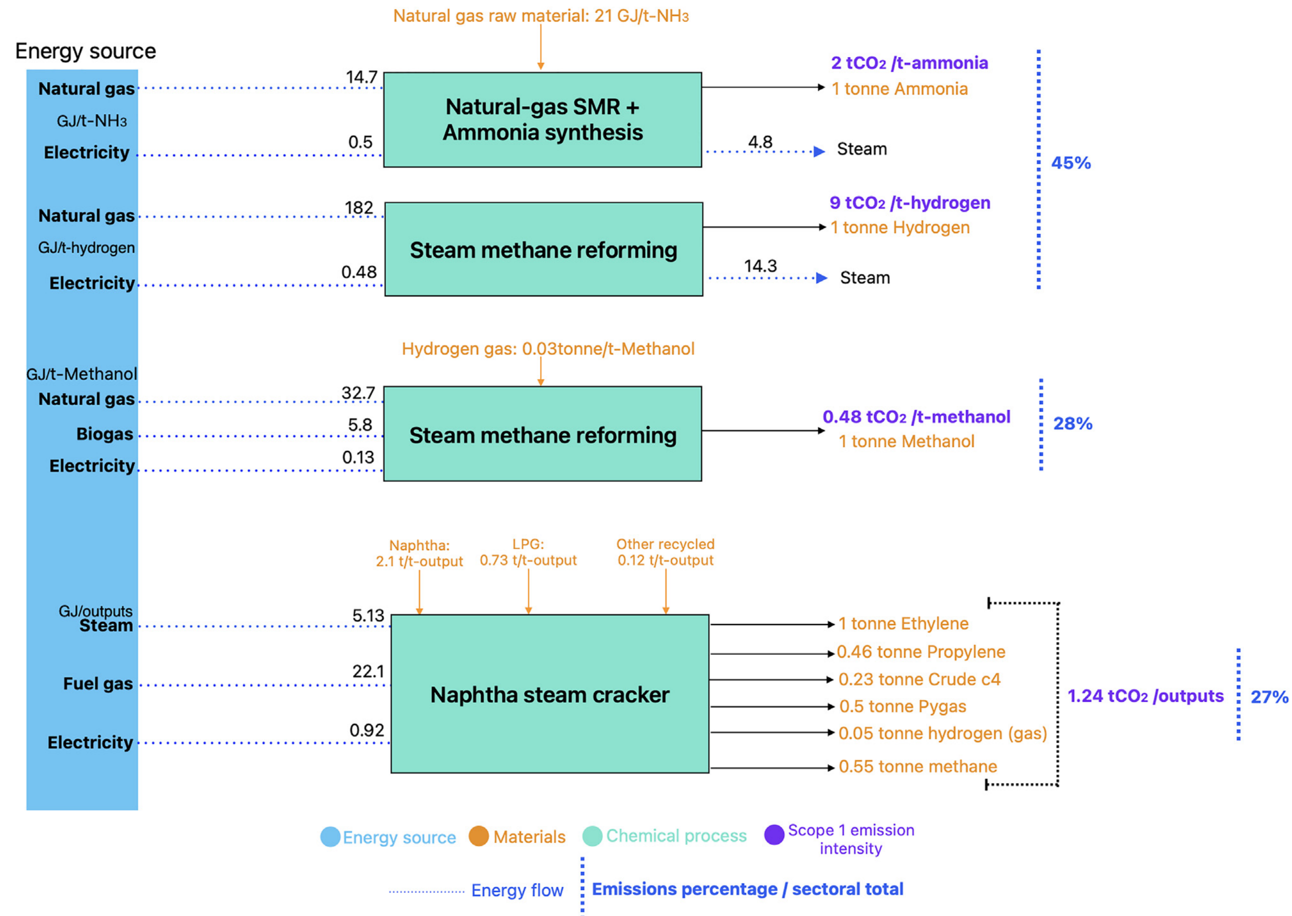

Figure 3. Main processes considered in this paper for the Chemicals sector
Produced based on the data from PBL,[57] Mission Possible Partnership,[58] and IEA.[59]

complete decarbonization depending on the capture rate of the CCS plant. In contract, using green hydrogen can lead to a complete decarbonization but with 13% increase in energy consumption.

Looking more closely to green hydrogen production, alkaline electrolysis (AEL) and proton exchange membrane (PEM) electrolysis are mature technologies to produce green hydrogen but with significant increase in energy consumption. In contrast, solid oxide electrolyzer is more energy efficient but less mature.[69]

In terms of the production of non-ammonia products, the steam cracking process can be decarbonized using CCS or fuel switching (via electricity or hydrogen) if its feedstock is based on fossil fuels (naphtha or gas). If biomass or waste-based feedstock is used along with non-coal-based methanol production, methanol to olefins (MTO) and methanol to aromatics (MTA) processes offer an alternative route to decarbonize high-value chemicals.

Cement and lime

Cement and lime have similar production route as shown in Figures 4 and 5. It starts from raw material preparation, then a calcination kiln which is an energy and emissions intensive process followed by a final product finishing process. Both sectors are distinct in the production of "process emissions" where they represent nearly

Table 5. Decarbonization options for the chemicals sector

Process	Decarbonization option	TRL	Maximum emission saving potential (%)	Total raw material/energy consumption effects (%)	Commodity changes effects vs. baseline technology	Source
Natural gas-based ammonia synthesis	blue hydrogen production + ammonia synthesis	7 – 8	87–94[a]	↑2	slight increase in electricity consumption.	Mission Possible Partnership[58] and Batool, and Wetzels [60]
	green hydrogen production + ammonia synthesis	7 – 8	100	↑13	electricity is used for hydrogen production.	IEA[61]
	biomass gasification/ digestion + ammonia synthesis	6 – 7	100	↑(14–175)	massive amount of biomass is required	Mission Possible Partnership[58] and IEA[62]
	methane pyrolysis + ammonia synthesis	7 – 8	100	↑50	massive increase in natural gas as a raw material	IEA[61]
Steam cracker	CCS	6 – 8	90	↑25	energy increase for the CCS capture plant	Mission Possible Partnership[58]
	electric steam cracker	5	100	↓30	massive amount of electricity is required	Eerens and van Dam[63]
	hydrogen fuel switching for steam cracker	5	100	no change	–	Element Energy[64]
	alternative feedstock for steam cracker (bio-naphtha 10 wt %)	5 – 6	10	–	energy use is different according to the technology used	dos Sontos et al.[65]
	methanol to olefins (MTO) and to aromatics (MTA)[b]	7 – 9	100	–	–	SYSTEMIQ[66]
Steam reforming—hydrogen and methanol	AEL/PEM electrolyzer	8 – 9	100	↑743	massive amount of electricity is required	PBL[57]
	solid oxide electrolyzer	6	100			PBL[57]
	CCS	7	52 – 88	↑10	energy increase for the CCS capture plant	IEA,[13] Collodi et al.,[67] and Cioli et al.[68]
	biomass/waste gasification	9	100		biomass and electricity are required	PBL[57]

[a]Depending on using SMR or ATR with the latter has higher emission saving potential.
[b]Assuming non-coal-based methanol production.

60% and between 66% and 73% of the total emissions from cement and lime production, respectively. The remaining emissions are related to fuel combustion mostly in the kiln.

The presence of process emissions makes CCS technologies unique to achieve deep decarbonization for both sectors as shown in Tables 6 and 7. Advanced-amine- and calcium-looping-based CCS technologies have high TRLs but with significant additional energy requirements. In contrast, CCS based on molten carbonate fuel cell can achieve the same emissions reduction with no additional energy use but have lower TRL in comparison.

Fuel/energy switching the lime and cement kilns can save up to 34%–40% of sectoral total emissions. This can be done by using biomass/waste, hydrogen, and electricity, which they have different TRLs for both sectors. Alternatively, existing energy efficiency options for the kilns can lead to emissions saving between 7% and 16% emissions saving for cement and lime, respectively.

There are also unique decarbonization options for both sectors. Clinker to cement ratio can be reduced in cement production leading to a sectoral emission saving between 9% and 47% depending on the option used with BF slag offers the highest potential. Nevertheless, alternative "cementitious" materials with different TRLs based on "belite cement" and "magnesium oxides derived from magnesium silicates" can

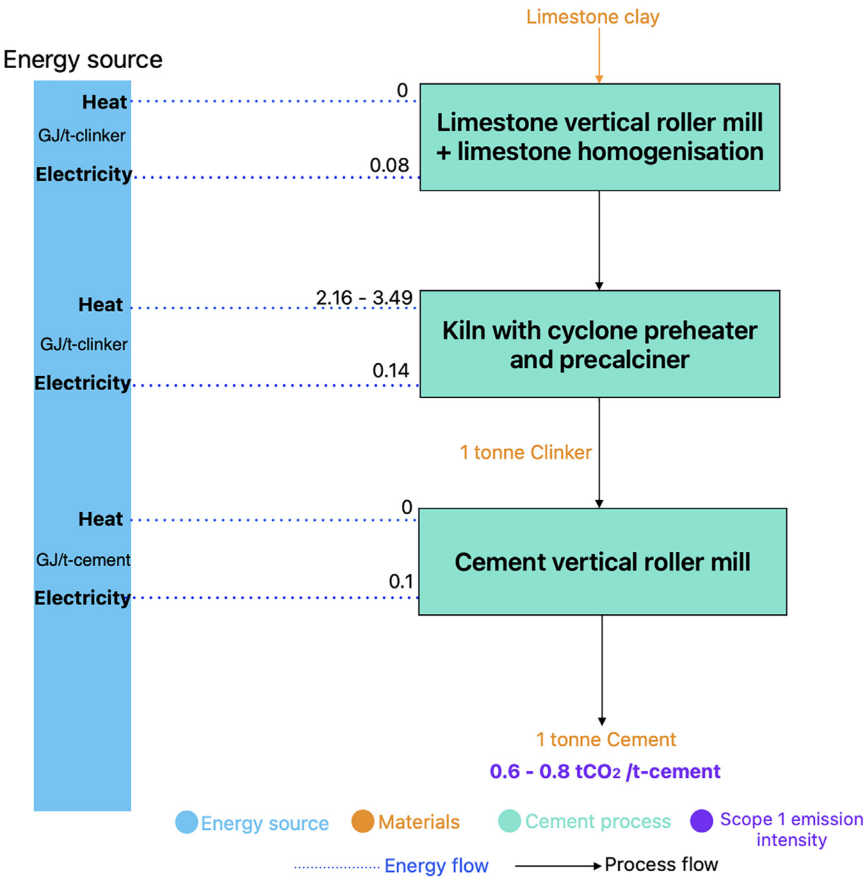

Figure 4. Main processes, energy use and emissions for cement production
Produced based on the data from Obrist et al.[70] and Global Cement and Concrete Association [71]

lead to 2%–60% sectoral emission saving. Low-carbon lime can also be produced based on a chemical synthesis process but with significantly low TRL.

Aluminum

As illustrated in Figure 6, to make aluminum, alumina is first produced in a high-temperature refining process by dissolving bauxite in a caustic soda and calcined lime. The alumina is then fed to an electrolysis cell together with carbon anodes to create liquid aluminum, which is then casted into billets and slabs.

The largest source of emissions in aluminum production comes from using electricity in the electrolysis cell. It contributes to 62%–67% of the total emissions with the rest are 13%–16% thermal-energy-related, and 9%–12% process-related emissions with remaining emissions are attributed to ancillary raw materials.[92,93]

Table 8 presents the decarbonization options for aluminum production. The highest emission savings comes from recycling aluminum scrap to produce it via the secondary production route, which can save 95% of the total emissions. Alternatively, using low-carbon electricity can save the majority of the emissions, which can be produced using nuclear small modular reactors at 4–5 TRL, and other advanced technologies at higher TRLs such as hydro power plants or low-carbon electricity grid.

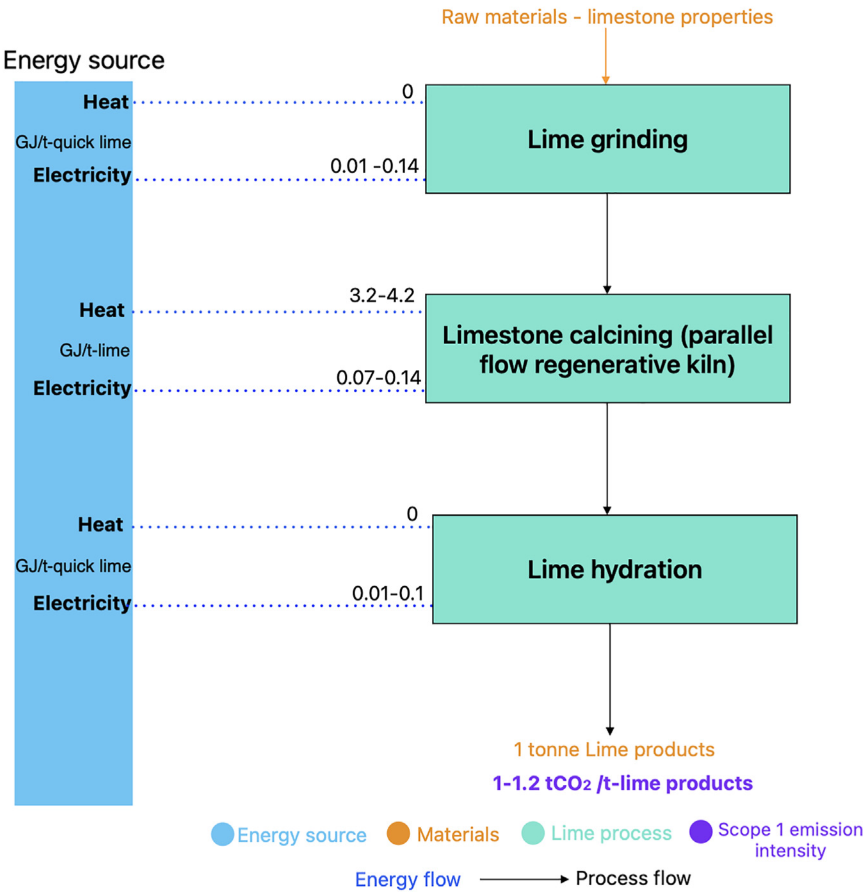

Figure 5. Main processes, energy use and emissions for lime production
Produced based on the data from Schorcht et al.[72] and Stork et al.[73]

To mitigate the remaining emissions from process emissions and thermal energy use, some options exist. First, for process emissions, inert anodes offer a promising alternative to the use of carbon anode, which can also reduce the operating cost for aluminum production due to their longer lifetime in comparison. However, they increase the total energy consumption by 20%. Second, electric and hydrogen boilers and calciners can be used in the alumina refining process to reduce the remaining 13%–16% of emissions.

Pulp and paper

Pulp and paper production steps are shown in Figure 7. Pulp is produced by separating the fibers in the wood from the lignin. This can be done in three ways. First, mechanical pulp where fibers are separated by mechanical treatments, which is an electricity-intensive process with recovered heat. Second, chemical (kraft pulping), which is the most popular method where pulp fibers are extracted by chemical treatment. Modern chemical pulp mills are energy self-sufficient and net producers of electricity due to the black liquor energy recovery cycle.[96] Third, recycled pulp can be produced from waste paper, which consumes significantly less energy that mechanical pulping.

Pulp is then prepared to remove impurities and ensure final product quality depending on the type of fibers. This then fed to the paper machine where energy is used to remove the water from the fibers and produce the paper products.

Table 6. Decarbonization options for cement making

Process	Decarbonization option	TRL	Maximum emission saving potential (%)	Thermal energy consumption effects (%)	Electricity consumption effects (%)	Source
Clinker to cement ratio	blast furnace slag	9	47	↓46	↑14	European Cement Research Academy[74] and IEA[75]
	fly ash	9	11	↓(0–10)	↓(3–21)	European Cement Research Academy [74]
	natural pozzolanas	9	11	↓(0–10)	↑(0–4)	European Cement Research Academy [74]
	calcined clay	9	9	↓4	↓(0–7)	European Cement Research Academy[74]
	calcined clay with limestone	9	22	↓11	↓(0–10)	European Cement Research Academy[74]
Cement production	belite cement	9	2–6	↓8	–	IEA[75] and Cao et al.[76]
	belite-ye'elimite-ferrite cement	9	17	↓35	–	Cao et al.[76] and Gartner and Sui[77]
	carbonatable calcium silicate cement	6	14–17	↓39	–	IEA[75] and Cao et al.[76]
	calcium sulfoaluminate cement	6	24–36	↓25 – 47	–	Cao et al.[76] and Gartner and Sui[77]
	celitement	6	19–29	↓51	–	Cao et al.[76] and Gartner and Sui[77]
	magnesium oxides derived from magnesium silicates	3–4	60	↓47	–	Cao et al.[76] and Hasanbeigi and Springer[78]
Cement kiln	fuel switching—biomass/waste	9	16–40	–	–	UK Concrete, MPA[79]
	fuel switching—hydrogen	6–7	16–40	–	–	UK Concrete, MPA[79] and Heidelberg Materials[80]
	plasma torches—electricity	3	40	–	–	Somers and Moya[81] and Element Energy[82]
	upgraded kiln with low pressure drop cyclone	9	7	↓11	↓4	Obrist et al.[70]
	upgraded kiln with cyclone preheater and precalciner	9	7	↓11	no change	Obrist et al.[70]
Cement process and combustion emissions	CCS—direct separation	6	60	↑1	↑62	AECOM [83] and IEA[84]
	CCS—advanced amines	8	95	↑89	↑135	AECOM[83]
	CCS—calcium looping	7	95	↑13	↑128	Element Energy[82] and EU Commission[85]
	CCS—molten carbonate fuel cell	6–7	96	0	0	AECOM[83] and Ferguson and Tarrant[86]
	CCS—partial oxyfuel	6–8	60	0	↑166	AECOM[83]

Table 9 presents the decarbonization options for pulp and paper. Since there are no process emissions in pulp and paper production, decarbonizing the CHP and boilers will decarbonize the sector. For pulp production, a modern chemical pulping mill can be considered carbon neutral because it is energy self-sufficient and the on-site emissions are of biomass-origin.[100] However, some energy saving measures exists such as using membrane technology to increase black liquor concentration, increasing the energy recovery for the pulping mill through black liquor gasification and using steam cycle washer to reduce steam consumption. These measures could reduce the energy consumption of a pulp mill by 17%–40%. Mechanical pulping, on the other hand, require low-carbon electricity production.

For paper production, there are new process design to paper drying such as supercritical CO_2 that relies on changing pressure and temperature for drying superheated steam drying, which can decrease paper emissions by up to 50%. Other promising energy saving technologies include using microwave drying and air-laid forming which can lead to energy saving between 12% and 50% compared with current conventional paper making.

Table 7. Decarbonization options for lime making

Process	Decarbonization option	TRL	Maximum emission saving potential (%)	Thermal energy consumption effects (%)	Electricity consumption effects (%)	Source
Lime production	chemical synthesis	2–3	100	–	–	Simoni et al.[87]
Lime production	electrochemical synthesis	2–3	27 − 34	–	–	Simoni et al.[87]
Lime kiln	fuel switching—biomass/waste	8	27 − 34	–	–	Reinvent decarbonisation[88]
	fuel switching—hydrogen	8	27 − 34	–	–	Simoni et al.[87] and Lhoist[89]
	plasma torches—electricity	8	27 − 34	–	–	LimeArc[90]
	kiln upgrade/continuous improvement	9	12 − 16	↓11	↓4	Stork et al.[73]
Lime process and combustion emissions	CCS—direct separation	6–8	60 − 70	↑1	↑112–223	AECOM [83]
	CCS—advanced amines	8	95	↑74–97	↑242–484	AECOM[83]
	CCS—calcium looping	7	95	↑10–14	↑230–460	Element Energy[82] and EU Commission[85]
	CCS—MCFC	6–7	96	0	0	AECOM[83] and Ferguson and Tarrant[86]
	CCS—partial oxyfuel	6–8	60–70	0	↑298–595	AECOM[83]

Glass

Glass manufacturing processes and energy needs are shown in Figure 8, which can vary depending on the final glass product type. High-purity and other materials are first mixed and then melted in a high-temperature glass furnace. The furnace is the most energy-intensive process, which is heated via a combination of combustion heating and direct electrical heating.[106] Finally, downstream processes such as glass forming and annealing are employed depending on the glass types needed. Glass-making process and fuel related emissions are 16% and 84% of the total emission, respectively.[107]

Table 10 presents the decarbonization options for the glass sector. To tackle combustion emissions, glass furnace electrification and fuel switching to biofuel are promising options due to their high TRLs. At low TRL, plasma melting offers fast melting time and high efficiency.[107] Other promising options include a hydrogen-powered furnace and a hybrid furnace design, which provides flexibility to use more than one fuel or energy source depending on their costs. To reduce process emissions, utilizing more cullet and calcined raw materials can together reduce up to 5% of the total sectoral emissions.

Food and drink

The direct emissions for the food and drink sector mostly stem from using steam for drying and heating processes or from combusting fossil fuels directly. Given the wide range of products and commodities in this sector, Figure 9 presents the energy requirements and emission intensities for key products by heat type demand.

Table 11 shows that abatement options for food and drink manufacturing. For a direct heat use equipment such as oven or bar marker, there is a potential to either electrify the process while using low-carbon electricity or use a low-carbon fuel such as hydrogen or biogas. If the technology uses indirect heat as in pasteurization/sterilization processes or oven, the abatement options are either to electrify these processes by using microwave alternatives or electric water heater, respectively, or decarbonize the steam supply. This includes decarbonizing the CHP and boilers as previously discussed in the section (decarbonization of cross-sectoral industrial processes) or using alternatives technologies for steam generation such as concentrated solar heating or utilizing geothermal energy.

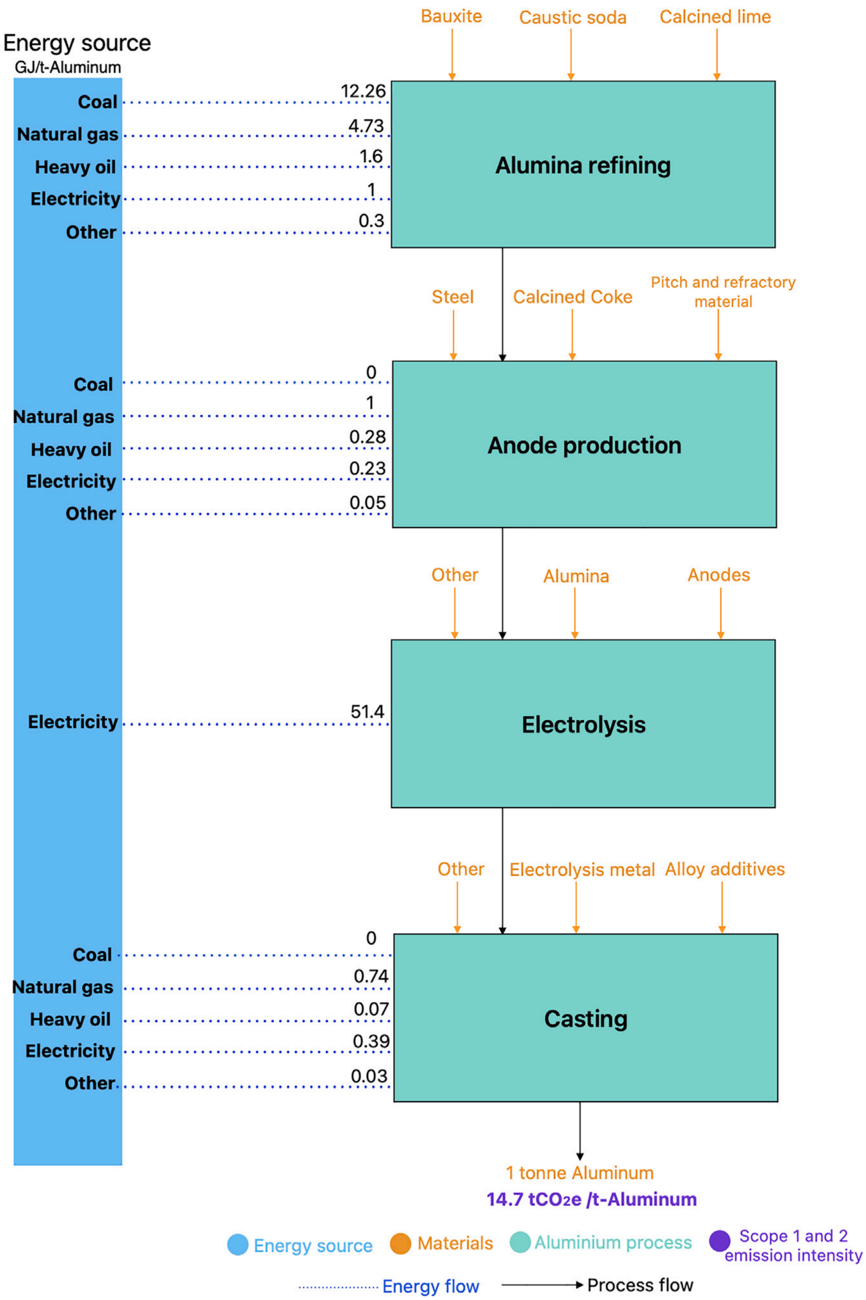

Figure 6. Main processes, energy use and emissions for aluminum production

Produced based on the data from International Aluminium Institute.[91]

Ceramics

The main manufacturing processes for ceramic products (bricks, roof tiles, wall tiles, floor tiles, and refractory products, etc.) are shown in Figure 10. Although the materials used and processes can be different for different ceramic products, the raw materials are often prepared by adding supplementary materials and water, reducing particle sizes, and maintaining a homogeneous mix. Then, the ceramics are shaped using different techniques and then dried intermittently or continuously to remove the water content with temperatures up to 90°C.[116] Part of the energy needed

Table 8. Decarbonization options for aluminum making

Production	Decarbonization option	TRL	Maximum emission saving potential (%)	Total energy consumption effects (%)	Source
Aluminum	low-carbon electricity	(4–9)	62–67	–	Mission Possible Partnership[92]
	secondary production route	9	95	–	ALFED[94]
	inert anodes	7	9–12	↑20	Mission Possible Partnership and Korten and Dril[92,95]
	boilers (high-temperature heat, see Table 3) and electric and hydrogen calciners.	(2–3)[a]	13–16	–	Mission Possible Partnership[93]
	CCS	(3–4)[a]	9–12	–	Mission Possible Partnership[93]
	mechanical vapor recompression	7	6–8	–	Mission Possible Partnership[93]
	energy efficiency measures	3–9	–	↓(1–15)	Korten and Dril[95]

[a]The TRLs here is specific to the aluminum industry.

(here 50%) for the drying process is supplied from the waste heat of the subsequent firing process. Ultimately, ceramics are fired in a kiln with a temperature 1,000°C–1,300°C and then cooled and stored.

The average direct emissions intensity of producing various ceramic products is approximated to 0.27 tCO_2/t-ceramic products,[116] of which 78% are fuel combustion emissions, and 16% process emissions.[117]

Table 12 presents the main decarbonization options for ceramics. In general, the decarbonization of ceramics manufacturing is challenging due to the low maturity of the deep decarbonization measures. However, fuel switching the drying and firing processes to hydrogen and biogas is potentially attractive option to keep utilizing the waste heat from firing process in the drying process. Alternatively, the electrification of both processes and using novel microwave/spark plasma can mitigate most of the combustion emissions. The remaining 22% process emissions can be tackled via CCS technologies.

Refining

A refinery site has complex array of process units that process crude oil into valuable products and fuels that can be used for heat generation, transport, and aviation. Figure 11 shows a simplified energy and emissions flow for these processes where energy and material use are represented in an absolute level (i.e., representing each unit separately due to the complexity involved in representing a complete energy and material flow across processes). When certain share of process outputs is utilized, a global average emissions intensity of 0.3tco_2e/t-crude oil is reported. Refinery furnaces (process heat) make-up 51%–63% of those emissions, with the rest being 21% hydrogen production through SMR, 10% for the fuel use in CHP and boilers, and 9% for the catalytic cracking process.

Table 13 present the abatement measures for the refining sector where CCS technologies offer between 60%–72% emissions reduction from the refinery furnaces and the catalytic cracking. CCS technologies can also reduce most refinery emissions if they tackle emissions from hydrogen production via steam reforming. Alternatively, furnaces electrification and hydrogen fuel switching can also save 51%–63% of the refinery emissions. Energy efficiency measures such as improving distillation processes by using multicolumn progressive distillation, using new motors, and heat exchangers can provide up to 50% energy savings in a refinery.

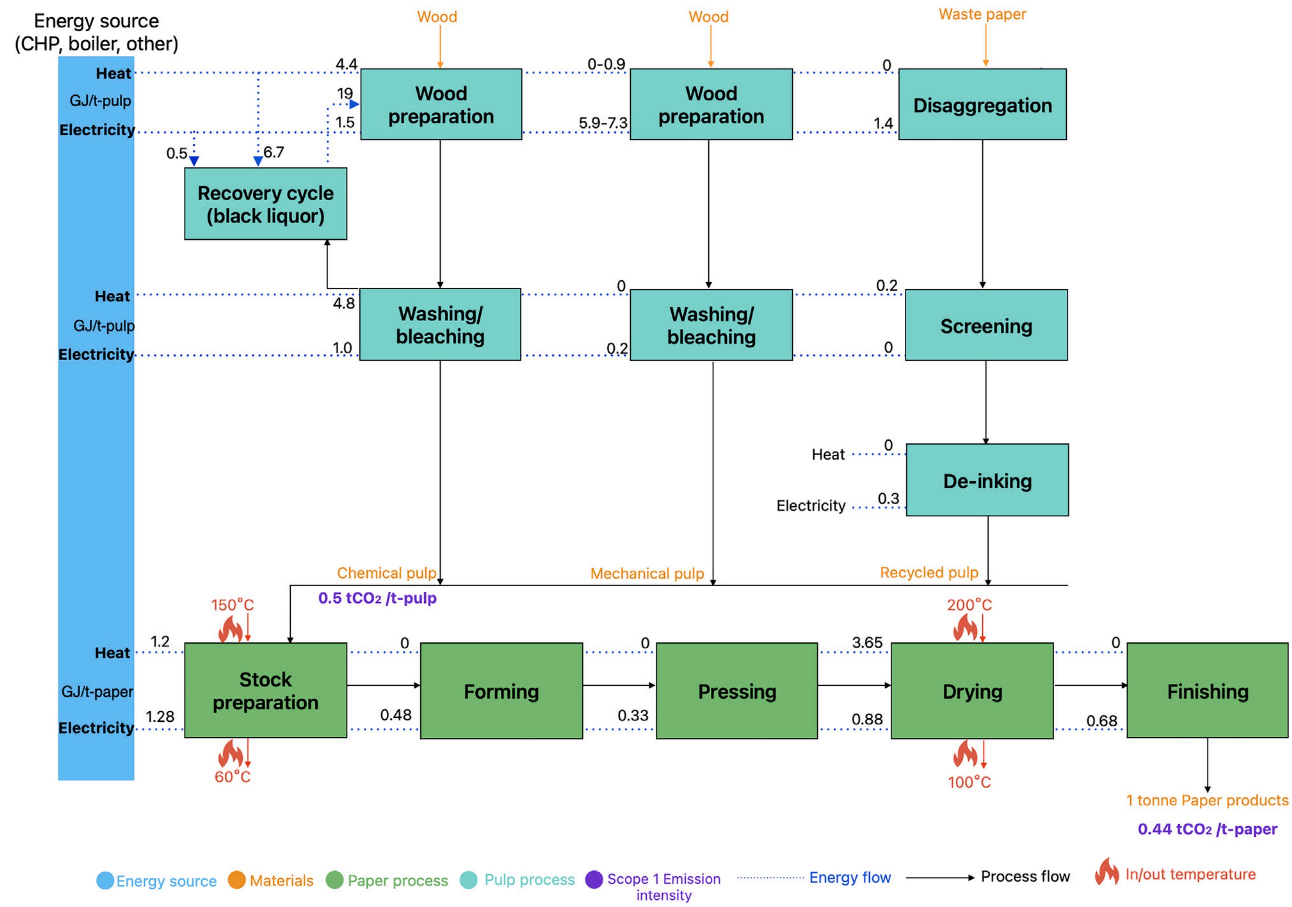

Figure 7. Main processes, energy use and emissions for pulp and paper production

Produced based on the data from Obrist et al.,[97] Ministry of Economy, Trade and Industry,[98] and Sun et al.[99]

Summary of decarbonization options potential for industrial sectors

Figure 12 provides a high-level summary of the potential for the different groups of mitigation options for each industrial sector. It is produced based on the option with the highest emissions saving potential in each sector (Tables 4, 5, 6, 7, 8, 9, 10, 11, 12, and 13). It shows that the decarbonization of industry is likely to require a combination of widely applicable and bespoke technologies that rely on electrification, fuel switching to hydrogen and biomass, CCS, novel processes including alternative production routes, and REE. The potential of these technologies varies significantly across sectors. For example, iron and steel, pulp and paper, and glass have several high-potential decarbonization routes, whereas the options for ceramics and refining are more limited.

Electrifying industrial processes and using low-carbon electricity for existing or novel processes is expected to be a key decarbonization option in most sectors. In sectors using low-to-medium temperature heat, such as food and drink, natural gas boilers can be replaced by an electrical steam generator. In addition, several other processes can be electrified, such as replacing a gas-fired oven with an electrical one.

In sectors requiring high-temperature heat, electrification is possible either by (1) switching to secondary production routes, such as using the electric arc furnace for steel production, or (2) technological radical innovation to existing production

Table 9. Decarbonization options for the pulp and paper sector

Production	Process	Decarbonization option	TRL	Maximum emission saving potential (%)	Energy saving potential (%)	Source
Pulp	steam supply—CHP and boilers	See Table 3	–	100	–	Rahnama Mobarakeh et al.[101]
	pulp production	deep eutectic solvents	3	20	40	Rahnama Mobarakeh et al. and Furszyfer Del Rio et al.[101,102]
	chemical pulping	membrane concentration of black liquor	6–7		36	Rahnama Mobarakeh et al. and Kong et al.[101,103]
	chemical pulping	steam cycle washing	7–8		30–40	Rahnama Mobarakeh et al., Furszyfer Del Rio et al., and Kong et al.[101–103]
	chemical pulping	black liquor gasification	8–9	10	17	Rahnama Mobarakeh et al. and Kong et al.[101,103]
	mechanical pulping	biological pre-treatment	8–9		25–40	Rahnama Mobarakeh et al. and Kong et al.[101,103]
	pulp production	energy management and maintenance	9	9 – 15	–	Rahnama Mobarakeh et al. and Furszyfer Del Rio et al.[101,102]
Paper	steam supply – CHP and boilers	see Table 3	–	80	–	Confederation of paper industries[104]
	paper drying	air-laid forming	8		50	dos Santos et al. and Campen[65,105]
	paper drying	microwave drying	6		12–20	dos Santos et al. and Rahnama Mobarakeh et al., Furszyfer Del Rio et al., and Kong et al.[65,101–103]
	paper drying	superheated steam drying	3–5	50	25	Rahnama Mobarakeh et al. and Furszyfer Del Rio et al.[101,102]
	paper drying	supercritical CO_2	3	45	20	Rahnama Mobarakeh et al., Furszyfer Del Rio et al., and Kong et al.[101–103]
	paper drying	other energy efficiency options such as boost dryers	6–7		20	Rahnama Mobarakeh et al., Furszyfer Del Rio et al., and Kong et al.[101–103]
	impingement dryers (direct fired)	electric dryers	9	20	–	Furszyfer Del Rio et al. and Confederation of paper industries[102,104]

routes, such as using the electric steam cracker and electric glass furnace in the chemicals and glass sectors, respectively.

Hydrogen fuel can play a cross-sectoral role to reduce GHG emissions, particularly where electrification is unsuitable. For example, hydrogen-based CHP is an option to displace fossil fuel combustion in food and drink and pulp and paper. In the iron and steel sector, hydrogen direct reduction technologies (process change) can result in nearly 90% emission savings compared with the BF-BOF production route. Other key sectors that can benefit from hydrogen fuel switching are chemicals (where it can be used for ammonia and methanol production) and glass manufacturing (as a fuel for the glass furnace).

A diverse array of biomass resources can be important energy or feedstock inputs for many industrial sectors. In the refining sector, some refineries use biomass-derived feedstocks to produce bioplastic products. In pulp and paper and glass, biofuels can be used in CHP and boiler technologies, and the glass furnace, respectively, resulting in significant emission savings.

CCS is a key mitigation option, particularly for sectors with significant unavoidable process emissions. It is expected to play a significant role in mitigating emissions in cement, lime, chemicals, refining, and iron and steel sectors. In cement and lime making, advanced amines, calcium looping, and molten carbonate fuel cells technologies can be used to capture 95% of the total produced emission. CCS can also be combined with novel low-carbon steelmaking options such as HIsarna and top gas recycling BF. It is also an option to decarbonize ammonia synthesis, cracking, and steam reforming processes in the chemicals sector.

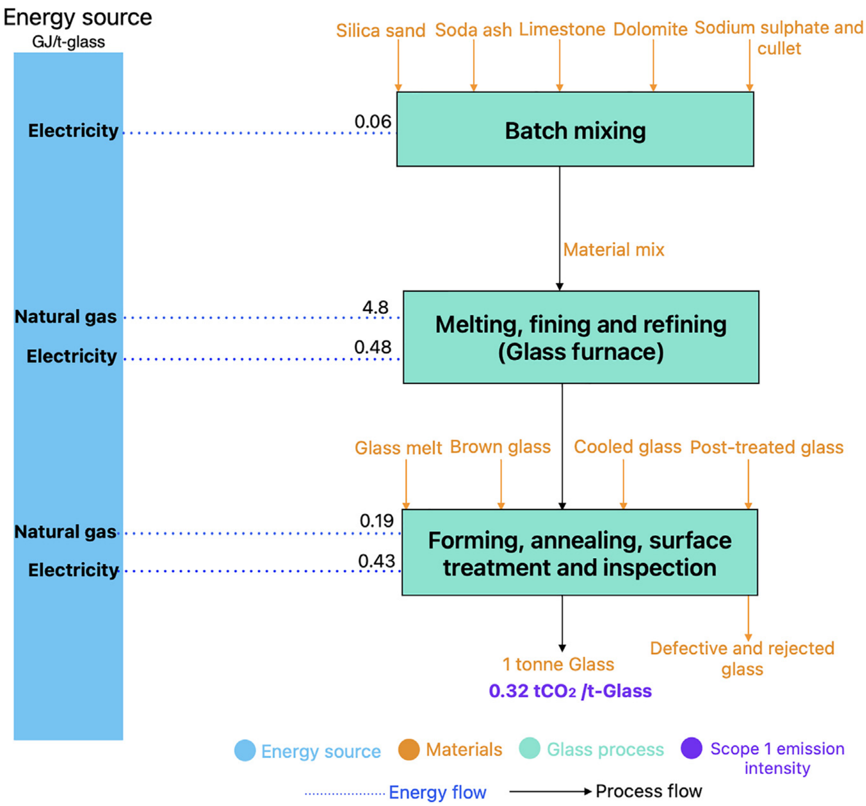

Figure 8. Main processes, energy use and emissions for glass production
Produced based on the data from Papadogeorgos and Schure.[108]

Some industrial sectors such, cement, lime, pulp and paper, and chemicals can be decarbonized using alternative production routes. For instance, new cementitious materials such as "magnesium oxides derived from magnesium silicates" can save up to 60% of cement production emissions. Alternative lime production routes such as chemical synthesis can completely decarbonize lime making. Similarly, new microwave paper

Table 10. Decarbonization options for glassmaking

Process	Decarbonization option	TRL	Emission saving potential (%)	Total energy consumption effects (%)	Source
Glass production-glass furnace	electric furnace	(7–9)[a]	80	↓(15–25)	Papadogeorgos and Schure, British Glass, and Furszyfer Del Rio et al.[106,108,109]
	plasma melting	2–3	80	–	Zier et al.[107]
	hybrid furnace	9	(67)[b]	–	British Glass and Zier et al.[106,107]
	fuel switching—biofuel	8	80	–	Papadogeorgos and Schure, British Glass, Zier et al., and Furszyfer Del Rio et al.[106–109]
	fuel switching—hydrogen	6	80	–	Papadogeorgos and Schure, British Glass, Zier et al., and Furszyfer Del Rio et al.[106–109], and British Glass[110]
	oxy-fuel furnace	9	8–10	–	–
	increased cullet use	9	3	↓2.5	British Glass[106]
	calcined raw materials	9	2	–	British Glass[106]
	heat recovery systems	9	–	↓(11–29)	Zier et al.[107]

[a]Depending on the capacity of the furnace. Furnaces with ~300 tpd capacity is available now (9 TRL).
[b]UP to 80% electricity use is demonstrated. That is assumed to reduce 80% of the fuel related emissions.

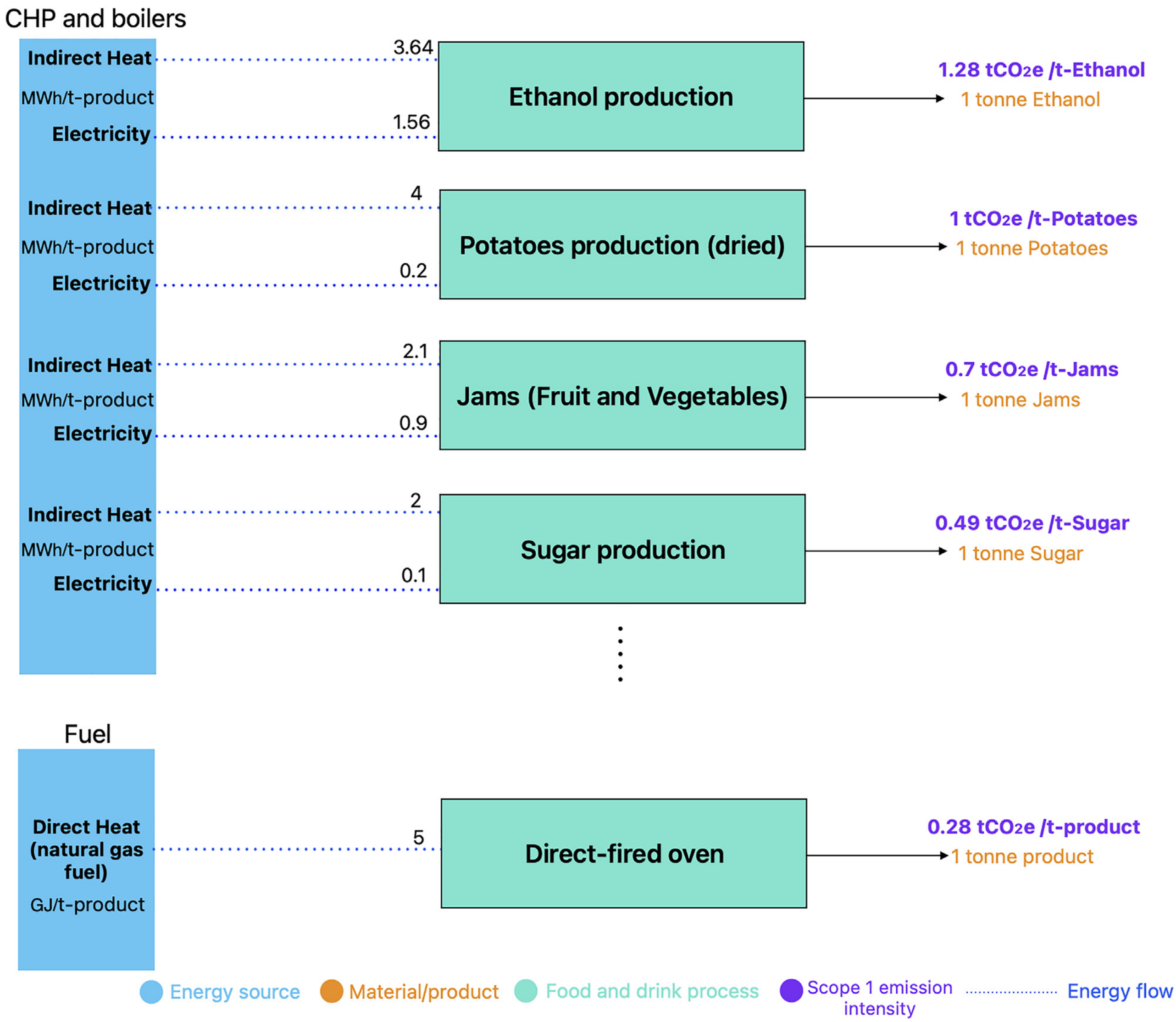

Figure 9. Energy use and emissions for key food and drink processes
Produced based on the data from PBL[57] and Cameron et al.[111]

drying technologies can lead to 80% emissions saving in papermaking. In chemicals, an emission saving of 27% is possible with novel MTO and to MTA production routes.

REE is a cross-sectoral foundational pillar that can save significant cumulative emissions over the entire life of industrial production. This includes emission savings due to upgrading to the best available technology such as parallel flow regenerative kilns in lime making or using complementary materials/technologies. For instance, using BF slag in clinker production can reduce 47% of emissions from cement making. Similarly, deep eutectic solvents can save 20% of emissions from pulp making.

DISCUSSION

The technical maturity of industrial decarbonization options and RD&D

Our results, which draw on a comprehensive review of the academic and gray literature, highlight the potential to decarbonize industry using a range of abatement

Table 11. Decarbonization options for food and drink manufacturing

Technology side	Heat type and range (°C); D, direct; In, indirect	Technology	Decarbonization option	TRL	Maximum emission saving potential (%)	Source
Demand	D (200–700)	bar marker	electric/laser bar marker	9	100	Food & Drink Federation and Marlen[112,113]
Demand	D (150–430)	oven	biogas/hydrogen fuel switch	9	100	Food & Drink Federation[112]
Demand	In (40–85)	cleaning in place	ultrasonic cleaning in place	9	100	Cameron et al. and Food & Drink Federation[111,112]
Demand	In (280–330)	oven	electric water heater	9	100	Cameron et al., Food & Drink Federation, and Sovacool et al.[111,112,114]
Demand	In (4–600)	food processing	microwave, ultrasonic, ultraviolet processes	9	100	Cameron et al., Food & Drink Federation, Sovacool et al., and Atuonwu and Tassou[111,112,114,115]
Demand	In	food processing	heat exchanger (recovery)	9	5—10	Cameron et al., Food & Drink Federation, and Sovacool et al.[111,112,114]
Demand	In	drying process	fluidized bed dryers	9	63	Cameron et al. and Atuonwu and Tassou[111,115]
Supply	In	CHP and boilers	see Table 3	–	–	–
Supply	In	steam supply	concentrated solar heating	9	100	Cameron et al., Food & Drink Federation, and Sovacool et al.[111,112,114]
Supply	In	steam supply	geothermal heat supply	9	100	Cameron et al., Food & Drink Federation, and Sovacool et al.[111,112,114]
Supply	In	steam supply	gasification/pyrolysis of solid waste	9	100	Cameron et al. and Food & Drink Federation[111,112]

options based on electricity, hydrogen, biomass, CCS, novel processes, and REE. While there have been previous studies on the potential of some of these options to decarbonize particular sectors,[10,17,18,22,109,114,124,126,127] this research adds to

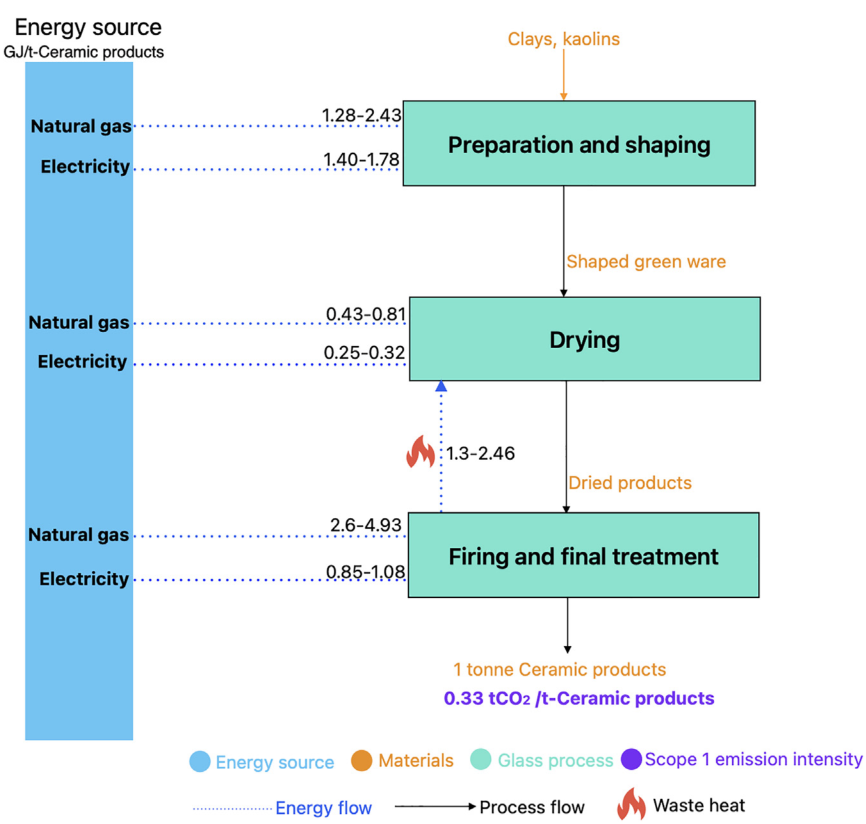

Figure 10. Main processes, energy use and emissions for ceramics production

Produced based on the data from Atuonwu and Tassou[116]

Table 12. Decarbonization options for ceramics making

Process	Decarbonization option	TRL	Maximum emission saving potential (%)	Energy saving potential (%)	Source
Ceramics firing	electrification	2–3	50	–	Besier and Marsidi, Unie, and Ibn-Mohammed et al.[116–118]
	fuel switching—hydrogen	5	50	–	Besier and Marsidi, Unie, and Ceramica[116,117,119]
	fuel switching—biogas	5	50	–	Besier and Marsidi and Unie [116,117]
	microwave/spark plasma sintering	1–2	50	–	Ibn-Mohammed et al.[118]
	energy efficiency optionsa	9	–	65	Furszyfer Del Rio et al. and Castro Oliveira et al.[18,120]
Ceramics drying	electrification	2–3	28	–	Besier and Marsidi, Unie, and Ibn-Mohammed et al.[116–118]
	fuel switching—hydrogen	5	28	–	Besier and Marsidi, Unie, and Ceramica [116,117,119]
	fuel switching—biogas	5	28	–	Besier and Marsidi and Unie [116,117]
	heat pumps	4–9	28	–	Besier and Marsidi [116]
	energy efficiency options[b]	9	–	65	Furszyfer Del Rio et al. and Castro Oliveira et al.[18,120]
Process emissions	CCS technologies	(2–3)[c]	(22)[d]	–	Unie[117]

[a]These include using hybrid kilns, high-efficiency burners, inertizing, Heat pipe heat exchanger among others, see Furszyfer Del Rio et al. and Castro Oliveira et al.[18,120].
[b]*Ibid.*
[c]Specific to the Ceramics industry, see Unie et al.[117]
[d]CCS assumed to tackle process emissions only.

the literature by being global in nature, covering the majority of industrial sectors, and having an explicit baseline against which the energy and emissions savings are calculated.

Currently, the policy focus in many countries is on decarbonizing the most significant energy and emissions intensive sectors, such as steel, cement and lime, and chemicals. We show that these are among the sectors best placed to make substantial emissions reductions. A range of medium to high maturity decarbonization options are available based on CCS, fuel switching to hydrogen and biomass, which in principle, can reduce emissions in these sectors by around 85% on average. Some fuel switching options and electrification technologies that are applicable to other sectors—including pulp and paper, glass, non-ferrous metals, and food and drink—also have relatively high TRL levels and result in similar emissions reductions.

Looking more broadly across the whole of industry, then there are a range of options with very high TRLs for decarbonizing low-temperature heat, including electric, biomass and hydrogen boilers, and CHP based on hydrogen and biomass. Fuel cells and heat pumps are also relatively mature options in many cases. In contrast, many options for decarbonizing high-temperature heat rely on novel uses of electricity or novel process change that are at low levels of technical maturity and can typically reduce 70% of emissions for most industrial sectors. Table 14 summarizes the key challenges and research development & demonstration (RD&D) needs for these options across sectors. It shows that most options need further technical assessments, optimization, and performance enhancements compared with conventional technologies. The RD&D programs should consider the time needed to develop, implement, and diffuse new technologies and that industrial emissions reduction is needed within the next 30 years.

Further RD&D is therefore needed for those technologies to reduce their cost accompanied by large-scale infrastructure development to provide the necessary

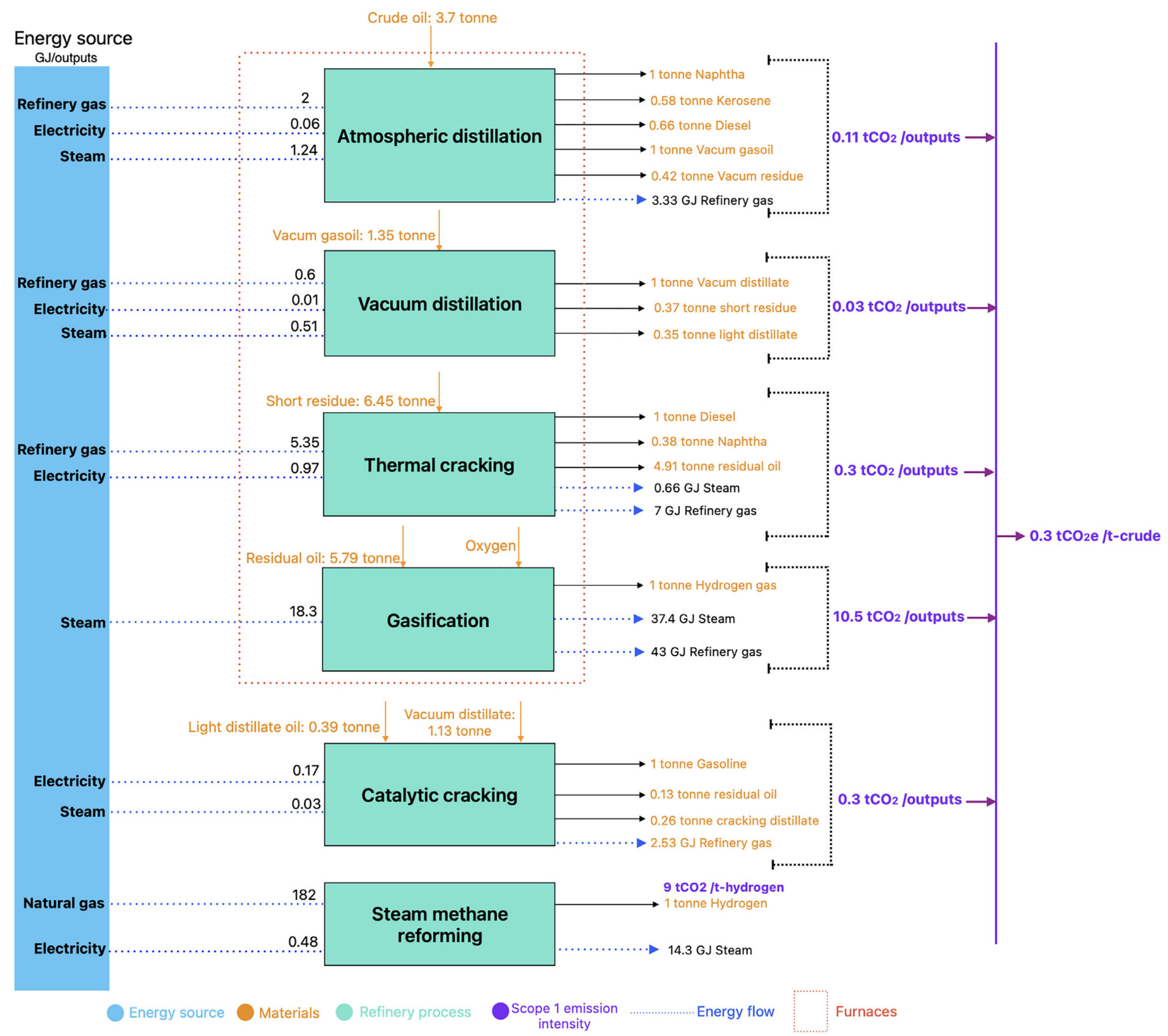

Figure 11. Main processes, energy use and emissions for oil crude production
Produced based on the data from PBL[57] and Jing et al.[121]

decarbonized energy supplies and CO_2 removal options. It is recommended to (1) prioritize options with high mitigation potential and high TRL for implementation and explore benefits and synergies across sectors, (2) provide funding for research and demonstration for mitigation options with high mitigation potential and low TRL such that they can be fully commercialized in the next 10 years, and (3) address barriers to technology adoption by adopting policy changes, providing financial incentives or other strategies.

The cost of decarbonization technologies

The uptake of many industrial decarbonization technologies is impacted by high capital and operational costs compared with counterfactual technologies, even if their technical challenges can be resolved. Electrification technologies typically have 2–3 times higher operational costs compared with fossil fuel-based

Table 13. Decarbonization options for the refinery sector

Process	Decarbonization option	TRL	Maximum emission saving potential (%)	Source
Process heat (furnaces)	fuel switching—hydrogen	3	51–63	Oliveira and Schure, Byrum et al., and Griffiths et al.[122–124]
	furnaces electrification	3	51–63	Oliveira and Schure and Byrum et al.[122,123]
	CCS	6–8	51 – 63	Oliveira and Schure, Byrum et al., Griffiths et al., and Güleç et al.[122–125]
Catalytic cracking (process emissions)	CCS	6–8	9	Oliveira and Schure, Byrum et al., and Griffiths et al.[122–124]
	cold cracking	2–3	9	U.S. Department of Energy[10]
Steam reforming (process emissions)	see Table 5	–	21	–
CHP and steam boilers	see Table 3	–	10	–
All refining processes	energy efficiency measures	–	50	U.S. Department of Energy and Griffiths et al.[10,124]

technologies due to the higher cost of electricity relative to fossil fuels in many markets.[137] Similarly, the cost of CCS technologies is the main barrier to their implementation with a capture cost of nearly USD10–250/tCO_2 depending on the technology and industry setting.[138]

This additional expense can substantially increase the production cost for some industries. Worldwide steel production cost could increase by 15% by 2050 if low-carbon technologies are used.[47,139] Producing olefins and aromatics via a decarbonized steam cracking route or MTOs process can increase their cost by 50%–220% by 2050.[66] Green ammonia production is likely to increase its cost by 13%–41% by 2030.[58] Decarbonized cement and paper production cost might increase by nearly 30% and 8%–15% in 2050, respectively.[70,97,140] Nevertheless, if the additional costs of these decarbonization technologies are passed to consumers through increases in the price of goods, then the overall impact is likely to be relatively small. A case study for the UK showed that industrial decarbonization consistent with the 2050 net-zero goal could be achieved with an aggregate increase in consumer prices of less than 1%.[141]

Implementation challenges

Investment in decarbonization technologies faces barriers related to the complexity of the industrial sector. The longevity of industrial equipment means that replacing it requires a planning process that can span several years. Cement kilns and steel BFs are typically refurbished every 25 years and have an average lifetime of 40 years.[142] Since industrial processes are highly integrated, downstream processes may also need to change which may result in investment cost increase.[10]

Utilization of self-produced fuels (fuels that are produced and consumed within an industrial sector) can undermine investment in low-carbon technologies even if their performance is proven. The recovery cycle of black liquor makes pulp mills energy self-sufficient.[143] The decision to invest in new refinery technologies is often dominated by the cost of self-produced fuels which constitute 61% of the total energy use in refineries.[122] Similarly, nearly 75% of the energy needs of steam crackers is satisfied using internal fuel gases, challenging the rationale for switching to different energy sources.[63]

Infrastructure challenges and biomass availability

Most of the industrial decarbonization technologies require new and upgraded supporting infrastructure. Upgrading the electricity network or finding ways to reduce the electricity demand with flexible technologies is necessary to meet the power needs of electrification technologies. Large, energy-intensive sites may require

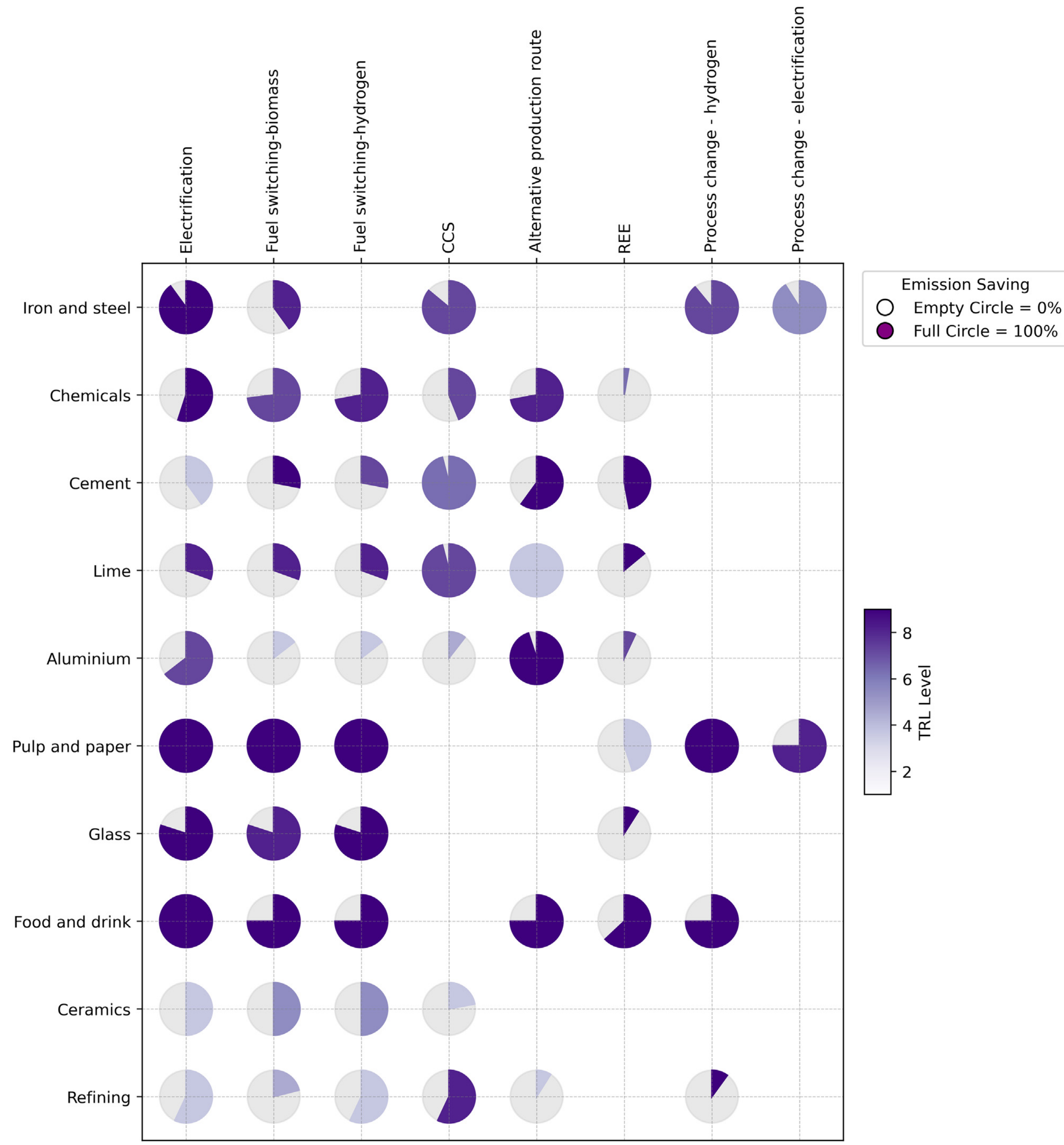

Figure 12. Maximum emission saving potential for industrial sectors by abatement category and technology readiness level

from 100 MW to 1 GW of additional electricity capacity if they adopt some electrification technologies.[137] This upgrade can cost £7m or £12m per site for glass and paper manufacturers, respectively, if adopting electric technologies.[106,144]

CCS and hydrogen technologies need infrastructure in terms of transport and storage platforms with the potential of re-using existing oil and gas industries to reduce cost.[26,142] Since industrial sites have different capacities, transport distance, and

Table 14. Key challenges and RD&D needs for low TRL technologies across sectors

Sector	Key low TRL abatement option	Challenges	Key RD&D need	Sources
Iron and steel	iron ore electrolysis + EAF hydrogen-based plasma reduction	production scale-up sensitive to different iron ore feeding	development of inert anodes better design of cathodic electrode	Draxler et al. and Cavaliere[51,128] Springer et al.[129]
Chemicals	electric steam cracker	high electricity use	efficiency increase	Middleton[130]
Cement	plasma torches—electricity magnesium oxides derived from magnesium silicates	low capacity of torches low alkalinity	further testing and operation develop reinforcements (fiber-reinforced polymer composite)	Schneider et al.[131] Badjatya et al.[132]
Lime	chemical synthesis	the dependence on other materials (soda ash and caustic soda)	perform full life-cycle assessment	Simoni et al.[87]
Aluminum	boilers	high capital cost	–	Mission Possible Partnership[93]
Pulp and paper	pulp—deep eutectic solvents paper—supercritical CO_2	poor conductivity discover optimal operating conditions	further assessment compared to traditional pulping further testing and integration with the paper machine	Gülsoy[133] CEPI[134]
Glass	plasma melting	production scale-up and expensive argon gas	–	Zier et al.[107]
Food and drink	–	–	–	–
Ceramics	microwave/spark plasma sintering	further evaluation to key operation parameters (distribution of electromagnetic field, etc.)	further process optimization	Karayannis[135]
Refining	cold cracking	material handling problems	further testing and comparisons with conventional refining	National Energy Technology Laboratory[136]

storage places and conditions, CO_2 and hydrogen infrastructure size varies significantly. CO_2 transport cost is found to be between €1.5–€5 and €3.5–€9.5 per tonne CO_2 for onshore and offshore pipelines, respectively.[145]

Building the necessary infrastructure is currently envisioned near clustered industries in many countries where industries will be able to share the investment cost.[12] However, some industries are located outside of those clusters such as cement sites in the UK and iron and steel sites in the US. This poses significant challenges for infrastructure roll-out especially for hydrogen and CCS.[10,11]

Biomass fuel switching for industrial processes is likely to be impacted by several barriers. First, its availability as an energy source and the impact on land use. Second, the alignment of biomass use with international sustainability standards and trade rules.

Further research on place-based potential assessment and technology costs

While we have attempted to provide a technical assessment for the abatement options across industrial sectors, the potential to implement these technologies require more careful understanding of the local context of industrial sites. This requires further analysis on the socio-economic context, policy, markets, and regulation, business models, infrastructure, and resource availability.

We also note that accurate technology costs need to be considered for techno-economic assessments and modeling purposes.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.joule.2024.01.007.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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