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Supplementary Material

Roadmap for Decarbonization of the Building and Construction Industry–A Supply Chain Analysis Including Primary Production of Steel and Cement

Ida Karlsson [1,*], Johan Rootzén [2], Alla Toktarova [1], Mikael Odenberger [1], Filip Johnsson [1] and Lisa Göransson [1]

[1] Department of Space, Earth and Environment, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden; alla.toktarova@chalmers.se (A.T.); mikael.odenberger@chalmers.se (M.O.); filip.johnsson@chalmers.se (F.J.); lisa.goransson@chalmers.se (L.G.)

[2] Department of Economics, University of Gothenburg, SE-405 30 Gothenburg, Sweden; johan.rootzen@economics.gu.se

* Correspondence: ida.karlsson@chalmers.se

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1. Cement/ Concrete Production and Use

The cement clinker production is responsible for the majority of GHG emissions related to concrete use with the main current emission abatement options comprising of reducing the binder intensity (amount of cement or cement substitutes) in concrete, reducing the amount of cement clinker by using alternative binders (i.e., waste-based or natural supplementary cementitious materials) and replacing fuels in the cement manufacturing process with waste- or bio-based fuels [1]. The only Swedish cement producer Cementa, is a frontrunner when it comes to alternative fuels with biofuels and waste-based alternative fossil fuels (e.g., plastic waste, tires, and solvents) together making up around 70% of the fuels for its kilns in 2017 [2]. In contrast Sweden is behind the rest of Europe in using alternative binders. While the average share of clinker in cement in Europe is 73% [3], Swedish cement production has an average clinker content of 86% [4].

Partly explained by regulations, national standards and norms historically being more restrictive [5,6], adoption of concrete with cement clinker substitutes is a key measure requiring further attention. However, as the main alternative binders used at current, i.e., fly ash from coal power production and blast furnace slag from steel production [7], are both set to reduce as coal power production is phased out and primary steel production is converted, the use of alternative SCMs, such as agricultural ashes and calcined clays, will need to upscaled [3,8–10].

Regarding optimization of concrete recipes, there is often 20–30% more cement in the concrete mix today than what is required by standards, which occurs for two reasons: over-specification of cement by concrete producers, and higher exposure classes for the concrete than the situation demands [3]. In Sweden, we are also facing an additional issue in that faster construction processes have led to highly set drying requirements, for example for slabs covered with plastic or parquet flooring concrete with very high cement content are used.

As a result, the average cement/binder content used in concrete is higher in Sweden than in other countries, with around 420 kg binder per m^3 concrete compared to an average 400 kg binder per m^3 concrete in Europe overall [11–13]. There is thus a large potential for the cement demand to be reduced by changing construction production planning to suit new cement types, adjust concrete recipes depending on the specified flooring and add a screed layers or apply floating flooring solutions to create a buffer zone between concrete and flooring [14].

Other prominent abatement options include design optimization to slim constructions, increased prefabrication to reduce waste and minimize construction process emissions, together with material substitutions towards wood-based solutions [15]. For building construction in particular, the development of engineered wood products, such as cross-laminated timber (CLT), laminated veneer lumber (LVL), and glued laminated wood (glulam), have enabled increased adoption of construction with a structural core of timber, predominantly for low- and medium-rise buildings [16], with recent examples also of high-rise buildings [17,18]. Indeed, engineered wood products have recently experienced annual growth rates between 2.5% and

15% [19], with future penetration levels highly uncertain, ranging from conservative expectations of 5% substitution from concrete to wood [15] to estimates of 50% to 80% of all new multi-family houses being built with wood in 2025 and 2050, respectively [20,21] (compared to the current rate of 13% multi-family buildings built in wood in Sweden [22]). A growth rate of 5% has been assumed in this study, leading to the share of new multi-family buildings constructed in 2050 being close to 60%.

In terms of the impact of upscaling of structural timber on harvesting levels, a recent Swedish study demonstrates that an annual growth rate of 2% increase in the share of wood framed multi-family buildings would in 2050 correspond to less than half the yearly amount of biomass that Swedish forests can produce [23], while, on a European scale, a calculation was made to suggest that if the entire European population would live in a wood-frame apartment, approximately 40–50 million hectares of forest would be required renew those buildings every 50 years, representing about 25–30% of Europe's forests with current management and harvest levels [18]. On a global level however, the annual volume of concrete used in the world is about ten times greater than the global forest harvesting rate [24].

A range of studies have shown that buildings with wooden structures require less energy and emit less CO_2 during their life cycle than buildings with other types of structures (see reviews in, e.g., Reference [25–29]). For wood products to have a low carbon footprint [7], the main prerequisite is sustainable forestry, which from a CO_2 perspective, implies that the managed forest must capture more CO_2 per year and area than does an equivalent standing forest [30,31]. LCA studies in general presume that this prerequisite is safeguarded and thus consider wood products to be carbon neutral over the lifecycle of a building, while this assumption along with considerations of long-lived wood products being considered as a temporary carbon sink being discussed heavily in literature of late [32–36].

While timber has a strength parallel to grain similar to that of reinforced concrete, timber has a low density compared with conventional structural materials [18]. On the other hand, using wood as a structural material often has the consequence of introducing other materials to achieve certain performance requirements, including gypsum boards for fire resistance [18]. We thus calculate that a structural core of timber requires on average 10% of the weight of a similar structure made of concrete, but an additional 7% plasterboard, based on data found in [23,37–40].

However, even if current abatement options are combined to its full potential, transformative technologies are still required to reach the goal of close to or net zero emissions in the cement industry by 2045. Carbon capture technologies (CCS) with or without electrification of the cement kilns are the key deep decarbonization alternatives. The Swedish cement industry roadmap is targeting climate neutrality by 2030, with the main focus being on biofuels together with CCS [4]. However, Cementa is also pursuing electrification together with Vattenfall through its CemZero project, with a pre-feasibility study released in 2018 [41]. Even with electrification or using biomass to abate the energy related emissions, process emissions remain, and CCS still needs to be applied. However, the electrification serves to purify the flue gas streams which eases CO_2 capture.

In terms of CCS there are two main options, where CO_2 can be either captured after being generated in the cement kiln (post combustion capture technologies) or purified from kiln flue gases by applying combustion with oxygen instead of in air (oxy-fuel capture technologies) [10,42]. Post-combustion capture technologies do not require fundamental modifications of cement kilns and could be applied to existing facilities provided there is enough physical space available on the site. These technologies include scrubbing of CO_2 in flue gases using solvents, such as amine solutions, or capturing CO_2 via a calcium looping cycle using lime-based sorbents [8,43]. Oxyfuel combustion requires more or less a new plant, as well as an air separation unit (ASU), for the production of oxygen [42,44].

Applying carbon capture only in the precalciner has a higher technical maturity than applying carbon capture in the cement kiln. While the capture rate is lower, at about 60%, it provides an important early capture opportunity and has the potential of reducing the energy penalty associated with the captured due to use of waste heat recovery [8,42,45]. Implementing carbon capture technologies in both the precalciner and the kiln could typically achieve 85–90% avoidance of onsite CO_2 emissions [43,46].

Oxy-fuel capture technologies require process modifications but are in general expected to have lower energy consumption and costs than post combustion capture using scrubbing technologies [43,47,48]. However, while some pilot plant projects for post combustion capture with amine scrubbing are underway, for example, in Norway [49], both calcium looping and oxyfuel technologies are still at the early development stage when it comes to cement application (while oxyfuel has been tested at pilot scale in power plant application) [50]. Details of the emission reduction measures for cement and concrete are found in Table S1, while further details and analysis of the emissions, energy and cost implications for the Swedish cement industry can be found in a recent technical report by Karlsson et al. [51].

Table S1. Overview of emission reduction measures for cement and concrete described in literature together with the described time aspect of implementation (if available). (Emissions reductions measures in italic have not been included in the pathway analysis.)

Emission Reduction Measures	Reduction Potential Identified [1]	Time Aspect of Implem-Entation[2]	Additional References
Use of wood as structural building construction material	5% [15] 5–10% [19] 22% [52] 32% [53] 34–69% [17] 9-48% [25] 42–61% [28]		
Use of alternative bridge construction materials (e.g., wood, composites)	9%; Timber [54] 19–31%; Timber [55] 34%; Soil-steel composite [56] 48%; Composite [57]	2025/ 2030-	
Reuse of concrete elements	4% [15] 9% [58] 10–20% including cement recycling [3]	Now/2025-	
Reduced binder intensity—Use of optimized concrete recipe	4-9% [6] 10% [59] 20% [3] 26–33% [15]	Now-	
Reduced overspecification of concrete—Adherence to standards	9% [3] 11–18% [15]	Now/ 2025-	
Design optimization	10% [58] 10% [59] 11% [60] 13% [15] 14% [61] 15% [6] 30% including recipe optimization [62] 33% [9] 20–40% [3]	Now/ 2025-	[9,63,64]
Precast/prefabricated concrete	3% [65] 3–4% [66] 14% [9] 15% [66]	Now-	
Concrete with traditional cement clinker substitutes (e.g., fly ash, granulated blast furnace slag, GGBS), according to current standards (≤35%)	9-35% [67] 13–15%; Fly ash [68] 22%; GGBS [68] 8–10%; 20% GGBS [6] 23%; 6–20% fly ash [69] 26%; 20% fly ash [70] 8–15%; 35% fly ash [6] 12–21%; 35% GGBS [6] 24%; 34% [1] 25%; 35% fly ash [71] 38%; 33% GGBS, 5% ground lime [72]	Now-	[8,54,64,74,75]

	41%; 35% fly ash, 5% ground lime [73]		
Concrete with traditional cement clinker substitutes outside current standards (>35%)	37% [8] 45%; 30% fly ash, 30% GGBS [71] 48%; 55% GGBS, 5% ground lime [76] 61%; 67% GGBS [77] 66%; 73% GGBS [78] 62%; 80% GGBS [79]	2030-	
Concrete with non-traditional waste-based cement clinker substitutes	11%; 10% EAF steel slag [67] 40%; calcium-carbide residue [42] 42%; calcium-carbide residue [1]	2025/2030-	[10,74]
Natural cement clinker substitutes	20%; Pozzolan [80] 20%; Barley/rice husks [81] 27%; Calcined clay [82] 40%; 30% fly ash, 10% silica [71] 47%; 14% silica, 8% fly ash [79]	2025/2030-	[10,74,83]
Advanced concretes	9%; Geopolymer [84] 34%; Geopolymer [1] 44–64%; Geopolymer [85] 45%; Fly-ash based geopolymer [86] 52%; Geopolymer [87] 54% [88] 66%; Geopolymer [42] 47%; Alkali-activated 70% volcanic pozzolan 30% GGBS [89] 55–75%; Alkali-activated [90] 85%; Magnesium-oxide based [42]	2030/2045	[8,91,92]
Cement recycling	6% [58]	2030/2045	
Biomass cement plant fuel substitution	7-30%; Biological sludge [93] 6–10%; Agricultural residues [94] 10%; 40% meat and bone meal [95] 10–12% [8] 10–15% [74] 20% [4] 21–28%; Sewage sludge [96]	2025/ 2030-	[1]
Wastes as cement plant fuel substitution	3–5%; 30% meat and bone meal/ municipal solid waste [97] 6% [98] 1–9% [99] 3–9%; 50% tires [100] 4-11% [74] 12%; 30% refuse-derived [93] 20%; Tires [101]	2025/ 2030-	[1]
Carbon capture and storage to capture cement plant CO_2 emissions	45% [4] 32–48% [74] 48% [8] 39–78% [1] 60–72%; Oxy-combustion/chemical-looping [101] 65-90%; Partial/full oxy-combustion [102] 89–99%; Oxy-combustion/chemical-looping [45] 76–100%; Oxy-combustion/ chemical-looping [44]	2030-	[46,103–105]
Electrification of cement production	32% [106] 33% [107] 54% [108]	2030/ 2045	[4]

[1] Compared with the reference GHG emissions factor for concrete based on Portland cement.

[2] Implementation timelines separated by a backslash denotes different expected timelines for implementation provided in literature. The dash symbolizes progressive implementation for the initial expected year of implementation.

2. Steel Production and Use

Construction steel, often galvanized, is predominantly produced by primary steel, i.e., from iron ore in integrated steel plants, while reinforcement steel is mainly produced by scrap steel in secondary steelmaking plants, called electric arc furnaces (EAF) or mini-mills, although this varies globally depending on the availability of scrap steel [109]. EAFs mainly use electricity but are also fueled by natural gas (25–30%) and a smaller share of coal (<5%).

Overall, enhanced material efficiency and circularity measures are key current abatement options to reduce embodied emissions associated with steel [9,15,58,110]. The main opportunities lie in reducing waste during the construction process; reduce the amount of material in each building by avoiding over-specification and using higher-strength materials; and reusing buildings and building components. Studies have demonstrated that between 35–45% of steel in construction is in excess of what is necessary to achieve the desired structural strength [58,111,112]. Further with better sorting and separation, there is potential for an increased scrap share in primary steel production [58,113].

In the short- to mid-term, bio-based fuels and reducing agents (charcoal or biocoke) is another feasible option to mitigate GHG emissions [114] in modern integrated steel plants. Further CO_2 emissions reductions are difficult without drastic changes in technology.

Technologies with potential for deep emission cuts include top-gas recycling blast furnaces with carbon capture, different smelting technologies, electrowinning, and hydrogen direct reduction [105]. For all of these, wider adoption is unlikely before 2030 [115]. Partial CO_2 capture however is a mature and low-cost technology that can be implemented in the coming 10–15 years without major changes to the existing process and which can be combined with biomass substitution.

For secondary steel production in electric arc furnace (EAFs), electricity is the main energy carrier, making the emission intensity of the electricity used an important factor. Biomass could substitute fossil process energy also here, both as a reducing agent and as fuel in reheating furnaces [116].

Fuel substitution from natural gas to bio-based syngas or biooil is similarly proposed in metallurgical processes [117]. Details of the emission reduction measures for construction and reinforcement steel are found in Table S2, while further details and analysis of emissions, energy, and cost implications for the Swedish steel industry, which are deemed applicable for developments also on a European level, can be found in a recent technical report by Toktarova et al. [118].

Table S2. Overview of emission reduction measures for construction and reinforcement steel described in literature together with the described time aspect of implementation (if available). (Emissions reductions measures in *italic* have not been included in the pathway analysis.)

Emission Reduction Measures	Reduction Potential Identified [1]	Time Aspect of Implem-entation[2]	Additional References
Structural optimization—Reduced overspecification	15% [9] 15–30% [111] 20–50% [15,58]	Now-	
Reinforcement steel produced by secondary (scrap-based) steel	37–56% [109,119,120]	Now-	
Reinforcement steel produced with low emission electricity	5–27% [6] 65% [121]	Now-	[6,121]
Increased scrap-ratio	10–20% [58,113]	Now/ 2025-	
Biomass fuel substitution in integrated steel plants	10% [122] 7–15% [123] 17–23% [124] 30% [125] 20–41% [126] 31–57% 25–37% BF only [127] 88–91% [117]	2025/ 2030-	[114,128]

Emission Reduction Measures	Reduction Potential Identified [1]	Time Aspect of Implem-entation[2]	Additional References
Carbon capture and storage (e.g., combined with blast furnace top-gas recycling, TGR)	23%/60%; TGR w/wo CCS [129] 50%; TGR w CCS [115] 56–62%; TGR w CCS [130] 60%; TGR w CCS [131] 20–80%; HISarna wo/w CCS [115] 5–55%; ULCORED wo/w CCS [115]	2030-	[92,125]
Hydrogen reduction	70%; Hydrogen [106] 53–91%; H-DR: current EU electricity emission factor - zero emission el [130]	2045	[92,108,125,132,133]
Biogas/ biocoke in secondary steel production heating ovens	7–21%; Biobased syngas [134] 6–11%; 50–100% biocoke [127] 28%; Biogas and biocoke [116]	2025/ 2030-	[124,125]
Biomass in steel metallurgy	10% [135]	2025/ 2030-	[117,125,134]

[1] Compared with the reference GHG emissions factor for galvanized steel (construction steel produced from iron ore in an integrated steel plant) and reinforcement steel (produced from 50% primary and 50% scrap steel), respectively.

[2] Implementation timelines separated by a backslash denotes different expected timelines for implementation provided in literature. The dash symbolizes progressive implementation for the initial expected year of implementation.

3. Asphalt Production and Paving

New asphalt technologies and mixes can reduce the temperatures required to produce and place the material, lessening fuel consumption and GHG emissions [136]. Another key advantage of warm mix asphalt (WMA) compared to conventional hot mix asphalt is the potentially greater use of recycled (or reclaimed) asphalt pavement (RAP), reducing the need for virgin bitumen binders [137]. Even lower temperature asphalt emulsions are currently used on low traffic roads, while mixes able to withstand heavier traffic are under development [136,138].

Fuel substitution in the asphalt plants to biofuels is another option being implemented widely in Sweden [139]. Other potential options include the use of secondary materials to replace natural aggregates [140] and introduction of bio-based binders [141]. Details of the emission reduction measures identified for asphalt are found in Table S3.

Table S3. Overview of emission reduction measures for bitumen-bound layers described in literature together with the described time aspect of implementation (if available). (Emissions reductions measures in *italic* have not been included in the pathway analysis.)

Emission reduction measures	Reduction potential identified [1]	Time aspect of implementation[2]	Additional references
Bio-based fuel in asphalt production	33% [142] 35% [139] 47% [143]	Now-	[144]
Biobased bitumen	16–23% [139] 30% [141]	2030-	
Low-tempered warm asphalt (WMA)	5–12% [137] 10%; incl. 40% RAP [137] 12%; WMA in base layer with 30% RAP [145] 15–16% [146] 19% [136]	Now-	
Cold asphalt emulsion mix	52% [138] 40–60% [137] 68%; incl. 40% RAP [136]	2025-	
Asphalt recycling and reuse	10%; WMA with 40% RAP [137] 12%; 20% RAP [136] 13–24%; 25% RAP [147] 13–14%; HMA and WMA with 15% RAP [146] 5–20%; 50% RAP [148] 16–25%; 30%-50% RAP [149] 23–36%; 77% RAP [150]	Now-	[151,152]
Reduce aggregate moisture content	1–5% [148] 4–14% [137] 9% [144]	Now-	
Use of other waste products in pavements	5%; Fly ash [153] 6%; Blast furnace slag [154]	2025-	[140,155]
Bio-fueled/electric aggregate production	2–3% [144] 3% [142] 6–7% [143]	2030-	[156]

[1] Compared with total reference GHG emissions for bitumen bound layers.

[2] Implementation timelines separated by a backslash denotes different expected timelines for implementation provided in literature. The dash symbolizes progressive implementation for the initial expected year of implementation.

4. Insulation

At present, polystyrene and mineral wool are the most frequently used for insulating buildings [157]. In comparison with polystyrene, mineral wools have a lower carbon footprint and primary energy demand [27,158]. Nevertheless, mineral wool production requires high temperature furnaces often fueled by oil or natural gas [159], and rock wool production, a certain consumption of coal to fuse the basaltic rock [158]. Fuel change together with energy efficiency measures are key abatement measures for production of both mineral wool and polystyrene insulation [15,159,160]. Regarding polystyrene, abatement options that are pertinent to plastic production are also of relevance. The introduction of recycled materials into the product composition is another option to improve the environmental performance of mineral wool insulation, particularly relevant for glass wool production [161,162].

Other abatement options the use of natural resins, such as wood fiber and cellulose, as insulation material [163,164]. However, while having lower embodied emissions lower than those of mineral wool, the natural insulation materials available in the market at current have higher thermal conductivity than that of mineral wool and this leads to a thicker insulation layer [165]. Details of the emission reduction measures identified for insulation are found in Table S4.

Table S4. Overview of emission reduction measures for use of insulation materials in buildings described in literature together with time aspect of implementation (if available). (Emissions reductions measures in *italic* have not been included in the pathway analysis.)

Emission Reduction Measures	Reduction Potential Identified[1]	Time Aspect of Implement-ation[2]	Additional References
Material substitution - Alternative conventional insulation materials (glass/rockwool)	32–75% [158,166,167]	Now-	[161,168]
Material substitution - Alternative non-conventional insulation materials (cellulose, wood chips, cork, hemp, flax)	63–94% [158,159,166,167,169]	2025-	[161,163,165]
Glass wool produced from recycled glass	30% [160,166] 37% [7]	Now-	
Energy efficiency and fuel change (including electrification) for mineral wool production	12% [160,170]	2025-	
Energy efficiency and fuel change for plastic and EPS/XPS production	21–44% [15,161]	2025-	

[1] For material substitution compared with reference GHG emissions data for polystyrene-based insulation. For specific material production measures compared with the reference production for the specific insulation material.

[2] Implementation timelines separated by a backslash denotes different expected timelines for implementation provided in literature. The dash symbolizes progressive implementation for the initial expected year of implementation.

5. Gypsum and Plaster

The most prominent abatement measure for the production of gypsum for plasterboards is the use of recycled gypsum, with studies confirming it is possible to substitute 100% of commercial gypsum with gypsum waste from industrial plasterboard production without any heating treatment [171]. A positive side-effect of gypsum recycling is also a lowered energy consumption for the fabrication of recycled gypsum [172]. Recycling can be combined with electrification of biofuel substation in the heating furnaces used in the production of gypsum [172].

Other abatement options include substituting part of the gypsum in the plasterboards with for example cardboard [173] or use building boards made of natural fibers, such as hemp, flax, or jute [174]. Details of the emission reduction measures identified for gypsum and plaster are found in Table S5.

Table S5. Overview of emission reduction measures for gypsum and plaster described in literature together with time aspect of implementation (if available). (Emissions reductions measures in *italic* have not been included in the pathway analysis.)

Emission Reduction Measures	Reduction Potential Identified [1]	Time Aspect of Implement-ation[2]	Additional References
Electrification/ biofuel substitution	25–85% [172]	2025/2030-	[170]
Recycled feedstock	58–65% [171,172]	Now/2025-	[175]
Biobased feedstock	47–59% [174]		

[1] Compared with total GHG emissions for gypsum plasterboard.

[2] Implementation timelines separated by a backslash denotes different expected timelines for implementation provided in literature. The dash symbolizes progressive implementation for the initial expected year of implementation.

6. Plastics

Plastics are made from fossil oil and gas, produced predominantly through steam cracking of naphtha and ethane, which obtained by refining crude oil and from natural gas, respectively. Indeed, the steam cracking is responsible for a large share of its carbon footprint (~40%) combined with feedstock production, refining, polymerization and blending [15]. Improved efficiencies in the refining, cracking and polymerization steps could be achieved via enhanced catalytic processes or advanced membrane separation [170,176]. Deep abatement options for plastics production otherwise include electrification of cracking and polymerization [108]. Another is to fit carbon capture and storage or use (CCS/U) to current processes. To reach deep abatement level, however, carbon capture would need to be applied not just to fit the core steam cracking process, but also to refining to capture CO_2 upstream (and to end-of-life incineration plants to capture CO_2 downstream) [15].

However, plastic can be also recycled, rather than incinerated, either by mechanical or chemical means [9,58,177]. A more current abatement option is reduced use of plastics in key value chains. Through greater materials efficiency in end products, plastics demand in the buildings value chains could be reduced by up to 35% [9,58]. There are also developments around alternative biobased or synthetic feedstocks [177]. Details of the emission reduction measures identified for plastics are found in Table S6.

Table S6. Overview of emission reduction measures for gypsum and plaster described in literature together with time aspect of implementation (if available). (Emissions reductions measures in *italic* have not been included in the pathway analysis.)

Emission Reduction Measures	Reduction Potential Identified [1]	Time Aspect of Implement-ation[2]	Additional References
Material efficiency	14–35% [15,58,177]	Now-	
Energy efficiency and fuel change	15–40% [15,178]	Now/2025-	
Novel catalysts and membranes	5–15% [170]	2025-	[177]
Electrification/CCS on refining, cracking and polymerization	60–65% [15,177]	2030-	[108]
Plastics recycling	56% [58] 91–100% [15]	2030-	[110]
Biobased/synthetic feedstock	40% [15,177]		

[1] Compared with average GHG emissions for polyethylene (PE) and polyvinylchloride (PVC).

[2] Implementation timelines separated by a backslash denotes different expected timelines for implementation provided in literature. The dash symbolizes progressive implementation for the initial expected year of implementation.

7. Construction Process

The main abatement technical measures for the various construction machinery used in road construction are fuel substitution, hybridization and eventually electrification [179–181]. Hybrid excavators are already available on the market along with a few examples of hybrid wheel loaders and this development is expected to continue, going towards electrification where possible [182].

Non-technical abatement measures include optimization of mass handling requirements and optimization of utilization of vehicles, speeds and routes, and choice of vehicles for the intended use [180].

The main abatement measures relating to crushing plants are also fuel substitution and electrification together with in-pit crushing and conveying [183]. Details of the emission reduction measures identified for construction equipment and the construction process are found in Table S7.

Table S7. Overview of emission reduction measures for construction equipment, including crushing plants described in literature together with time aspect of implementation (if available).

Emission Reduction Measures	Reduction Potential Identified [1]	Time Aspect of Implem-entation[2]	Additional References
Shifts to biofuels in construction equipment	86%; HVO 2017 well-to-tank vs Diesel MK1 [184] 36–90%; HVO well-to-tank from various sources vs fossil diesel [185] 66–90%; HVO well-to-tank from various sources vs fossil diesel [184] 1–+3%; Tank-to-wheel [186]	Now-	[180,181,186, 187]
Hybridization of construction equipment	15–25%; General [180] 13–26%; Excavators [188] 15%; Excavators [189] 25–40%; Excavators [180] 21–41%; Excavators [190] 10–35%; Wheel loaders [180] 20–50%; Wheel loader [191] 30%; Wheel loader [192]	Now/ 2025-	[181]
Fuel-celled/ plug-in hybrid construction equipment	50% [192] 56–59% [193] 60%; Supercapacitor and batteries [190]	2030-	[180,181,191]
Electrified construction equipment	67%; Energy efficiency [194] 95% [182] 95% [195]	2030/ 2045	[181,196]
Optimization of mass handling/ equipment use	4–13% [191] 10% [180] 12% [197] 17% [198] 21% [183]	Now-	[199]
Bio-fueled/ electric rock crushing plants	17%; Bio-fueled [198] 94–97%; Electric [200] 91–97%; Electric [183] 91%; Electric [201] 95%; Electric [202]	Now/ 2025-	[195]
Work shed/office efficiency	7–9% [40] 7–10% [178]	Now-	[203]

[1] Compared with total GHG emissions based on the reference energy use of the specific construction equipment/construction process activity.

[2] Implementation timelines separated by a backslash denotes different expected timelines for implementation provided in literature. The dash symbolizes progressive implementation for the initial expected year of implementation.

8. Heavy Transports

Like construction equipment, heavy-duty trucks are predominantly driven by internal combustion engines fueled by diesel. Fuel substitution is thus a key emission reduction measure, with other opportunities being vehicle efficiency technologies including hybridization with double power trains, waste heat recovery, and regenerative braking expected to offer the largest emission reduction potential [204,205].

Complete electrification with battery electric trucks for long-haul trucking could be possible in the mid- to long-term but to allow their wide-spread usage the road-freight sector would have to transform well beyond the vehicle, including large-scale infrastructure investments, such as a vast, comprehensive rollout of fast-charging infrastructure and/or electric road infrastructure [206]. Finally, improving the logistics of trucking movements also bear significant potential [207]. Details of the emission reduction measures identified for heavy transports are found in Table S8.

Table S8. Overview of emission reduction measures for heavy transport (trucks and on-road haulers) described in literature together with time aspect of implementation (if available).

Emission reduction measures	Reduction potential identified [1]	Time aspect of implement-ation[2]	Additional references
Shifts to biofuels in heavy transports	86%; HVO100 2017 well-to-tank compared to Diesel MK1 [184] 36–90%; HVO well-to-tank from various sources compared to fossil diesel [185] 66–90%; HVO well-to-tank from various sources compared to fossil diesel [184] 1–+3%; Tank-to-wheel [186]	Now-	[206–208]
Hybridization of heavy transports (double power trains)	6–19% [209] 16% [210] 11–22% [211] 31% [212] 33% [213]	2030-	[205,206,214]
Fuel-celled/ plug-in hybrid heavy trucks (potentially in combination with electric road systems)	27–39% [215] 40–50% [208] 50% [206] 70% [213]	2030/ 2045	[58,207,216]
Optimization of logistics and road freight operations	20% [206] 10–33% [207]	Now-	

[1] Compared with total GHG emissions based on the reference energy use of a 32-ton Euro 6 truck.

[2] Implementation timelines separated by a backslash denotes different expected timelines for implementation provided in literature. The dash symbolizes progressive implementation for the initial expected year of implementation.

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