Table A. Overview of breakthrough low-CO_2 iron and steel production technologies

The table maps some key parameters of breakthrough low-CO_2 production technologies in the EU iron and steel industry. Data marked with an asterisk (*) and the column 'Other comments' are the authors' own assessments based on previously presented references. For unreferenced cells, see previous reference.

Break-through low-CO_2 technologies for EU steelmaking	Technology	Description	Development period	Actors involved	Estimated theoretical emission mitigation (compared to BF/BOF steelmaking)	Estimated theoretical energy demand (compared to BF/BOF steelmaking)	Estimated TRL	Funding and estimated costs (including CAPEX and OPEX)	Other comments
The Hydrogen path	**SALCOS**[1]	The SALCOS technology is based on hydrogen-based DRI-EAF steelmaking. Project linked to the GrInHy project, for production of green industrial hydrogen.	First phase: feasibility study 2017⇒2020[2]	Salzgitter AG, Fraunhofer[3]	26-95% (-26% CO_2 compared to current BF-BOF production; -82% CO_2 if operated with 55% H2; -95% CO_2 if operated with 100% H2)[4]	n.a. (Assuming operation with 55% H_2, additional renewable electrical power demand amounts to ~12.43 TWh/year and additional natural gas demand ~23 PJ/year. This equals approx. 6.9% renewable generation and approx. 0.8% natural gas consumption in Germany 2016)[5]	1-3*	Capex of the integrated project is estimated to around €1.3 Bn.[6]	A demo-plant is under construction in Germany, and developments in local infrastructure (e.g. grid extensions)[7] and regulatory conditions[8] are expected to determine the success of large-scale implementation.
	SUSTEEL[9]	Based on hydrogen-based DRI-EAF steelmaking (Hydrogen Plasma Smelting Reduction: HPSR process). Project linked to the H_2 future hydrogen technology.[10]	First phase: first stage R&D 2017⇒2019[11]	Voestalpine Group, K1-MET Metallurgical Competence Center, Primetals, MUL[12]	n.a. (The consortium has chosen not publish any emission reduction values, and are currently computing predictions that will be ready for publication within 1-2 years)	n.a. (The consortium has chosen not publish any estimated emission reduction values, and are currently computing predictions that will be ready for publication within 1-2 years)	1-3*	Funding received under Austrian FFG Project: Production of the Future (15th Call). Expected project cost is €2,6Mn.[13]	The technology can act as a possible reserve power for grid services with rapid response during fluctuating renewable energy[14]. Upscaling from 100g to 20kg, from an existing laboratory reactor batch to operation, is currently planned at the Voestalpine Donawitz site.[15]

	Hybrit[16]	Direct reduction of iron into steel using with hydrogen and renewable energy, which generates water as a byproduct instead of carbon dioxide. Hybrit uses hydrogen for steel production –but no decision over which hydrogen-making tech will be used.	Second phase: pilot plant construction 2018⇒2024[17]	SSAB, LKAB, Vattenfall. Large involvement by the Swedish state, which owns parts of the firms and has granted funding through the Swedish Energy Agency.	95%[18]	75% (Based on the Swedish energy mix) Lower primary energy demand from approx. 5200kWh to 600kWh per ton of steel Higher electricity demand, from approx. 200 kWh to 3500 kWh[19]	2-4*	The three actors have, together with the Swedish Energy Agency (which will take about one third of the cost), committed to invest €135,5 Mn in the pilot plant.[20] Cost of steel product expected to be 20-30% more expensive[21]	Advantage for SSAB is the timing of the expenditure, since they can coordinate the new installations with out-phasing of old installations (that otherwise would need reinvestments). Challenges are to successfully produce 100% hydrogen on a commercial scale, and to maintain energy efficiency to ensure a competitive technology.[22] The Swedish state has strong involvement in the project (see e.g. Industriklivet)[23]
The carbon capture and usage path	**Carbon4PUR**[24]	Based on transformation of the flue gas streams (containing CO_2/CO) from the energy-intensive industries into higher value intermediates for market-oriented consumer products.[25]	Second phase: development and demonstration 2017⇒2020[26]	Covestro, ArcelorMitta, Dechema [14 partners][27]	20-60% [Secondary reduction] (20-60% reduction in carbon footprint of PUR intermediates compared to today's crude-oil based production)[28]	70% (70% reduction of process energy in the polyol producing industry, including 15-36% reduction of petrochemical epoxy compounds)[29]	2-4*[30] (Target TRL of current phase: 4-6)[31]	The project is funded under H2020 Spire (H2020-EU.2.1.5.3. - Sustainable, resource-efficient and low-carbon technologies in energy-intensive process industries).[32]	The project is expected to result in strong industrial symbiosis between consortium partners in the Port Maritime de Fos (France).[33]

	Steelanol[34]	Steelanol is making industrial waste gases into liquid fuels, through biotech solutions for transformation of carbon monoxide to ethanol.[35]	Second phase: pilot plant construction 2018⇒2020[36]	ArcelorMittal Primetals Technologies, Lanzatech, E4tech[37]	Reduced direct emissions and 65% secondary reduction[38] (CO_2 emissions from Steelanol-biofuels are 50-70% lower than petroleum-based fuels, and around 35% compared to when steel plant off-gases are converted into electricity.[39] If fully deployed, emission reductions of 65% could be achieved through EU bioethanol production of 2.5 Mn tons).[40]	Low additional energy demand (Improved overall efficiency for steel plant off-gases. Meanwhile, the CO will not be valorised in an electric power plant)[41]	4-6[42] (Target TRL of current phase: 5-7)[43]	The project has received €10,2Mn funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 656437.[44] Expected project cost is €14Mn.[45]	In a next step, the ethanol can be transformed into ethylene through a relatively straightforward and energy efficient dehydration process. For this, estimated emission reductions, when compared to ethylene production through steam-cracking of naphtha, would be around 35-40%. However, to have a high yield of ethanol, additional hydrogen is required in the Steelanol process. It is possible that more diverse basic chemicals (C_3-C_4 or even aromatics) can be produced directly or indirectly through the Steelanol process (although this research is still at an early stage).
	Carbon2Chem[46]	Based on utilisation of industrial waste gases, aiming to use smelting gases for chemicals production (e.g. methanol).[47]	Second phase: pilot plant construction 2017⇒2030[48]	ThyssenKrupp AG, Fraunhofer UMSICHT, and the Max Planck Institute for Chemical Energy Conversion [18 partners][49]	n.a.	n.a.	2-4*	The project has received over €60Mn from the German Federal Ministry of Education and Research.[50] The partners involved intend to invest >€100Mn by 2025. They have earmarked > €1Bn for commercial realisation[51]	The Carbon2Chem project is expected to have capacity to transform 2 million Nm3 waste gas per hour. Fluctuations in operations and changes in temperatures and pressures are expected to be a core challenge at plant level.[52]

	FReSMe[53]	The FReSMe technology captures CO_2 from steel production for production of methanol fuel to be utilised in the ship transportation sector. Project linked to the STEPWISE and the $MefCO_2$ technologies.[54]	Second phase: Pilot plant construction 2016⇒2020[55]	TataSteel, SSAB [11 partners] [56]	n.a.	n.a.	3-5[57] (Target TRL of current phase: 6) [58]	This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727504.[59]	The project comprises the full value chain, from CO_2 capturing at a steel plant, to end user demonstration in the ship transportation sector.[60]
Other technologies	**HIsarna**[61]	HIsarna is a new type of furnace in which iron ore is directly injected and liquefied in a high-temperature cyclone so that it drips to the bottom of the reactor where powder coal is injected. The two react into liquid iron.[62]	Third phase: upscaling 2017⇒2020[63]	TataSteel, Rio Tinto, ArclorMittal, ThyssenKrup, Voestalpine, Paul Wurth (former consortium under ULCOS) [64]	Min 20% emission mitigation; 35% (with high scrap use); 80% (with CCS)[65]	80% (At least 20% lower energy demand than BF-BOF) [66]	7[67]	The project has received funding under Horizon2020 (SILC-II). To date, €75 has been invested into the project, of which 60% has been funded by the partner companies and 40% from the EU, the Dutch Economics Minstry and the European Research Fund for Coal and Steel. Expected project cost €300Mn.[68]	The Hisarna technology was one of the technologies investigated under ULCOS. A demonstration plant of industrial size (0.5 – 1.0 Mt per year) is expected to require an investment of €300-350Mn. A demonstration plant is expected to be constructed at TataSteel's plant Ijmuiden (NL) in 2020-2025.[69]
	SIDERWIN (previously ULCOWIN) [70]	Based on CO_2-free steelmaking through electrolysis, transforming iron oxide (e.g. hematite) into a steel plate (at the cathode) and oxygen (anode).[71]	Third phase: pilot plant construction 2017⇒2022[72]	ArcelorMittal [12 partners] [73]	87% (Reduction by 87% of direct CO_2 emissions.) [74]	31% (Reduction by 31% of direct energy use) [75]	4-5[76] (Target TRL of current phase: 6)[77]	The project has received €6,8 Mn through SPIRE (H2020 2.1.5.3)[78]	The SIDERWIN technology is based on the ULCOWIN technology- one of the technologies investigated under ULCOS. Energy consumption could amount to 2.6-3.7 Mwh/tons if used for both melting and reduction, or slightly less if only reduction. It requires a higher amount of electricity compared to the BF-BOF route.[79]

	IGAR (Injection de Gaz Réformé)	Based on process-integrated CO_2-capture through top-gas recycling in a blast furnace. Use of plasma torch and reactor to heat and reform gases, enabling less coke/coal consumption.[80]	n.a. (Validation in 2020) [81]	ArcelorMittal (others n.a.)[82]	n.a. (Potential CO_2 savings of 0,1 - 0,3 ton CO_2/ton of crude steel) [83]	n.a.	n.a.	n.a.	Expected CO_2 savings of approx. 500 ktCO_2eq/year, with EU-wide application of approx. 10 MtCO2eq/year. [84]
	PEM (Primary Energy Melter)	Enables melting of low-quality scrap with metallurgy/natural gas (pre-melting in shaft vessel, subsequent superheating process).[85]	n.a. (Part of the technology has been tested for decades. PEM installation expected 2019, integration in 2021)[86]	SMS Group, ArcelorMittal (others n.a.)[87]	n.a. Potential CO_2 savings of 1 ton CO_2 per ton melted scrap[88]	32% (32% lower overall primary energy consumption) [89]	n.a.	n.a.	Expected CO_2 savings of approx. 200 ktCO2eq/year, with EU-wide application of approx. 2500 ktCO2eq/year[90]. Flexible use of primary energy (oil, natural gas, process gas). No losses from power generation and transmission and lower impact on the electricity grid. Specific energy costs are lower.[91]

[1] Salcos (2018). Official webpage. Available at: https://salcos.salzgitter-ag.com/en/
[2] Schaper (2017). CO2 -Reduktion in der Industrie: Grüner Wasserstoff im Hüttenwerk. Available at: https://www.dena.de/fileadmin/dena/Dokumente/Veranstaltungen/Jahreskonferenz_Power_to_Gas/Praesentationen/Block_II_4_Schaper_FINAL.pdf
[3] Salcos (2018). Official webpage. Available at: https://salcos.salzgitter-ag.com/en/
[4] Hille, V. (2018). SALCOS - SAlzgitter Low CO2 Steelmaking. Presentation at EC-JRC Workshop 'Green Hydrogen Opportunities in Selected Industrial Processes' Brussels, 26.06.2018.
[5] ibid.
6[6] ibid.
[7] Verbal source 31.01.2018
[8] https://salcos.salzgitter-ag.com/en/index.html?no_cache=1
[9] Voestalpine (2018). The three pillars of decarbonization. Available at: https://www.voestalpine.com/blog/en/innovation-en/the-three-pillars-of-decarbonization
[10] K1MET (2018). Energy in future steelmaking. Presented at EU seminar "European Steel: The Wind of Change" 31.01.2018 (Brussels). Available at: https://europa.eu/sinapse/webservices/dsp_export_attachement.cfm?CMTY_ID=0C46BEEC-C689-9F80-54C7DD45358D29FB&OBJECT_ID=80BB405C-DA08-56D3-800BC46FC9A6F350&DOC_ID=604E51C2-BF68-0811-55466D1CB8DE995D&type=CMTY_CAL
[11] Birat, Jean-Pierre. (2017). Low-carbon alternative technologies in iron & steel. Presented at IEA 20.11.2017 (Paris). Available at: https://www.iea.org/media/workshops/2017/ieaglobalironsteeltechnologyroadmap/ISTRM_Session3_Birat_201117.pdf
[12] K1MET (2018). Energy in future steelmaking. Presented at EU seminar "European Steel: The Wind of Change" 31.01.2018 (Brussels). Available at: https://europa.eu/sinapse/webservices/dsp_export_attachement.cfm?CMTY_ID=0C46BEEC-C689-9F80-54C7DD45358D29FB&OBJECT_ID=80BB405C-DA08-56D3-800BC46FC9A6F350&DOC_ID=604E51C2-BF68-0811-55466D1CB8DE995D&type=CMTY_CAL

[13] Eurofer (2017). EU ETS REVISION: Unlocking low carbon investments in the steel sector. Presentation 18.01.2017 (Strasbourg). Available at: https://www.google.be/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwii3b2ysevYAhWEZlAKHXMSABsQFggpMAA&url=http%3A%2F%2Fwww.eurofer.be%2FNews%26Events%2FPress%2520releases%2Fws.res%2F180117New%2520Unlocking%2520presentations%2520All.pdf&usg=AOvVaw2CdiIuMMIv7jRM3q7VCS7U

[14] Verbal source 31.01.2018

[15] Sorman, Axel (2018). CDA - Steelmaking without carbon. Presented 22.02.2018 at EU Industry Day 2018 (Brussels). Available at: https://europa.eu/sinapse/webservices/dsp_export_attachement.cfm?CMTY_ID=0C46BEEC-C689-9F80-54C7DD45358D29FB&OBJECT_ID=3978AFA1-B5F7-F82B-80B5AA99F67F40D5&DOC_ID=3A6FBBDD-9CC0-243B-349A95ECD36DC891&type=CMTY_CAL

[16] Hybrit (2018). Official webpage. Available at: http://www.hybritdevelopment.com/

[17] Jernkontoret (2018). Klimatfärdplan för en fossilfri och konkurrenskraftig stålindustri i Sverige. Report in Swedish. Available at: http://fossilfritt-sverige.se/wp-content/uploads/2018/04/ffs_stalindustrin.pdf

[18] Hybrit Brochure (2018). Summary of findings from HYBRIT Pre-Feasibility Study 2016–2017. Available at: http://www.hybritdevelopment.com/

[19] ibid.

[20] Vattenfall (2018a). Available at https://group.vattenfall.com/press-and-media/news--press-releases/pressreleases/2018/hybrit-construction-start-for-globally-unique-pilot-plant-for-creating-fossil-free-steel

[21] Vattenfall (2018b). Available at: https://news.vattenfall.com/sv/article/gront-ljus-for-pilotanlaggning-for-fossilfritt-stal

[22] Verbal source 31.01.2018; Verbal source 28.02.2018; Verbal source 21.06.2018.

[23] Energimyndigheten (2018). Industriklivet. Available in Swedish. Available at: http://www.energimyndigheten.se/forskning-och-innovation/forskning/industri/industriklivet/

[24] Carbon4PUR (2018a). Official webpage. Available at: http://www.carbon4pur.eu/

[25] ibid.

[26] Cordis - Carbon4PUR (2018). Turning industrial waste gases (mixed CO/CO2 streams) into intermediates for polyurethane plastics for rigid foams/building insulation and coatings. Available at: https://cordis.europa.eu/project/rcn/211464_de.html

[27] ibid.

[28] Carbon4PUR (2018b). Flyer. Available at: https://www.carbon4pur.eu/wp-content/uploads/2018/05/Carbon4PUR-Flyer.pdf

[29] ibid.

[30] Own assessment of TRL, based on that targeted TRL for current phase is 4-6. See e.g. Cordis – Carbon4PUR (2018) at https://cordis.europa.eu/project/rcn/211464_de.html

[31] CORDIS – SPIRE 08.2017 (2017). Carbon dioxide utilisation to produce added value chemicals. Available at: https://cordis.europa.eu/programme/rcn/701834_en.html

[32] ibid.

[33] Carbon4PUR (2018a). Official webpage. Available at: http://www.carbon4pur.eu/

[34] Steelanol (2018). Official webpage. Available at: http://www.steelanol.eu/en

[35]ibid.

[36] Vlaamseklimattop (2015). Project “Steelanol” - First commercial project for advanced bio-fuel production from waste gas. Available at: http://www.vlaamseklimaattop.be/sites/default/files/atoms/files/ArcelorMittal%20-%20project%20Steelanol.pdf

[37] Steelanol (2018). Official webpage. Available at: http://www.steelanol.eu/en

[38] Vlaamseklimattop (2015). Project “Steelanol” - First commercial project for advanced bio-fuel production from waste gas. Available at: http://www.vlaamseklimaattop.be/sites/default/files/atoms/files/ArcelorMittal%20-%20project%20Steelanol.pdf

[39] Steelanol (2018). Official webpage. Available at: http://www.steelanol.eu/en
Lanzatech (2013). Siemens and LanzaTech partner to transform steel mill off-gases into bioethanol. Available at: http://www.lanzatech.com/siemens-and-lanzatech-partner-to-transform-steel-mill-off-gases-into-bioethanol/

[40] INEA (2017). Horizon 2020 – Energy and Transport. Compendium of projects implemented by INEA. Available at: https://ec.europa.eu/inea/sites/inea/files/h2020-compendium_2017_web.pdf

[41] Vlaamseklimattop (2015). Project “Steelanol” - First commercial project for advanced bio-fuel production from waste gas. Available at: http://www.vlaamseklimaattop.be/sites/default/files/atoms/files/ArcelorMittal%20-%20project%20Steelanol.pdf

[42] Own assessment of TRL, based on that targeted TRL for current phase is 5-7. See previously presented references.
[43] Steelanol (2018). Official webpage. Available at: http://www.steelanol.eu/en
[44] ibid.
[45] INEA (2017). Horizon 2020 – Energy and Transport. Compendium of projects implemented by INEA. Available at: https://ec.europa.eu/inea/sites/inea/files/h2020-compendium_2017_web.pdf
[46] Carbon2Chem (2018). Official homepage. Available at: https://www.thyssenkrupp.com/en/carbon2chem/#420627
[47] ibid.
[48]IDW (2018). Carbon2Chem®: Keeping carbon in the loop. Available at: https://idw-online.de/en/news696022
[49] Ibid.
[50] Materials and Corrosion (2016). Corrosion News. Materials and Corrosion 2016, 67, No. 8. Available at: https://onlinelibrary.wiley.com/doi/pdf/10.1002/maco.201670084
[51] The Bio Journal (2018). 60 million euros for Carbon2Chem project. Available at: http://www.thebiojournal.com/60-million-euros-for-carbon2chem-project/
[52] Eurofer (2017). EU ETS REVISION: Unlocking low carbon investments in the steel sector. Presentation 18.01.2017 (Strasbourg). Available at: https://www.google.be/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwii3b2ysevYAhWEZlAKHXMSABsQFggpMAA&url=http%3A%2F%2Fwww.eurofer.be%2FNews%26Events%2FPress%2520releases%2Fws.res%2F180117New%2520Unlocking%2520presentations%2520All.pdf&usg=AOvVaw2CdiIuMMIv7jRM3q7VCS7U
[53] FReSMe (2018). Official webpage. Available at: http://www.fresme.eu/about.php
[54] ibid.
[55] CORDIS – FreSMe (2018). From residual steel gasses to methanol. Available at: https://cordis.europa.eu/project/rcn/205958_en.html
[56] FReSMe (2018). Official webpage. Available at: http://www.fresme.eu/about.php
[57] Own assessment of TRL, based on that targeted TRL for current phase is 6. See previously presented references.
[58] CORDIS – FreSMe (2018). From residual steel gasses to methanol. Available at: https://cordis.europa.eu/project/rcn/205958_en.html
[59] ibid.
[60] FReSMe (2018). Official webpage. Available at: http://www.fresme.eu/about.php
[61] HIsarna (2018). Official webpage. Available at: https://www.tatasteeleurope.com/en/innovation/hisarna
[62] ibid.
[63] Eurofer (2017). EU ETS REVISION: Unlocking low carbon investments in the steel sector. Presentation 18.01.2017 (Strasbourg). Available at: https://www.google.be/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwii3b2ysevYAhWEZlAKHXMSABsQFggpMAA&url=http%3A%2F%2Fwww.eurofer.be%2FNews%26Events%2FPress%2520releases%2Fws.res%2F180117New%2520Unlocking%2520presentations%2520All.pdf&usg=AOvVaw2CdiIuMMIv7jRM3q7VCS7U
[64] HIsarna Factsheet (2018). Factsheet. Available at: https://www.tatasteeleurope.com/static_files/Downloads/Corporate/About%20us/hisarna%20factsheet.pdf
[65] Eurofer (2017). EU ETS REVISION: Unlocking low carbon investments in the steel sector. Presentation 18.01.2017 (Strasbourg). Available at: https://www.google.be/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwii3b2ysevYAhWEZlAKHXMSABsQFggpMAA&url=http%3A%2F%2Fwww.eurofer.be%2FNews%26Events%2FPress%2520releases%2Fws.res%2F180117New%2520Unlocking%2520presentations%2520All.pdf&usg=AOvVaw2CdiIuMMIv7jRM3q7VCS7U
[66] HIsarna Factsheet (2018). Factsheet. Available at: https://www.tatasteeleurope.com/static_files/Downloads/Corporate/About%20us/hisarna%20factsheet.pdf
[67] Birat, Jean-Pierre. (2017). Low-carbon alternative technologies in iron & steel. Presented at IEA 20.11.2017 (Paris). Available at: https://www.iea.org/media/workshops/2017/ieaglobalironsteeltechnologyroadmap/ISTRM_Session3_Birat_201117.pdf
[68] HIsarna Factsheet (2018). Factsheet. Available at: https://www.tatasteeleurope.com/static_files/Downloads/Corporate/About%20us/hisarna%20factsheet.pdf
[69] Eurofer (2017). EU ETS REVISION: Unlocking low carbon investments in the steel sector. Presentation 18.01.2017 (Strasbourg). Available at: https://www.google.be/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwii3b2ysevYAhWEZlAKHXMSABsQFggpMAA&url=http%3A%2F%2Fwww.eurofer.be%2FNews%26Events%2FPress%2520releases%2Fws.res%2F180117New%2520Unlocking%2520presentations%2520All.pdf&usg=AOvVaw2CdiIuMMIv7jRM3q7VCS7U
[70] Siderwin (2018). Official webpage. Available at: https://www.siderwin-spire.eu/
[71] ibid.
[72] CORDIS – SIDERWIN (2017). Development of new methodologies for industrial CO2-free steel production by electrowinning. Available at: https://cordis.europa.eu/project/rcn/211930_en.html
[73] Siderwin (2018). Official webpage. Available at: https://www.siderwin-spire.eu/

[74] ibid.
[75] ibid.
[76] Own assessment of TRL, based on that targeted TRL for current phase is 6. See previously presented references.
[77] Siderwin Work Packages (2018). Work packages. Available at: https://www.siderwin-spire.eu/content/work-packages
[78] CORDIS – SIDERWIN (2017). Development of new methodologies for industrial CO2-free steel production by electrowinning. Available at: https://cordis.europa.eu/project/rcn/211930_en.html
[79] Verbal source 28.02.2018
[80] Hensmann et al (2018). Smart Carbon Usage, Process Integration and Carbon Capture and Usage. Presentation at EU Industry Day, 22.02.2018, Brussels. Available at: https://europa.eu/sinapse/webservices/dsp_export_attachement.cfm?CMTY_ID=0C46BEEC-C689-9F80-54C7DD45358D29FB&OBJECT_ID=3978AFA1-B5F7-F82B-80B5AA99F67F40D5&DOC_ID=3A6FBC05-DAFF-1861-B14414BB2A8E8560&type=CMTY_CAL
[81] ibid.
[82] Birat, Jean-Pierre. (2017). Low-carbon alternative technologies in iron & steel. Presented at IEA 20.11.2017 (Paris). Available at: https://www.iea.org/media/workshops/2017/ieaglobalironsteeltechnologyroadmap/ISTRM_Session3_Birat_201117.pdf
[83] Hensmann et al (2018). Smart Carbon Usage, Process Integration and Carbon Capture and Usage. Presentation at EU Industry Day, 22.02.2018, Brussels. Available at: https://europa.eu/sinapse/webservices/dsp_export_attachement.cfm?CMTY_ID=0C46BEEC-C689-9F80-54C7DD45358D29FB&OBJECT_ID=3978AFA1-B5F7-F82B-80B5AA99F67F40D5&DOC_ID=3A6FBC05-DAFF-1861-B14414BB2A8E8560&type=CMTY_CAL
[84] ibid.
[85] ibid.
[86] ibid.
[87] SMS-Group (2018). ARCCESS® PEM - PRIMARY ENERGY MELTER. Available at: https://www.sms-group.com/plants/all-plants/electric-steelmaking/pem-primary-energy-melter/
[88] Hensmann et al (2018). Smart Carbon Usage, Process Integration and Carbon Capture and Usage. Presentation at EU Industry Day, 22.02.2018, Brussels. Available at: https://europa.eu/sinapse/webservices/dsp_export_attachement.cfm?CMTY_ID=0C46BEEC-C689-9F80-54C7DD45358D29FB&OBJECT_ID=3978AFA1-B5F7-F82B-80B5AA99F67F40D5&DOC_ID=3A6FBC05-DAFF-1861-B14414BB2A8E8560&type=CMTY_CAL
[89] ibid.
[90] ibid.
[91] SMS-Group (2018). ARCCESS® PEM - PRIMARY ENERGY MELTER. Available at: https://www.sms-group.com/plants/all-plants/electric-steelmaking/pem-primary-energy-melter/

Table B. Overview of breakthrough low-CO_2 iron and steel production enabling technologies

The table maps some key parameters of breakthrough low-CO_2 production enabling technologies in the EU iron and steel industry. Data marked with an asterisk (*) and the column 'Other comments' are the authors' own assessments based on previously presented references. For unreferenced cells, see previous reference.

Break-through low-CO_2 enabling technologies for steelmaking	Technology	Description	Development period	Actors involved	Estimated theoretical emission mitigation (compared to BF/BOF steelmaking)	Estimated theoretical energy demand (compared to BF/BOF steelmaking)	Estimated TRL	Funding and estimated costs (including CAPEX and OPEX)	Other comments
Hydrogen-making technologies for application in steel production	**GrInHy (Green Industrial Hydrogen)**[xcii]	Produces green industrial hydrogen from natural gas via solid oxide electrolysis. Project linked to SALCOS steelmaking.[xciii]	Second phase: development and demonstration 2017⇒2019[xciv]	Salzgitter AG [8 partners][xcv]	n.a.	n.a. (Electricity demand of around 40kWh/kg. Electrical efficiency during power production designed for 50%)[xcvi]	3-4*	GrInHy has received €4,5Mn EU funding from FCH2-JU under EU's Horizon 2020 in 2016 (no. 700300).[xcvii]	Demo-plant under construction in Germany, and local infrastructure (e.g. grid extensions) expected to be a prerequisite for successful large-scale implementation.[xcviii]
	Methane pyrolysis by BASF/Linde/Thyssenkrupp[xcix]	BASF, the Linde Group and ThyssenKrupp are developing a technology for hydrogen production through methane pyrolysis, where natural gas is processed under high-temperature to obtain hydrogen and carbon.[c]	First phase conducted from 2013⇒2016[ci] Current phase: n.a.	BASF, the Linde Group, ThyssenKrupp[cii]	50% (Approx. 50% reduction in the hydrogen production process compared to steam methane reforming)[ciii]	n.a.	1-3*	Received €9Mn funding from German Federal Ministry of Education and Research (BMBF), under "Technologies for Sustainability and Climate Protection – Chemical Processes and Use of CO2"[civ]	Natural gas with its high hydrogen and carbon content can be decompositioned thermally (without addition of oxygen or water) into hydrogen and solid carbon. The process uses immediate waste heat recycling. The solid carbon can be used in the steelmaking process.[cv]

	H_2 future[cvi]	H_2 Future aims at full-scale demonstration of hydrogen production through PEM electrolysis. Project linked to SUSTEEL.[cvii]	Second phase: Development and demonstration 2017⇒2021[cviii]	Voestalpine, K1-MET, Siemens [5 partners]	n.a.	n.a.	3-4*	Received funding under EU Horizon 2020's project Fuel Cell and Hydrogen (FCH-02-7-2016). Expected project cost is €17Mn[cix]	The technology can act as a possible reserve power for grid services with rapid response during fluctuating renewable energy. The Voestalpine Linz site has the world largest PEM electrolysis unit with 6 MW power and min. 1.200 m3/h H_2 production. Upscaling from 100 g to 20 kg, from an existing laboratory reactor batch to operation, is planned at the Voestalpine Donawitz site.[cx]
Carbon capture and valorisation technologies for application on steel production	**STEPWISE**	STEPWISE captures blast furnace gases and processes them through advanced water-gas shift technology. The cases are cleaned through SEWGS (Sorption Enhanced Water-Gas Shift).[cxi] Project linked to FReSMe.	Second phase: Development and demonstration 2015⇒2019	TataSteel, SSAB [9 partners]	85% (85% reduction in carbon intensity due to higher carbon capture rate)[cxii]	60% (60% lower SPECCA - Specific Energy Consumption for CO_2 Avoided)[cxiii]	3-4*	Received funding under EU Horizon 2020's project (LCE-15-2014). Expected project cost is €13Mn.[cxiv]	The technology is aiming to achieve a 25% reduction in cost of CO_2 avoided.[cxv]
	MefCO_2 (methanol fuel from CO_2)	Based on synthesis of methanol from captured CO_2 using surplus electricity. The technology will use H_2 from water hydrolysis as reactant. Project linked to FReSMe.	First phase: R&D 2014⇒2018[cxvi]	Partners include several research institutes [8 partners][cxvii]	n.a.	n.a.	1-3*	Received €8,6 Mn from the EU's Horizon 2020 research and innovation programme under grant agreement No 637016 Expected cost is €11 Mn.[cxviii]	The technology will have a modular design, to enable adaptation to varying plant sizes and gas composition.[cxix]

[xcii] GrInHy (2018). Official webpage. Available at: http://www.green-industrial-hydrogen.com/home/
[xciii] ibid.
[xciv] Fuel cells and hydrogen (2018). GREEN INDUSTRIAL HYDROGEN VIA REVERSIBLE HIGH-TEMPERATURE ELECTROLYSIS. Available at: http://www.fch.europa.eu/project/green-industrial-hydrogen-reversible-high-temperature-electrolysis
[xcv] Schalper, R. (2017). CO2 -Reduktion in der Industrie: Grüner Wasserstoff im Hüttenwerk. Presented at Jahreskonferenz Power to Gas 20.06.2017. Available at: https://www.dena.de/fileadmin/dena/Dokumente/Veranstaltungen/Jahreskonferenz_Power_to_Gas/Praesentationen/Block_II_4_Schaper_FINAL.pdf
[xcvi] GrInHy – Innovation. (2018) GrInHy's Innovation. Available at: http://www.green-industrial-hydrogen.com/technology/grinhys-innovation/
[xcvii] CORDIS – GrInHy (2016). GREEN INDUSTRIAL HYDROGEN VIA REVERSIBLE HIGH-TEMPERATURE ELECTROLYSIS. Available at: https://cordis.europa.eu/project/rcn/204283_en.html
[xcviii] *Verbal source 31.01.2018*
[xcix] The Linde Group (2015). Linde develops a new production process for synthesis gas. Available at: https://www.the-linde-group.com/en/news_and_media/press_releases/news_20151015.html
[c] ibid.
[ci] Opfermann, A. (2015). The hydrogen option as a carbon free energy carrier. Slideshare presentation. Presented at BASF Science Symposium 10.03.2015 (Ludwigshafen). Available at: https://www.slideshare.net/basf/dr-andreas-opfermann-at-basf-science-symposium-2015
[cii] BASF (2013). Research cooperation develops innovative technology for environmentally sustainable syngas production from carbon dioxide and hydrogen. Available at: https://www.basf.com/en/company/news-and-media/news-releases/2013/07/p-13-351.html
[ciii] ibid.
[civ] Opfermann, A. (2015). The hydrogen option as a carbon free energy carrier. Slideshare presentation. Preseted at BASF Science Symposium 10.03.2015 (Ludwigshafen). Available at: https://www.slideshare.net/basf/dr-andreas-opfermann-at-basf-science-symposium-2015
[cv] BASF (2013). Research cooperation develops innovative technology for environmentally sustainable syngas production from carbon dioxide and hydrogen. Available at: https://www.basf.com/en/company/news-and-media/news-releases/2013/07/p-13-351.html
[cvi] H2-Future (2018). Official website. Available at: https://www.h2future-project.eu/
[cvii] ibid.
[cviii] Sorman, Axel (2018). CDA - Steelmaking without carbon. Presented 22.02.2018 at EU Industry Day 2018 (Brussels). Available at: https://europa.eu/sinapse/webservices/dsp_export_attachement.cfm?CMTY_ID=0C46BEEC-C689-9F80-54C7DD45358D29FB&OBJECT_ID=3978AFA1-B5F7-F82B-80B5AA99F67F40D5&DOC_ID=3A6FBBDD-9CC0-243B-349A95ECD36DC891&type=CMTY_CAL
[cix] CORDIS – H2 Future (2017). HYDROGEN MEETING FUTURE NEEDS OF LOW CARBON MANUFACTURING VALUE CHAINS Available at: https://cordis.europa.eu/project/rcn/207465_en.html
[cx] ibid.
[cxi] STEPWISE (2018). Official webpage: http://www.stepwise.eu/project/
[cxii] CORDIS – STEPWISE (2018). STEPWISE. SEWGS Technology Platform for cost effective CO2 reduction the in the Iron and Steel Industry Available at: https://cordis.europa.eu/project/rcn/193748_en.html
[cxiii] CORDIS – STEPWISE (2018). STEPWISE. SEWGS Technology Platform for cost effective CO2 reduction the in the Iron and Steel Industry Available at: https://cordis.europa.eu/project/rcn/193748_en.html
[cxiv] ibid.
[cxv] Ibid.
[cxvi] CORDIS – MefCO2 (2018). MefCO2. Synthesis of methanol from captured carbon dioxide using surplus electricity. Available at: https://cordis.europa.eu/project/rcn/193453_en.html
[cxvii] SPIRE – MefCO2 (2018). MefCO2. Partners. Available at: https://www.spire2030.eu/mefco2
[cxviii] CORDIS – MefCO2 (2018). MefCO2. Synthesis of methanol from captured carbon dioxide using surplus electricity. Available at: https://cordis.europa.eu/project/rcn/193453_en.html
[cxix] MefCO2 (2018). Teaser. Broschure. Available at: http://www.mefco2.eu/pdf/mefco2-teaser.pdf

Table C. Overview of breakthrough low-CO_2 chemical production technologies

The table maps some key parameters of breakthrough low-CO_2 production technologies in the EU chemical industry. Data marked with an asterisk (*) and the column 'Other comments' are the authors' own assessments based on previously presented references. For unreferenced cells, see previous reference.

Break-through low-CO_2 chemical production technologies	Technology	Description	Estimated theoretical emission reduction (compared to the fossil route) [% lower than -100% mean negative emissions]	Estimated theoretical energy demand (compared to fossil fuel feedstock route) [100% means equal energy use]	Estimated TRL	Estimated costs (including CAPEX and OPEX)	Other comments
Direct use of low-carbon electricity	**Electricity based steam production**[cxx]	Enables decarbonisation by use of renewable energy, since process energy demand for chemicals production is mainly in the form of heat (steam). 60% of total fuel used in chemicals production comes from fuel used to generate steam.	Up to -100% (Provided decarbonisation of the power sector)	n.a.	7	n.a.	Implies strong industrial symbiosis between chemical sector and power sector.
Hydrogen/ CO2-based production routes	**Alkaline electrolysis**[cxxi]	State-of-the art industrial process for electrolytic hydrogen production, using a 20-40% solution of KOH, with Ni-coated electrodes as catalyst.	Up to -100% (Provided decarbonisation of the power sector)	Around 108-113% (4.3 kWh/nm3 (H2) compared to 3,8-4,2 kWh/nm3 (H2) though steam methane reforming)	7-9	CAPEX currently at €1100/kW, predicted to decrease to €600/kW in 2030. OPEX per kW are expected to almost half by 2050.	About 4% of global hydrogen production is based on this process. Efficient plants require 4.3 kWh per Nm_3 of H_2, which amount to a conversion efficiency of around 70%.

	PEM-electrolysis[cxxii]	Runs on pure water and is designed for high pressures (up to 100 bars). The technology is dynamic and can be used in dynamic systems (for example following the power-profile of a wind turbine)	Up to -100% (Provided decarbonisation of the power sector)	Around 105-116% (4.4 kWh/nm3 (H_2) compared to 3,8-4,2 kWh/nm3 (H_2) though steam methane reforming)	7-8	CAPEX currently at €1000/kW, predicted to decrease to €500/kW in 2030. OPEX per kW are expected to almost half by 2050	Fueled with renewable electricity, the PEM electrolyser enables hydrogen to react with CO2 separated from biogas to produce methane, which can be fed into the natural gas grid (see e.g. Audi's E-Gas project)
	High-temperature solid-oxide electrolysis[cxxiii]	Operating at a high temperature (around 700-1000°C) reduces the electricity requirements for splitting water into its elements to 2.6 kWh per Nm3. Due to the high temperature, a ceramic material capable of conducting oxygen ions is required in the cell membrane	Up to -100% (Provided decarbonisation of the power sector)	Around 50-55% (2,1 kWh/nm3 (H_2) compared to 3,8-4,2 kWh/nm_3 (H_2) though steam methane reforming)	6-7	CAPEX currently at €1000/kW. OPEX per kW are expected to almost half by 2050	The technology is especially useful at industrial sites with significant waste heat sources at high temperatures (see e.g. Sunfire in Germany)
	Methane pyrolysis[cxxiv]	Methane or other lower hydrocarbons are decomposed in a high temperature pyrolysis process generating hydrogen and solid carbon	Up to -100% (If heating happens through electricity, and provided full decarbonisation of the power sector)	176% (126.2 Kcal/mol H_2 vs 71.9 Kcal/mol H_2 SMR) assuming electricity is used as energy source for heating	4-5	n.a.	A consortium between BASF, the Linde Group and ThyssenKrupp is investigating this technology, for use in H_2-based steelmaking. The US-based company Monolith42 is investigating plasma pyrolysis

	Thermochemical processes[cxxv]	Can be used for splitting water (with high-temperature heat) and CO_2. Direct water splitting requires more than 2000°C- therefore requiring catalytic thermochemical cycles to reduce the temperature. Thermochemical processes allow generation of syngas (synthesis gas).	n.a.	n.a.	4	n.a.	The process needs to be improved in terms of efficiency and durability of reactant materials, and requires sustainable heat generation to be carbon-neutral.
	Photocatalytical processes[cxxvi]	Splits water at the surface of a catalyst by using solar light energy.	n.a.	n.a.	2-3	n.a.	Limited research to date.
	Low-carbon ammonia (H_2 based)[cxxvii]	Low-carbon ammonia synthesis is limited to an alternative, low-CO_2 H_2 production, where H_2 is produced through electrolysis. No CO_2 is formed as co-product in this synthesis route.	Up to -100% (Provided full decarbonisation of the power sector; compared to 1.83 tCO_2/tNH_3 for CH_4 based ammonia production)	130% (including feedstock)	7	The low-carbon route has 2 times higher CAPEX and 3 times higher OPEX than conventional production.[cxxviii]	Around 100-250 bar is needed to compress both hydrogen (H_2) and nitrogen (N_2) and enable synthesis into ammonia (NH_3).[cxxix]
	Hybrid Ammonia production (H_2 and CH_4)[cxxx]	In a hybrid plant for ammonia production, natural gas is used as second feedstock and in addition to the previously described hydrogen-based ammonia production.	n.a. Higher CO_2 emissions than pure H_2 based ammonia, due to use of natural gas	n.a.	n.a.	Lower CAPEX than electrolysis-based low-carbon ammonia production, since no Air Separation Unit is needed.	Allows for flexibility in the operation. CO_2 produced in the process can be used directly for urea production.
	Low-carbon methanol production (CO_2 + H_2)[cxxxi]	Low-CO_2 methanol produced using H_2 (e.g. produced by water electrolysis with low-carbon electricity), with hydrogenation of CO_2 as carbon source. Hydrogenation of CO_2 is used in conventional methanol production by adding CO_2 to adjust the CO/H_2 ratio of syngas. Synthesis of methanol from CO and CO_2 are tied through water gas shift reaction.	-145% (Compared to natural gas based methanol production; negative number due to utilisation of CO_2)	105 to 111%; or 5-11% higher if feedstock (GJ) is included in natural gas based methanol production (37.5 GJ/t)	7	CAPEX and OPEX similar to production from natural gas.	For the hydrogenation of pure CO_2 to methanol, catalysts are commercially available, See e.g. the *George Olah Renewable Methanol Plant* in Iceland, by Carbon Recycling International (CRI).

	Low-CO_2 ethylene and propylene via MTO (Methanol to Olefins) and methanol is made using H_2 and CO_2[cxxxii]	Low-carbon ethylene and propylene can be produced via MTO (Methanol to Olefins), if methanol is made using H_2 and CO_2 as previously described. The MTO reaction is strongly exothermic and the process follows a two-step dehydration of methanol to dimethyl ether and water, to control the heat of reaction and the adiabatic temperature increase, followed by the conversion to olefins.	-50% (in the MTO process, compared to the naphtha route)	500% (In comparison to the naphtha route 16.9 GJ/t)	8-9	Major economic constraints: new investments needed in both hydrogen-based methanol plants and MTO plants.	Current commercial operations are located in China and no MTO plant is operated in Europe so far.
	Olefins out of H_2 and CO_2 in single system[cxxxiii]	Olefins can be created from H_2 and CO_2 in a single system, for example in a single-stage electro-catalytic process, which omits the need for intermediate products (e.g. methane and methanol as feedstock for olefin synthesis).	n.a.	n.a.	3-4	n.a.	See e.g. the project eEthylene by Siemens.
Ethylene and propylene via hydrogen based methanol	**Benzene, toluene and xylenes (BTX) via H_2 and CO_2 based methanol**[cxxxiv]	BTX can be produced from hydrogen and CO_2 based methanol, which requires a lower temperature and requires higher catalyst acidity.	-416% (Compared to Naphtha based process)	1000% (176 GJ/t compared to naphtha based process 16.9 GJ/t)	7	n.a.	BTX demand expected to grow to around 29Mt by 2050, compared to today's EU production of 15.7Mt.
	Poly(propylene)carbonate and polycarbonate etherols using CO_2	Poly(propylene)carbonate is a polymer that can be produced using CO_2 as building block. It is mainly used for packaging foils/sheets. Polycarbonate etherols can also be produced from CO_2, and is mainly used in polyurethane foams.	n.a.	n.a.	7-9	n.a.	See e.g. project by Novomer Inc. and Covestro (former Bayer MaterialScience).

	Formic acid (using electrochemical CO_2 reduction)[cxxxv]	Formic acid can be produced through electrochemical CO_2 reduction, and is mainly used (for example) as a preservative, adhesive, precursor or as fuel in fuel cells.	n.a.	n.a.	7	n.a.	DNV in Norway has a pilot plant producing 1kg/day, and Mantra Energy Alternatives Inc. is building a plant in Vancouver Canada) with the capacity of 100 kg/day.
	Mineral carbonation[cxxxvi]	Mineral carbonation can be used for treatment of industrial waste, metallurgy slag, production of cementitious construction materials etc.	n.a.	n.a.	7-9	n.a.	See e.g. Solidia in the cement industry.
	Dimethylether DME (direct synthesis from CO_2)[cxxxvii]	Dimethylether (DME) can be produced through direct synthesis from CO_2, and used as a fuel additive or a LPG substitute.	-30%	n.a.	1-3	n.a.	n.a.
	Sodium acrylate from ethylene and CO_2[cxxxviii]	Sodium acrylate from ethylene and CO_2 is currently being investigated at lab scale.	n.a.	n.a.	1-3	n.a.	n.a.
	Electrocatalytic processes to convert CO_2 to ethylene[cxxxix]	Conversion of CO_2 to ethylene through an electro-catalytic process is currently being investigated at lab scale.	n.a.	n.a.	1-3	n.a.	n.a.
Biomass as feedstock	**Biomethanol**[cxl]	Biomethanol is produced via gasification of bio-based feedstock, in the same way as coal-based methanol production. A large variety of biomass feedstock can be used (e.g. wood compared to sugar and starched crops), which generate different yields, costs etc.	-24% without sequestered carbon and -187% including carbon sequestered in biomass (compared to gas-based route; ref. 0.84 t CO_2/tons of methanol via CH_4)	117% (Compared to gas-based route; 14.6 GJ/ton of methanol compared to 12.5 GJ/t for CH_4 based methanol production excl. feedstock)	6-7	200-500 €/ton of product. OPEX around 1.5 times higher and CAPEX (per unit of capacity) around 3.4 times higher for the biomass route. Biomethanol plants are around 1.8 times more expensive (based on the same energy output) compared to bioethanol facilities.	See e.g. project by VärmlandsMetanol AB and Thyssenkrupp engineering, which has managed to achieve a process efficiency of around 66-72%.

	Bioethanol[cxli]	Bioethanol is produced via biomass pre-treatment (extraction of sugar e,g, via heat extraction and vaporisation), refinement, and then fermentation to an ethanol solution with about 12% ethanol content, which is being distilled to 96% ethanol. Further dehydration is needed for use as biofuel.	n.a. (Strongly dependent on type of biomass, process and scope; Dechema report estimates 0,305 ton avoided CO_2/ton of product)	n.a. (47.7 GJ/ton of ethanol)	7-9	975 €/ton of product. Production costs mainly depend (55-80%) on biomass feedstock prices	Current feedstock is mainly based on corn (37%), wheat (33%) and sugar beets (20%), which generates competition with food production. Second generation bio-ethanol production (using agriculture and forestry) waste based on transformation of ligno-cellulosis is being demonstrated at commercial scale in the EU.
	Bioethylene[cxlii]	Bioethylene production is based on bioethanol as feedstock (as described above), through dehydration of the ethanol. One ton of bioethylene requires 1.74 t of (hydrated) ethanol, and wood-based bioethylene production requires 10.5 t feedstock/ton bioethlyene.	0% without sequestered carbon, -270% including sequestered biomass	506% (85.5 GJ/t of ethylene compared to 16.9 GJ/t via naphtha route)	8-9	2250-2800 €/ton of product	See e.g. the Atol™ project by Axens, Total and IFP Energies Nouvelles.
	Biopropylene[cxliii]	Bio-propylene production is based on bio-ethylene production through catalysis. A couple of alternative routes exist, but at lower TRL. Among them is fermentative production of propanol or isopropanol.	+62% without sequestered carbon and -120% including sequestered carbon	565% (95.5 GJ/t of propylene compared to 16.9 GJ/t via naphtha route)	6-7	2200-2500 €/ton of product	See e.g. project by the Brazilian company Braskem.

	BTX from biomass[cxliv]	BTX can be produced from biomass through several routes, but the most developed route is gasification of biomass, thereafter methanol synthesis and thereafter methanol to aromatics (MTA) (with these individual process steps as previously described). Alternative routes are synthesis of p-xylene (pX), selective degradation of lignin and fast pyrolysis of lignocellulosic biomass.	+210% without sequestered carbon and -180% including sequestered carbon	426% (72 GJ/t of BTX compared to 16.9 GJ/t via naphtha route)	6-7	>3000 €/ton of product	See also biomass section 3.3 in chemical chapter.
	Ethanol to ethylene (with ethanol originating from biomass or syngas)[cxlv]	Ethanol can be turned into ethylene through a relative straightforward and energy efficient dehydration process.	n.a.	-90% of energy use (1.68 GJ/t) for ethanol to ethylene, compared to Naphtha to ethylene (16.9 Gt/t)	n.a.	n.a.	See e.g. the Steelanol project in section 2.2 in steel chapter. Mitigation potential and total energy use depend on source and process to create ethanol from syngas. The technology is already available at commercial scale in Brazil (TRL 9).[cxlvi]

[cxx] DECHEMA
(2017). Technology study: Low carbon energy and feedstock for the European chemical industry. Commissioned by
CEFIC. P. 36-38. Available at: https://dechema.de/dechema_media/Technology_study_Low_carbon_energy_and_feedstock_for_the_European_chemical_industry-p-20002750.pdf
[cxxi] ibid., 46-48
[cxxii] ibid., 47-48
[cxxiii] ibid., 47-48
[cxxiv] ibid., 53
[cxxv] ibid., 53-54
[cxxvi] ibid., 54
[cxxvii] ibid., 56-57
[cxxviii] ibid., 127
[cxxix] ibid., 56
[cxxx] ibid., 59-60
[cxxxi] ibid., 63-64

[cxxxii] ibid., 68-69
[cxxxiii] ibid., 68
[cxxxiv] ibid., 70-72
[cxxxv] ibid., 83
[cxxxvi] ibid.
[cxxxvii] ibid.
[cxxxviii] ibid.
[cxxxix] ibid.
[cxl] ibid., 85-96
[cxli] ibid., 87-96
[cxlii] ibid., 90-92
[cxliii] ibid., 92-93
[cxliv] ibid., 93-96
[cxlv] ibid., 101-103
[cxlvi] Chemicals Technology (2018). Braskem Ethanol-to-Ethylene Plant. Available at: https://www.chemicals-technology.com/projects/braskem-ethanol/

Table D. Overview of breakthrough low-CO_2 cement and concrete production technologies

The table maps some key parameters of breakthrough low-CO_2 production technologies in the EU cement and concrete industry. Data marked with an asterisk (*) and the column 'Other comments' are the authors' own assessments based on previously presented references. For unreferenced cells, see previous reference.

Break-through low-CO_2 cement techno-logies	Technology	Description	Actors involved	Estimated theoretical emission mitigation	Estimated TRL	Funding and estimated costs (including CAPEX and OPEX)	Applicability	Other comments
Portland cement substitutes (alternative binders)	**CSA-Belite cement**[cxlvii]	Alternative binder (sulpho-aluminate belite). Less $CaCO_3$ carbonated and oven temperature 200˚C (lower compared to Portland cement clinker).	Lafarge (Aether), Italcementi, HC group	20-30% (compared to CEM I)	9	Equal to CEM I; 0 EUR/t CO_2	Limited*	Availability of belite rocks might be restricted. Limited availability of substitute.
	Alternative CSH[cxlviii]	Alternative binder (alternative CSH cement). Ca-Si/CSH similar to cement clinker but production process is (radically) different. Works with autoclave (pressure) and lower temperature.	Schwenk (Celitement)	50% (compared to CEM I)	4-5	High CAPEX (investments) but much lower OPEX compared to existing cement clinker production. Estimated at 0 EUR/t CO_2	Limited*	Limited application in reinforced concrete (up to 20%), broader application in non-reinforced concrete (up to 50%). Doubts about alkalinity and hence application in reinforced concrete. Key issue will be to ensure that this new type of cement complies with safety demands. Potential of broader application after 2020 therefore. Limited applicability of product and scaling of process.
	Calcinated clay[cxlix]	Alternative binder based on calcinated clay and limestone. Reduced clinker content up to 50%. Strength largely dependent on calcinated kaolinite content.	See e.g. the EPFL led LC3 project[cl]	30% (compared to Portland cement)[cli]	n.a.	n.a.	Relatively wide*	Higher strength than Portland cement for all blends at 28 days and 90 days (for some blends also at 7 days). Expected to be available for large global application, enabling emission reductions in 2050 of approx. 200Mt/year.
	Super-sulphated cement[clii]	Alternative binder (supersulphated cement). Consists of granulated blast furnace slag, gypsum and (limited amount of) cement clinker.	Holcim (CEMROC)	90-95% (compared to CEM I)	9	At least equal to CEM I; 0 EUR/t CO_2	Limited*	Product likely has limited applicability and will be constrained by availability of raw materials (e.g. granulated blast furnace slag). Limited availability of substitute.

	Solidia[cliii]	Alternative binder (CO_2-activated cement) based on $CaSiO_3$, with sand and marl as main ingredients. During the cement/concrete setting reaction, CO_2 from the air is captured. Around 300kg CO_2 can be captured per ton of Solidia cement. The binder reduces emissions in two ways: a) it replaces Portland cement b) it reacts with CO_2 in the air during the setting process. Solidia should be able to replace fly ash and GBFS in cement.	Lafarge-Holcim (commercialised first in US)	60% (compared to Portland cement)	8-9	Negative costs. CEM I price at 82-87 EUR/t. Solidia estimated at 46 EUR/t. Mitigation costs are -86 to -100 EUR/t CO_2	n.a.	Can be produced in the same factories that make Portland cement. During production 550 kg CO_2 per ton Solidia are produced, and during carbonation phase 300 kg CO_2 is captured per ton of Solidia. In principle, Solidia could replace CEM I, but EU standards (currently) do not allow application of Solidia in carrying structures. Main ingredients are sand and marl.
	Carbstone/ Carbinox (Registered Trademark)[cliv]	Alternative binder (CO_2-activated cement), which can be used as a replacement of Portland cement. During the setting process, the carbstone binder reacts with CO_2 in the air (carbonation). The main input material is steel slag (from BOF), which needs to be crushed and cleaned to remove heavy metals. The milled slag is mixed with water and put in an oven (80-140^{C} for carbonation). For one m3 carbonstone, around 2 ton steel slag is required. Around 300 kg CO_2 can be captured per m3 carbstone.	Orbix, VITO (commercialised in Belgium 2017)	Twofold mitigation: replacement of clinker and carbonation during production process. Net negative emissions due to absorption of CO_2 (-0,15 to -0,20 tons CO_2 per m3 carbstone concrete) (compared to concrete 0,155 tons CO_2/m3 concrete).	7-8	Similar cost to regular concrete; no additional costs expected; 0 EUR/t CO_2	Limited*	Application limited as limited availability of steel slag. The production volume is limited to the available steel slag. Presence of chlorine can make it unsuitable for reinforced concrete.
	Geopolymers/ Alkali activated[clv]	Alternative binders (alkaline-activated materials), such as fly-ash from coal fired power plants, granulated blast furnace slag and alkali activator.	Diverse initiatives	min. 70-80% (compared to CEM I)	9	20% cheaper compared to CEM I	Limited*	Limited application in reinforced concrete (up to 20%), broader application in non-reinforced concrete (up to 50%). Limited availability of raw materials.

Changes in concrete composition	**Improved aggregate packing**[clvi]	Optimisation of aggregate packing. Denser packing of aggregates will lead to lower requirement of binding agent. Notably, next to size, also shape and texture are important in aggregate packing.	n.a.	20-40% less cement in concrete for non-constructive purposes; 0-5% less cement for constructive concrete.	4-9	-49 to -43 EUR/t CO2	Relatively wide*	Possibility for wide scale application.
Recycling of concrete	**Mechanical cement recycling (Smartcrusher)**[clvii]	Mechanical cement recycling via 'smart crushing' of used concrete enables the extraction of sand, aggregates and cement stone. The crushed product outside the cement fraction can be used as filler in concrete with binding capacities, the cement fraction can be used as filler in cement with binding capacities, or added to the production process of Portland cement (lowering the process emissions).	Consortia funded under Interreg Europe, Flanders-Netherlands region[clviii]. (Smartcrusher, Rutte Groep[clix])	80%, by using a mix of crushed concrete and CEM III; Up to 98%, by using only crushed concrete. (compared to CEM I)[clx]	4-8* (Reuse of hydrated cement around TRL 4; crushing with smart-crusher around TRL 8)	0-2 EUR/t CO_2 for mechanical cement recycling in general[clxi] Smartcrusher has the potential to reduce direct costs (capital costs, energy, transportation) by 0-6 euro per ton of end-of-life of concrete compared to BAU.[clxii]	Limited*	Availability dependent on volume and quality of waste concrete. However, advantage is the possible application on the entire concrete recycling industry. The pilot version uses 10% of the energy of a traditional crusher/breaker.[clxiii] Limited to availability of concrete waste, although application available on the complete concrete recycling industry. (For other mechanical cement recycling projects, see also e.g. the C2CA technology[clxiv].)
	Thermal cement recycling[clxv]	Based on 'circular construction' concept. Cleaned and broken up concrete is heated to 650-700˚C. The process facilitates further processing of recycling concrete. When reused it can replace 10-20% Portland cement (half as efficient binding agent as fly-ash).	n.a.	17,5-32,5% (compared to CEM I)	4-8	Mitigation costs are (negative) -131 EUR to -261 EUR/t	Limited*	Costs are two times lower than for CEM X. Limited to availability of concrete waste.

CO_2 utilisation in concrete	**Mineral CO_2**[clxvi]	Use of filler in which CO_2 is sequestered in this case replacement of sand in concrete. The mitigation in principle uses Olivine minerals, which react with CO_2. Olivine is crushed finely to increase reacting surface with CO_2 (under pressure).	n.a.	40-60 kg CO_2 can be captured per m3 of concrete.	4	Between 86 and 152 EUR/ton CO_2.	Limited*	The mineral olivine and CO2 replaces sand in concrete. The chemical process releases heat, which in turn can be used. Olivine availability is geographically limited and must in most cases be imported (e.g. from Norway).
	Carbon8[clxvii]	Gravel substitute based on fly ash and/or bottom ash and CO_2. Based on chemical reaction of CO_2 with fly ash. Per ton aggregate, 45-55 kg CO_2 is used (but lower because purifying and concentrating CO_2 stream requires energy).	Carbon8[clxviii]	n.a.	5 (for waste incinerator ash) - 9 (for fly ash)[clxix]	Costs similar to other aggregates; 0 EUR/t CO2[clxx]	Limited*	Cannot be applied for reinforced concrete due to presence of chlorine in aggregates. Wide-scale application expected to be limited, since main feedstock used is fly ash from coal fired power plants.

[cxlvii] CE Delft (2013). Update prioritering handelingsperspectieven Verduurzaming betonketen 2016. P.86. Available (in Dutch, with English summary) at: https://www.ce.nl/publicatie/update_prioritering_handelingsperspectieven_verduurzaming_betonketen_2016/1859

[cxlviii] ibid, page 32.

[cxlix] Scrivener, K. (2018). Supplementary Cementitious Materials. Workshop presentation. Internal document.

[cl] LC3 (2018). Official webpage. Available at: https://www.lc3.ch/

[cli] Scrivener, K. (2018). Supplementary Cementitious Materials. Workshop presentation. Internal document.

[clii] CE Delft (2013). Update prioritering handelingsperspectieven Verduurzaming betonketen 2016. P.86. Available (in Dutch, with English summary) at: https://www.ce.nl/publicatie/update_prioritering_handelingsperspectieven_verduurzaming_betonketen_2016/1859

[cliii] ibid., 69-70

[cliv] ibid., 71-72

[clv] ibid., 86

[clvi] ibid., 19-24

[clvii] Slimbreker (2018). SmartCrusher. Webpage. Avaialble at: https://www.slimbreker.nl/smartcrusher.html

[clviii] Interreg Vlaanderen-Nederland (2018). Beton naar hoogwaardig beton. Webpage. Available at: http://www.grensregio.eu/projecten/beton-naar-hoogwaardig-beton

[clix] Rutte Groep (2018). Official webpage. Available at https://www.ruttegroep.nl

[clx] Verbal source 04.07.2018.

[clxi] CE Delft (2013). Update prioritering handelingsperspectieven Verduurzaming betonketen 2016. P.43. Available (in Dutch, with English summary) at: https://www.ce.nl/publicatie/update_prioritering_handelingsperspectieven_verduurzaming_betonketen_2016/1859

[clxii] Universiteit Leiden & TU Delft (2015). Closed Loop Economy: Case of concrete in the netherlands. Page 29. 4413INTPGY Interdiciplinary Project Groups. Available at: https://www.slimbreker.nl/downloads/IPG-concrete-final-report(1).pdf

[clxiii] Universiteit Leiden & TU Delft (2015). Closed Loop Economy: Case of concrete in the netherlands. Page 7. 4413INTPGY Interdiciplinary Project Groups. Available at: https://www.slimbreker.nl/downloads/IPG-concrete-final-report(1).pdf

[clxiv] C2CA (2018). Official webpage. Available at: http://www.c2ca.eu/

[clxv] CE Delft (2013). Update prioritering handelingsperspectieven Verduurzaming betonketen 2016. P.49-50. Available (in Dutch, with English summary) at: https://www.ce.nl/publicatie/update_prioritering_handelingsperspectieven_verduurzaming_betonketen_2016/1859

[clxvi] ibid., 74-75
[clxvii] ibid., 77-78.
[clxviii] Carbon8 (2018). Official homepage. Available at: http://c8s.co.uk/
[clxix] CE Delft (2013). Update prioritering handelingsperspectieven Verduurzaming betonketen 2016. P.77-78. Available (in Dutch, with English summary) at: https://www.ce.nl/publicatie/update_prioritering_handelingsperspectieven_verduurzaming_betonketen_2016/1859
[clxx] Ibid, 77-78.

Table E. Overview of breakthrough low-CO_2 pulp and paper production technologies

The table maps some key parameters of breakthrough low-CO2 production technologies in the EU pulp and paper industry. Data marked with an asterisk (*) are the authors' own assessments based on previously presented references. For unreferenced cells, see previous reference.

Break-through low-CO_2 pulp and paper production technologies	Technology name	Description	Estimated theoretical emission mitigation	Estimated theoretical energy demand (compared to current practice)	Estimated TRL	Funding and estimated costs (including CAPEX and OPEX)	Other comments
	Deep Eutectic Solvents[clxxi]	Plant based solvents that can be used to fractionate biomass into its constituent parts - lignin, hemicellulose and cellulose - to be further processed.	20%	60%	5-6*	Funding for the PROVIDES project under H2020 with additional support from industry. DES is expected to reduce investment costs by 50%.	Winner of the CEPI two team project and the technology that has shown most promise since publication of the report.
	Flash Condensing with Steam[clxxii]	Blasting mostly dry, high-consistency fibres with agitated steam into a forming zone where the combination of condensing and steam expansion enables bonding.	50%	80%	1-3*	Reduced OPEX due to reduced need for water and energy, and from smaller production units which cost less per capacity.	Whilst completely novel, the concept is expected to fit nicely with existing technology and industry can draw on research from other sectors in high temperature refining.
	Use of Steam in the Paper Drying Process[clxxiii]	Full power of steam enables total recovery of thermal energy, to be used in subsequent processes. In papermaking, steam and heat-boosted forming and pressing take place within an air-free paper machine.	50%	75%	1-3*	Full application could reduce costs by 30%. Further cost reductions from reduced paper weight, reduced water handling and treatment costs. Reduced CAPEX as forming and drying sections would be shorter, and faster production speeds would increase machine output. Further savings in raw materials and energy, as sheet stratification would present opportunities for recycling.	n.a.

	Dry-Pulp for Cure-Formed Paper[clxxiv]	Two technologies that enable paper production without water: 1) DryPulp and 2) cure-forming. DryPulp, a high concentration of fibres treated with a bio-based protective layer and suspended in a viscous solution, is pressed during cure-forming to remove the viscous solution, forming a thin sheet.	55%	75%	1-2*	Lower energy demand would reduce operating costs for the entire manufacturing chain and due to simplification of the process, losses would also be minimised. CAPEX would be 20 times less due to smaller production units.	This concept is based on new production processes and even though all technology is founded on existing knowledge, fundamental R&D is still needed to progress the innovation further.
	Supercritical CO_2[clxxv]	Liquid-like characteristics of $scCO_2$ allow for substitution of steam-heated cylinders with $scCO_2$ in the extraction drying process. With gas-like characteristics, $scCO_2$ has uses removing contaminants, adhesives and mineral oils in the recycling process.	45%	80%	1-3*	Using $scCO_2$ in extraction drying has the potential to reduce energy costs by 10-20% and to reduce capital costs, through lower infrastructure costs and boiler capacity. Using $scCO_2$ to enable upcycling could increase material efficiency at mill level by 10%.	The $scCO_2$ process has been discarded in its drying application[clxxvi] for being economically non-viable on a commercial scale. The technological and economic feasibility of using $scCO_2$ in the removal of contaminants as a stand-alone technology has not been assessed.
	100% electricity[clxxvii]	Transition to green energy through 1) use of electricity-based, energy efficient tech in place of fossil fuel-based alternatives and 2) development of capacity to store cheap surplus energy from the grid- generated by renewable sources. Involving replacement of gas-fired boilers with electric/hybrid boilers and use of electro-thermal technologies in the drying process.	20-100% (depending on electricity mix)	n.a. (Energy demand likely to increase)	n.a. (No TRL calculated, as electrification is based on a cluster of technologies)*	High CAPEX from investments in new machines and because it is expensive to replace them before the end of their lifetimes. Energy-savings could reduce OPEX by 8%	Technology for electrification of papermaking is generally advanced- conditions related to the market for electricity may impede dissemination.
	Black Liquor Gasification[clxxviii]	Recovery and gasification of black liquor can be used to generate energy in the form of steam and on-site electricity (to be used in the pulping plant) or as feedstock in the synthesis of liquid fuels and chemicals.	n.a.	n.a.	7-8	n.a	2 keys designs: a low-temperature steam reforming process (TRL 8) and high-temperature entrained flow reactor (TRL 7).

	Lignin extraction[clxxix]	Extraction of lignin from wood pulp can enable its use in new industrial products, or as biofuel in boilers or lime kilns.	n.a.	n.a.	5-8	n.a.	Research in Europe exploring diverse lignin pathways, such as for: energy, food additives (Borregaard) and carbon fibre (RI.SE).

[clxxi] Confederation of European Paper Industries (CEPI) (2013). The Two Team Project Report. p. 16-17. Available at http://www.cepi.org/system/files/public/documents/publications/innovation/2013/finaltwoteamprojectreport_website_updated.pdf
[clxxii] ibid., 18-19
[clxxiii] ibid., 20-21
[clxxiv] ibid., 22-23
[clxxv] ibid., 24-25
[clxxvi] Verbal source
[clxxvii] ibid., 26-27
[clxxviii] International Energy Agency (2018). Tracking clean energy progress. Available at http://www.iea.org/tcep/industry/pulpandpaper/
[clxxix] International Energy Agency (2018). Tracking clean energy progress. Available at http://www.iea.org/tcep/industry/pulpandpaper/

Table F. Overview of breakthrough low-CO_2 ceramic production technologies

The table maps some key parameters of breakthrough low-CO_2 production technologies in the EU ceramics industry. Data marked with an asterisk (*) and the column 'Other comments' are the authors' own assessments based on previously presented references. For unreferenced cells, see previous reference.

Break-though low-CO_2 ceramic production technologies	Technology	Description	Actors involved	Estimated theoretical emission mitigation	Estimated theoretical energy demand	Estimated TRL	Funding and estimated costs (including CAPEX and OPEX)	Other comments
New Kiln Design	**Large-Scale Electric Kiln**[clxxx]	Electric kilns to substitute gas-fired kilns.	n.a.	Up to 80%	n.a.	5-6	CAPEX €22.6m per site	Needs to be developed and demonstrated in practice. Take-up expected to be dependent on electricity price or incentives to reduce emissions.
	Hybrid Kiln (Hybrid-ring tunnel kiln with flue-gas-based combined heating system is given as example)[clxxxi]	Restructure of kiln to disband the thermal link between kiln cooling and drying systems. Instead, use of desulpherised kiln and dryer exhaust gases supplemented with a gas-driven heat pump to maximise quantity of high-quality thermal energy. This coupling allows choice between electric heating (using CHP is an option) and primary fuel.	University of Applied Science, Department of Materials Engineering Glass and Ceramics	n.a.	35%	1-4	Optimisation of processes to reduce OPEX. For CAPEX, innovation based around converting/supplementing existing facilities. Approximate payback period of 2-3 years.	Take-up of technology to be dependent on electricity price or availability of on-site CHP.

	Design for energy efficient Kiln [clxxxii]	Radically improved kiln architecture through the design of innovative hardware furnace components (biofuel-fed CHP unit, heat pipes and emissions abatement system), and major developments in hardware-software kiln parts (kiln control tool, refractory materials).	The Dream project, funded under horizon 2020, has 10 partners from 4 countries: Spain, Italy, Germany and UK.	n.a.	80%	4-6	OPEX reduction of 20% and CAPEX reduction of 19%	n.a.
Energy Alternatives & Heat Recovery	**On-site CHP**	Concurrent production of electricity and thermal energy in an integrated system. Heat that would have otherwise have been lost can be used to supply demand directly. Applied to recover waste heat from the cooling stage of ceramic production by channeling hot air from the drying stage to use in the cogeneration system via a heat exchanger placed in the cooling zone.[clxxxiii]	Under SPIRE 2016, the Dream project (see above) calls for retrofitting new and existing installations with CHP	± 0.7 M tons CO2 saved in the Spanish wall & floor tile and brick & roof tile sectors[clxxxiv]	Fuel consumption savings of 30%[clxxxv]	7-9*	Lower distribution costs, supplies 25% of electricity needed internally in installations[clxxxvi]	250 CHP ceramic plants in operation in EU MSs (Italy, Spain, Portugal)[clxxxvii]. At EU level, the national treatment in countries facilitates CHP.
	Heat recovery technologies (closed-loop heat pump used as example)[clxxxviii]	Technology to maximise heat recovery from kiln exhausts, kin dryers and from cooling zones e.g. heat pumps, ORC etc.	Closed-loop heat pump due for industrial demonstration under the DryFiciency project	57-73%	20-40%	5-7*	Reduce production costs by up to 20%/Kg	n.a.
	Biomass Gasification[clxxxix]	Application of biomass gasifiers to convert biomass into fuel by gasification; to act as feedstock in replacement of fossil fuels (LPG or natural gas) for thermal energy production.	n.a.	29% (in heavy clays sub-sector)	n.a.	5-6*	CAPEX €17m per site	Debatable role biomass should play in decarbonisation due to issues such as e.g. air quality. Biomass availability and increasing demand to be considered.

End-of-pipe Procedures	**CCS**	Capturing CO_2 from exhaust gases to sequester.	LIFE ZEF-tile demonstrated the in-plant application of oxy fuel combustion technology during ceramics firing for CC and for utilisation in production processes. The project also carried out a theoretical study for uses for sequestered CO_2[cxc]	50% (in the heavy clays subsector)[cxci]	No savings in fuel consumption. Added energy consumption for CCS process[cxcii]	5-6[cxciii]	CAPEX for carbon capture technology is estimated to be €11.3m per site (for the heavy clay subsector)[cxciv]. No expected OPEX savings.	Due to high % of SMEs, CCS might be more challenging in ceramics sector than other EIIs. May only be applicable to larger sites or through collaboration.[cxcv]
	CCU	Capturing CO_2 from exhaust gases to use in other processes.	LIFE ZEF-tile demonstrated the in-plant application of oxy fuel combustion technology during ceramics firing for CC and for utilisation in production processes. The project also carried out a theoretical study for uses for sequestered CO_2[cxcvi]	90%[cxcvii]	75%[cxcviii]	3-6[cxcix]	OPEX gains from end-of-pipe procedures that lower fuel consumption, higher productivity and from ease to treat exhaust gases with reduced carbon dioxide, nitrogen dioxide and particulates[cc]	See above

[clxxx] Department for Energy and Climate Change and the Department for Business, Energy and Skills (2015). Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050 - Ceramic Sector Appendices. P.62-70. Available at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/416194/Ceramic_Appendices.pdf
[clxxxi] Schaffer C. (2015). Hybrid-ring tunnel kiln flue-gas-based combined heating system: 65% savings on energy - a concept study. In Ziegelindustrie International
[clxxxii] www.spire2030.eu/dream
[clxxxiii] Delpech B., Axcell B. & Jouhara H. (2017). A review on waste heat recovery from exhaust in the ceramics industry. P.5. Available at https://www.researchgate.net/publication/320912464_A_review_on_waste_heat_recovery_from_exhaust_in_the_ceramics_industry
[clxxxiv] Batier, R (2013). The Cogeneration in the EU Ceramic Industry. Presentation for the Europe Annual Conference 2013. Available at http://www.cogeneurope.eu/medialibrary/2013/04/23/5358df6a/Renaud%20Batier%20-%20Cerame-Unie.pdf
[clxxxv] ibid.
[clxxxvi] ibid.
[clxxxvii] CerameUnie (2012). Paving the way to 2050: The Ceramic Industry Roadmap. p.12. Available at http://cerameunie.eu/topics/cerame-unie-sectors/cerame-unie/ceramic-industry-roadmap-paving-the-way-to-2050/?media=4249&f=Ceramic%20Roadmap%20to%202050%20EN.pdf
[clxxxviii] www.dry-f.eu/About
[clxxxix] Department for Energy and Climate Change and the Department for Business, Energy and Skills (2015). Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050 - Ceramic Sector Appendices. Available at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/416194/Ceramic_Appendices.pdf
[cxc] www.ceramicaalta.com/life-technical-progress

[cxci] Department for Energy and Climate Change and the Department for Business, Energy and Skills (2015). Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050 - Ceramic Sector Appendices. p.64. Available at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/416194/Ceramic_Appendices.pdf
[cxcii] Department for Energy and Climate Change and the Department for Business, Energy and Skills (2015). Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050 – Ceramic Sector. P.75. Available at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/416676/Ceramic_Report.pdf
[cxciii] Department for Business, Energy and Industrial Strategy (UK) (2017). Ceramic Sector: Industrial Decarbonisation and Energy Efficiency Roadmap Action Plan. P.20. Available at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/651229/ceramics-decarbonisation-action-plan.pdf
[cxciv] Department for Energy and Climate Change and the Department for Business, Energy and Skills (2015). Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050 - Ceramic Sector Appendices. p70. Available at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/416194/Ceramic_Appendices.pdf
[cxcv] CerameUnie (2012). Paving the way to 2050: The Ceramic Industry Roadmap. p.14. Available at http://cerameunie.eu/topics/cerame-unie-sectors/cerame-unie/ceramic-industry-roadmap-paving-the-way-to-2050/?media=4249&f=Ceramic%20Roadmap%20to%202050%20EN.pdf
[cxcvi] www.ceramicaalta.com/life-technical-progress
[cxcvii] ibid.
[cxcviii] ibid.
[cxcix] Department for Business, Energy and Industrial Strategy (UK) (2017). Ceramic Sector: Industrial Decarbonisation and Energy Efficiency Roadmap Action Plan. P.20. Available at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/651229/ceramics-decarbonisation-action-plan.pdf
[cc] www.ceramicaalta.com/life-technical-progress