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Enhanced fly ash use in concrete: Ex-ante LCA on an emerging electro-mass separation technology

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ABSTRACT

A new treatment process for Class F fly ashes is being developed, using a proprietary technology to separate the fly ash into several fractions based on their particle size, with the ultra-fine fly ashes being used to act as a substitute for silica fume in Ultra-High-Performance Concrete. The goal of this study is to assess the potential future environmental impact of using this technology when it becomes available on an industrial scale and to compare these results to that of the direct use of Class F fly ashes in concrete by performing an ex-ante life cycle assessment. This involves theoretically upscaling the technology from a pilot to an industrial scale and taking into account potential changes to the foreground and background data by the time the technology reaches the industrial scale. The preliminary results indicate that an additional environmental benefit can be gained when fly ashes are separated before use.

1. Introduction

In order to reach the climate goals set by the EU, the cement and concrete sector will need the assistance of innovative technologies. To guarantee the success and maximize the performance of these technologies, the way in which life cycle assessment (LCA) is traditionally performed will need to change.

The cement and concrete sector have a substantial impact on the environment, being responsible for 7% of global CO2 emissions (Fernandes et al., 2018). This is mainly due to the production of clinker, where a large amount of CO_2 is produced during combustion of fuels to obtain the required processing temperatures as well as during the decarbonation of the raw materials and calcination process, where CO_2 is formed as a by-product. Several pathways to reduce the environmental impact of concrete have been put forward by Cembureau (2020), the Net Zero 2050 Initiative (Material Economics, 2019), the International Energy Agency (IEA) (IEA, 2018) and the Cement Sustainability Initiative (CSI) (Fernandes et al., 2018).

There are three main strategies used in these pathways to lower the environmental impact of cement and concrete. The first one is the use of carbon capture technologies to lower the amount of CO_2 that is released in the atmosphere (Cembureau, 2020; Fernandes et al., 2018; Material Economics, 2019). The second one is supplanting fossil fuels with biomass, electricity or hydrogen from electrolysis, to lower the amount of CO_2 produced (Cembureau, 2020; Material Economics, 2019; MPA et al., 2019). The last one is lowering the amount of cement or clinker produced, either by substituting clinker or cement by other materials, lowering the amount of cement used in concrete or lowering the amount of concrete used in structures (Cembureau, 2020; Material Economics, 2019).

Lowering the use of cement has long been a focussed mitigation strategy but will face difficulties in the future. Cement has traditionally been substituted in concrete by waste materials such as fly ash, which mainly comes from coal power plants, and blast furnace slag, a by-product of steel production. These waste materials are pozzolanic, which means that by reacting with calcium hydroxide (CH), formed during hardening of cement clinker, calcium silicate hydrate (CSH) binder is formed (Rajapakse, 2017). It is because of this pozzolanic effect that these waste materials can be used to partially replace ordinary Portland cement (OPC) as a binder in concrete. The use of these waste materials has however been maxed out and might even decline in the coming years, due to the expected phase out of coal power plants and alternate steel production routes which may supplant blast furnaces (Material Economics, 2019).

In some of the pathways proposed, the decrease of SCMS's is acknowledged, but the hope is that other materials, which are currently

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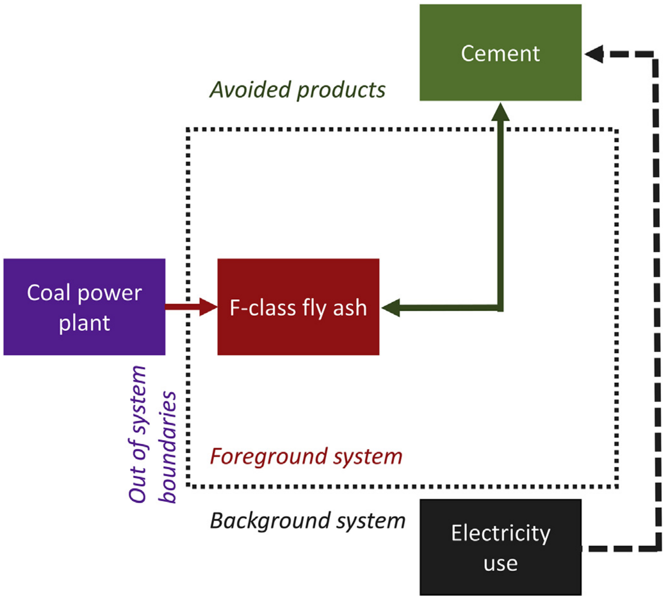


Fig. 1. System scope for the direct use of fly ash.

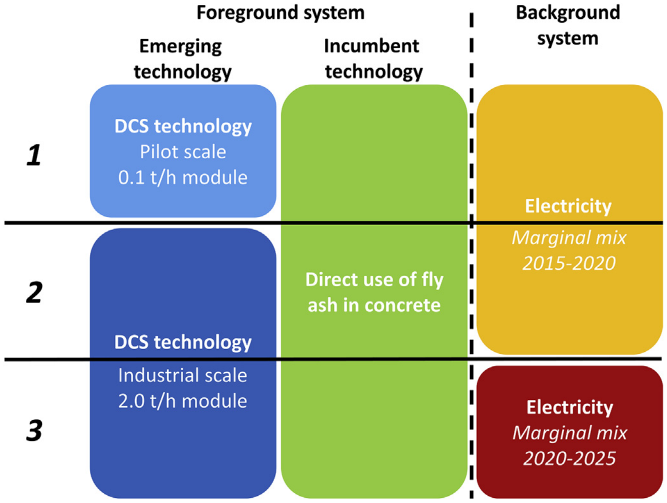
being investigated, such as calcined clay, may level out the decreasing availability of fly ash and slag and even potentially increase the use of use of supplementary cementitious materials (SCMs). Another potential way to increase the amount of cement substituted is by maximising the value of existing SCMs. For example, a downside to the use of fly ash or slag is the lower early strength, which might lead to an increase in demoulding time or cause the execution of a concrete structure to be delayed. This can be solved by using an early-strength accelerator (Kim and Lee, 2017). Then there are also geopolymers, which provide a way to substitute OPC completely and make use of slag and fly ash (Reddy et al., 2018). Lastly there are also potential pre-treatments for fly ash, such as mechanical activation, grinding and classification, which aim to get a finer fly ash resulting in more reaction surface and a potential higher packing when used in concrete (Jovanovic et al., 2014). However, Best Available Technologies (BAT) are often found to be costly, energy inefficient, separation inefficient or difficult to use due to for instance dust generation (Krishnaraj and Ravichandran, 2019; Lecomte et al., 2017).

Value Ash Technologies (VASHT) NV is a company currently working on a proprietary technology to increase the environmental benefit gained from using fly ash in concrete, more specifically Class F fly ash, which is a

Table 1
Inventory data DCS per ton fly ash treated.

	Pilot scale 0.1 t/h		Industrial scale 2 t/h	
Input	class F fly ash	1 t	class F fly ash	1 t
Output	ultra-fine fly ash	0.200 t	ultra-fine fly ash	0.175 t
	medium fly ash	0.650 t	medium fly ash	0.675 t
	coarse fly ash	0.150 t	coarse fly ash	0.150 t
Land use	Transformation from unknown	0.025 m^2	Transformation from unknown	0,005 m^2
	Transformation to industrial area	0.025 m^2	Transformation to industrial area	0,005 m^2
	Occupation, industrial area	0.0025 m^{2}a	Occupation, industrial area	0.0005 m^{2}a
Equipment	Dust collector, multicyclone adapted to 1.5 t of steel	1p/(650 t/y × 10 y)	Dust collector, multicyclone adapted to 4 t of steel	1p/(13000 t/y × 10 y)
Use	Electricity medium voltage	40 kW h	Electricity medium voltage	30 kW h

Table 2
Overview of LCA scenarios.



	Foreground system		Background system
	Emerging technology	Incumbent technology	
1	DCS technology Pilot scale 0.1 t/h module	Direct use of fly ash in concrete	Electricity Marginal mix 2015-2020
2	DCS technology Industrial scale 2.0 t/h module		
3			Electricity Marginal mix 2020-2025

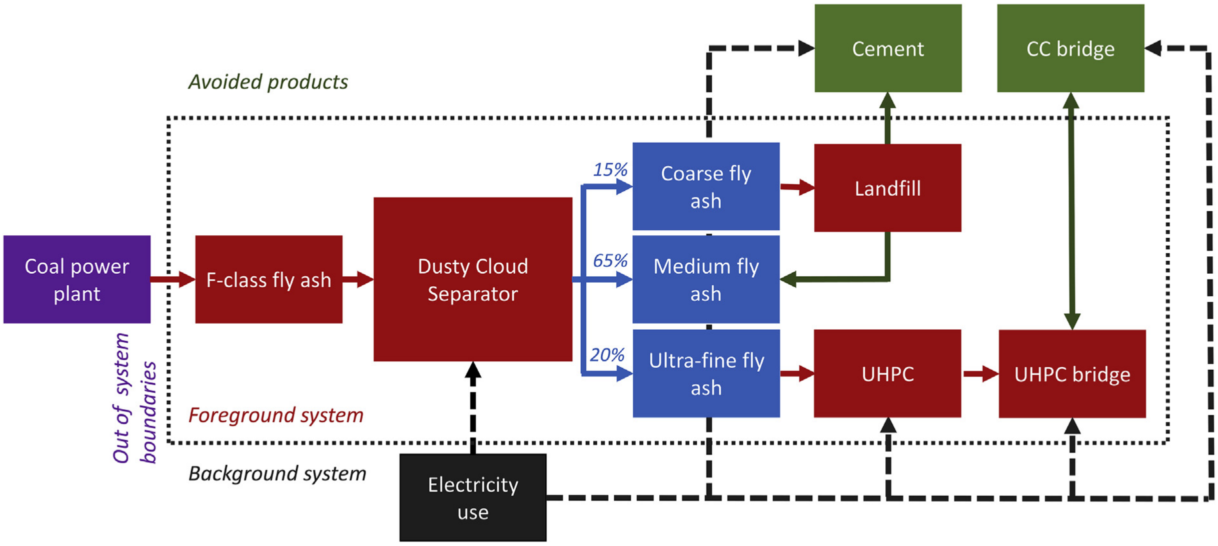


Fig. 2. System scope for the use of fly ash with DCS treatment.

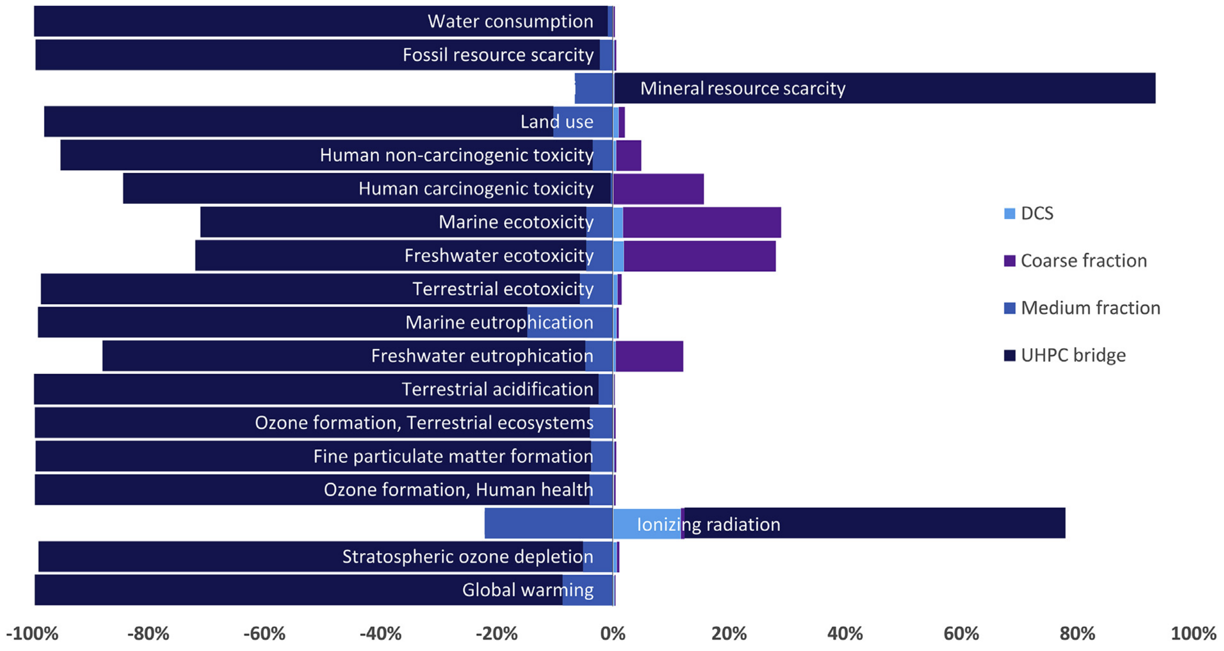


Fig. 3. Contribution of each step on the environmental impact of fly ash separation for scenario 1.

fly ash that contains less than 10 percent calcium oxide and is mostly derived from burning anthracite and bituminous coals (ASTM C 618-12a, 2012). This technology, called a Dusty Cloud Separator (DCS), can be used to separate the Class F fly ashes in several fractions based on particle size. The separation of Class F fly ash yields an ultra-fine fly ash fraction, which consists for 90% out of fly ash with a particle size smaller than 10 μm. This ultra-fine fly ash has similar advantages to the application of silica fume in concrete (Silica Fume Association, 2014), which can be used to obtain a stronger concrete with a lowered permeability and as a consequence a higher durability (Kara De Maeijer et al., 2020). Using ultra fine fly ashes will therefore reduce the amount of concrete needed for the same function and increase the estimated service life at the same time or result in superior functions with a similar estimated service life.

In order to evaluate if a reduction on the environmental impact can be gained by first treating the fly ash with the DCS, a life cycle assessment (LCA) should be performed. This to determine if the advantages of the DCS weigh up against the environmental burdens associated to using this technology, such as the energy needed to operate the DCS and the disposal of the coarse fraction, which cannot be used to substitute cement due to the large particle size. LCA is an often-used method to assess the environmental profile of a technology and support informed decision making on whether the proposed alternative is in fact better than the reference technology. It has been used often for the cement and construction industry as well (Buyle, 2018; Lu et al., 2009). It is especially a valuable tool nowadays to assess the many new technologies and alternative cements proposed for the industry (An et al., 2019; Burman and Engvall, 2019; Miller and Myers, 2020).

LCA's are often performed after the technology has been fully developed. Performing the LCA this late misses an opportunity to use the LCA results to optimize the technology's environmental performance, as it will cost too much time and money to alter the design at this point (Buyle et al., 2019). If the LCA would instead be performed now, at the current stage of development of the DCS technology, the results could be used to optimize the technology, by giving the developer information on how a design choice would affect the environmental performance of the technology. The earlier such a future oriented LCA, also called ex-ante LCA, is applied in the development of a technology the better, since it is in the early stages where the most impactful decisions are made at a low cost.

Several studies have been published, discussing how ex-ante LCA should be performed and what is yet missing in existing studies (Arvidsson et al., 2018; Buyle et al., 2019). It was found that most studies tend to focus only on the upscaling of the innovative technology and forget to take into account any changes that may occur to the incumbent technology and background system by the time the innovative technology is fully developed. This same problem can be found as well in LCAs on innovative technologies for the cement industry (Tomatis et al., 2020; Yao et al., 2020). This could substantially impact the results from the LCA, as large changes are expected in the future in order to reach the current climate goal set (European Commision, 2018b).

In this context it is clear that in order to make an objective assessment of the innovative technology and make the right decisions during development, there is a need to look further than just the innovative technology when performing ex-ante LCA. Therefore, the goal of this paper is to perform ex-ante LCA on the DCS technology, looking not only at the innovative technology, but also at changes that may occur to the incumbent technology and background system. The technology sits currently at the pilot scale level.

2. Methods

2.1. Goal and scope definition

The goal of this study is to assess the environmental impact of waste treatment techniques of Class F fly ash. The functional unit is therefore the treatment of 1 t of Class F fly ash. Two techniques are compared. The first one is the incumbent practice (see Fig. 1), in which fly ash is directly used in conventional concrete (CC). The second one is the treatment of fly ash with the DCS (see Fig. 2). A consequential approach is chosen for this study, to see what the impact would be if the treatment practice for fly ash would change (Weidema, 2010). This has two main effects. The first is that average values are replaced by a mix of marginal suppliers. These mixes reflect the technologies in the market that will be affected by a change in demand. Second is the use of system expansion to deal with by-products and avoid allocation as advised by ISO 14044 (BS EN ISO 14044, 2006).

In the current practice Class F fly ashes are directly used in concrete to substitute cement (see Fig. 1). Fly ashes can substitute around 15–30% of OPC in standard concrete at a weight ratio of fly ash to OPC of 1:1 up to 1.5:1 (American Coal Ash Association, 1999). When used at these

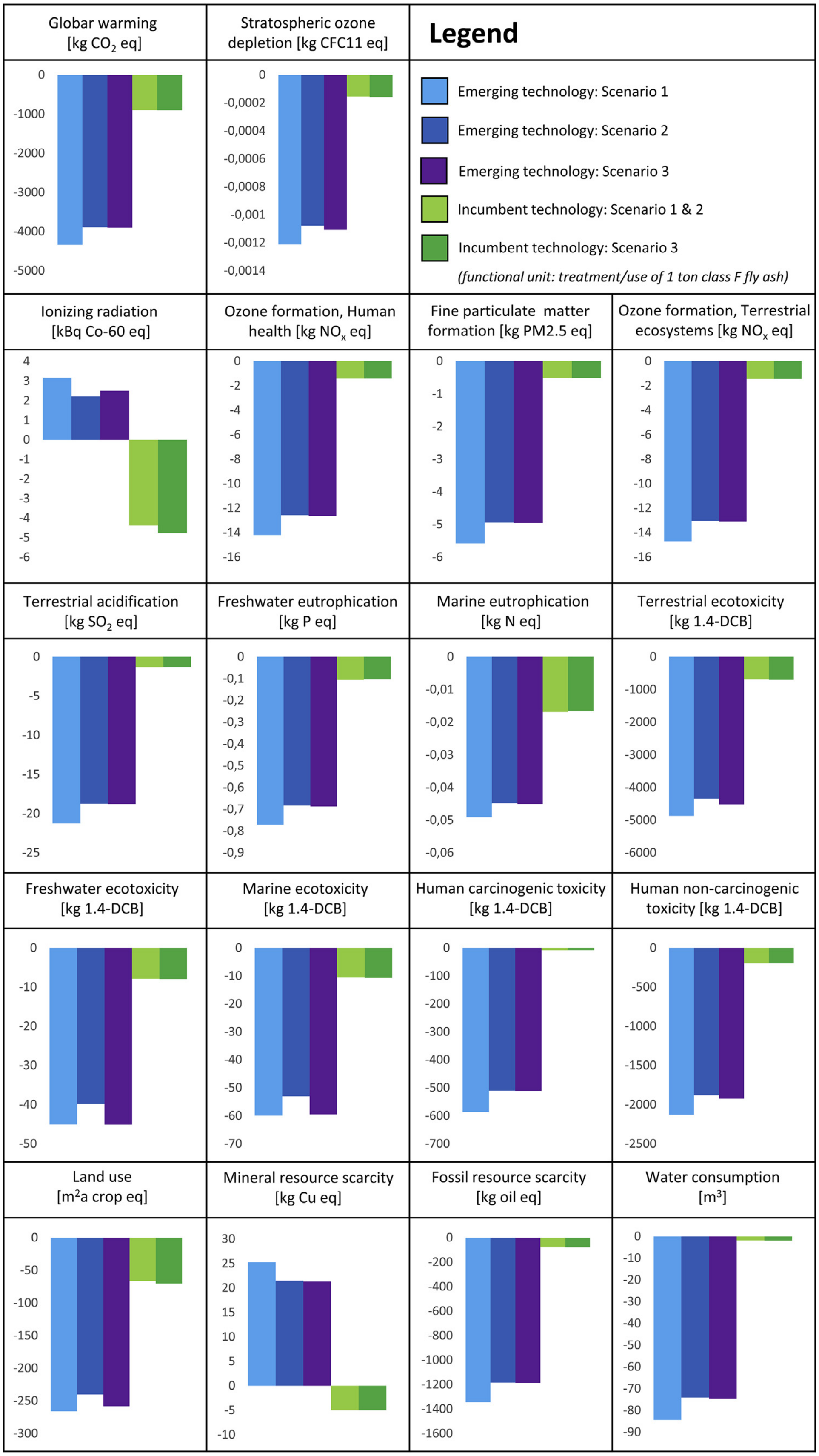


Fig. 4. LCIA for the fly ash treatment methods for scenario 1-3.

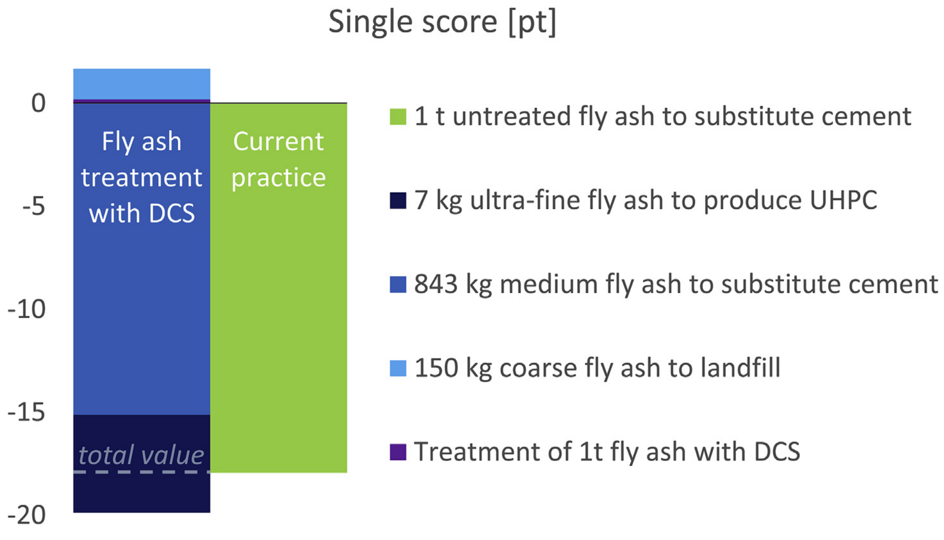


Fig. 5. Sensitivity analysis on the collection efficiency of ultra-fine fly ash for scenario 2.

percentages, at a 1:1 ratio, a concrete can be gained with similar compressive strengths to that of concrete for which no cement was substituted, albeit at a longer setting time (Harison et al., 2014).

The DCS (see Fig. 2) is planned to be installed at the coal power plant itself, meaning no transportation is needed between the two. Emission of fly ash particles is prevented by its closed design. The DCS separates the Class F fly ash into three fractions:

1) The ultra-fine fraction (≤10 μm): this fly ash can be used in concrete just as regular fly ash but with a better performance. Just as with regular fly ash the optimal replacement level lies at around 15–25%. At these levels an increase in compressive strength was gained from 70 to 80 MPa for CEMI and a similar strength can be gained when used in a mixture with CEMIII (Kara De Maeijer et al., 2020). Its greatest value lies however as an alternative to silica fume to produce ultra-high-performance concrete (UHPC), which can be used to substitute a large amount of standard concrete due to its greater strength and durability. Currently, a concrete with a compressive strength of 150 MPa can be achieved, by replacing silica fume at a 1:1 wt ratio in a UHPC mixture.
2) The medium fraction (10–30 μm): this fly ash portrays similar characteristics to that of untreated Class F fly ash and can therefore also be used to substitute OPC at a 1:1 wt ratio of fly ash to OPC.
3) The coarse fraction (≥30 μm): this fly ash is too coarse to be used in concrete and will likely need to be landfilled.

Currently UHPC is rarely applied in constructions, mainly due to the low availability of silica fume, as well as its high price (Damineli et al., 2013). Introducing ultra-fine fly ashes to the market will most likely not result in a competition with silica fume as both are constrained waste recourses with a relatively low availability compared to the possible demand for UHPC by the construction sector. Instead it is assumed that providing this ultra-fine fly ash will result in an increase of UHPC production, as developers say the ultra-fine fraction will cost less, which may incentivize more people to produce UHPC and also allows people to produce UHPC which couldn't before due to experiencing problems with silica fume availability. This extra UHPC that will be produced can then be used instead of CC in constructions. The environmental benefit of being able to produce more UHPC cannot be simply estimated by comparing UHPC and CC on a volumetric level. Using UHPC to build complex constructions will result in a different design for the construction with a thinner profile, use of different materials, and less maintenance due to its increased durability. In order to take these aspects into account the environmental impact for a post-tensioned concrete bridge using conventional concrete was compared with one using UHPC. This example was chosen as UHPC is often used for bridges (Azmee and Shafiq, 2018). The inventory data for this example was derived from a paper (Sameer et al., 2019), which compared a UHPC bridge with a CC bridge from cradle to gate. The bridge is a two-pass bridge of 44 m long with an expected lifetime of 90 years for both the UHPC and CC design. In those 90 years part of the concrete elements of the CC bridge will need to be renewed twice. This is mainly due to concrete damage related to chloride induced corrosion of steel elements inside the concrete elements. This is not the case for UHPC thanks to its high durability. The silica fume used in the mix designs for UHPC were replaced with the ultra-fine fly ash in a 1 to 1 ratio. No further alterations were made to the UHPC mix designs used in the paper.

2.2. *Inventory analysis and scenario description*

Three aspects are important when trying to assess what the environmental impact would be of a technology that is currently under development, when it becomes available on an industrial scale (Buyle et al., 2019):

1) The changes that occur to the emerging technology by scaling up from its current technology readiness level (TRL) to the industrial scale level.
2) The changes that occur in the current practice by the time the innovative technology is on an industrial scale.
3) The changes that occur in the background system by the time the emerging technology is available on an industrial scale. The background system consists of processes that are used during the life cycle of the technology, but over which the technology developer has no control. This study focusses specifically on changes to the electricity mix (see Figs. 1 and 2), as it the main consumption of the DCS. This will be broadened in future work to include other changes, such as to the fuel mix used for clinker production. All other technologies in the background system are included in the Life Cycle Inventory (LCI) but have just not been updated to any possible changes in the future.

Upscaling the DCS could cause a change in its energy efficiency, the amount of materials needed to make the separator and the collection efficiency of the ultra-fine fraction. The pilot scale DCS can process 0.1 ton fly ash per hour, the industrial scale DCS would consist of 30 lines of 2 t/h machines. In this study the industrial scale DCS was compared as a singular 2 t/h machine to the 0.1 t/h pilot scale DCS. The 2 t/h machine was estimated by the developers to be 2 times the width and length of the

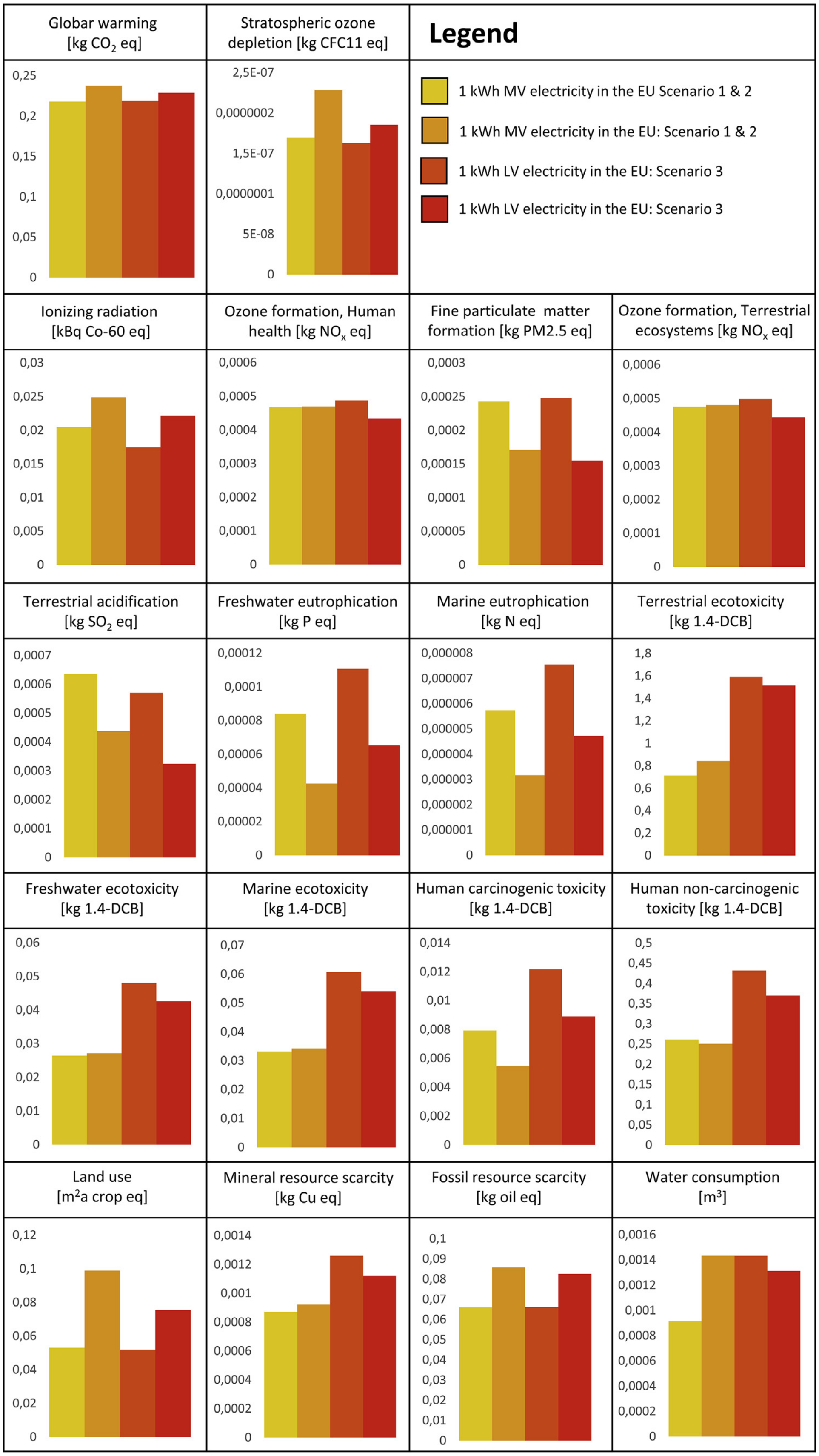


Fig. 6. LCIA for the EU electricity mix for scenario 1-3.

0.1 t/h pilot scale DCS and 1.5 times the height, for which 4 tonnes of steel would be necessary. The energy consumption for the pilot scale version is 40 kW h per ton of fly ash treated and is assumed by the developers to decrease to 30 kW h/t for the industrial scale version. This seems plausible as a similar trend can be found when looking at the energy consumption of other classifier technologies at different scales (Comex, 2016; Elcan Industries, 2018) It is still unsure how the collection efficiency will change when the technology scales up. The developers suspect that the collection efficiency may remain the same, though it could potentially decrease. In order to take this potential decrease into account a slight decrease of the collection efficiency was assumed (see Table 1). Any ultra-fine particles which are not extracted to the ultra-fine fraction remain in the medium fraction. The expected lifetime for both DCS systems is 10 years. Table 1 shows the effect of the changes on the inventory data for the DCS per ton fly ash treated.

Changes in the background system were taken into account by incorporating projections made for the electricity mix, taken from the European Commission's projections on Energy, transport and GHG emissions (Carpos et al., 2016). No predicted changes were found for the current waste treatment of fly ash, which consists of either landfilling or directly using the fly ashes in cement or concrete. Favier et al. (2018) do suggest in their technology assessment the possibility to implement additional grinding to blended cement to increase the performance of the cement, but also adds that it will be difficult to implement this technology due to the high investment costs. For this study it is assumed that the high costs will prevent the implementation of the technology and that no changes will have been made by the time the DCS technology becomes available on an industrial scale.

Three scenarios are included in order to assess the impact of using an ex-ante approach in LCA (see Table 2). The first one representing the current pilot scale situation, using no projected or upscaled data, the second one using the upscaled DCS technology but assuming that no changes occur in the background system and the last one accounting for both changes in the foreground and background system. Ecoinvent 3.5 was used for the life cycle inventory data. This is also the case for the UHPC and CC bridge which originally used GaBi XIV construction materials for its LCI (Sameer et al., 2019). The DCS technology was modelled using the existing data for a cyclone, which was scaled up to match the amount of steel needed for the pilot scale and industrial scale DCS. The current and future marginal electricity mixes were obtained by looking at the electricity generation growth of the technologies in that period, as these are the technologies most likely to be affected by an increase in production of UHPC and other materials (Buyle, 2018; Weidema et al., 1999). The current market mix looked at the change in electricity generation from 2015 to that of the projected electricity generation for 2020, while the future market mix looked at the projected change in electricity generation from 2020 to 2025 for EU countries (Carpos et al., 2016). Two marginal mixes where developed for each time period. One at medium voltage and one at low voltage. The main difference between the two is the inclusion of photovoltaic energy on the low voltage grid (Treyer and Bauer, 2016). Most processes in the LCA require electricity at medium voltage, except for the production of steel fibres which uses energy at low-voltage (Sameer et al., 2019). The Life Cycle Impact Assessment (LCIA) is performed with ReCiPe methodology 2016 hierarchist version (Huijbregts et al., 2017) using midpoint indicators to discuss the results for all three scenarios, as well as endpoint indicators for a sensitivity analysis.

3. Results

Results from the ex-ante LCA indicate that the treatment of Class F fly ash using the DCS results in an overall greater environmental benefit than directly using the fly ash to substitute cement. The DCS treatment however has a negative impact on mineral resource scarcity and ionizing radiation, unlike the direct use of fly ash, because of the high environmental impact of using steel fibres in UHPC (see Fig. 4). The environmental benefit of being able to substitute CC with UHPC heavily outweighs the environmental impact of the coarse fraction that is to be landfilled and the construction and use of the DCS itself for all impact categories, except mineral resource scarcity and ionizing radiation (see Fig. 3).

The industrial scale DCS is more energy efficient, and thanks to its lower surface-area-to-volume ratio there is a decrease in land and material use per ton fly ash treated as well. These changes have however little impact on the total environmental impact of the fly ash treatment, which is instead largely influenced by changes made to the collection efficiency of the DCS. This can be seen in Fig. 4 where an overall decrease in the environmental benefit of the fly ash treatment can be observed for the emerging technology between scenario 1 and 2.

Because the results are mostly influenced by the amount of fly ash that can be extracted the collection efficiency was varied, to see at which amount the environmental benefit of using the DCS becomes equal to that of the current practice. To compare the environmental benefit of the two techniques ReCiPe's endpoint indicators were used. The single score value of the fly ash treatment becomes equal to that of the current practice when only 0.007 ton ultra-fine fly ash is extracted per ton fly ash treated (see Fig. 5).

While the EU is generally moving away from using fossil fuels for energy production and is moving towards using more renewable energy sources, projections indicate that a lot of countries will still experience growths in the short term for technologies using fossil fuel. This is especially the case for natural gas (Carpos et al., 2016). This is noticeable in the results where categories such as the Global Warming Potential (GWP) and fossil resource scarcity are higher for 2025 (see Fig. 6). Because the current practice substitutes part of the cement that needs to be produced, it also saves on the amount of electricity that needed to be used to produce that cement. Therefore, the higher the environmental impact of the electricity is, the higher the environmental benefit is for substituting the cement and vice versa (see Fig. 4, scenario 3). A similar trend can be noticed for the treatment of fly ash with the DCS, which does use electricity for the DCS and UHPC bridge, but less than the products it is substituting.

4. Discussion

The goal of this study was to assess the environmental impact of a technology that is still under development, called the Dusty Cloud Separator using ex-ante LCA. To do this, potential changes that may occur by the time the innovative technology is out on the market where investigated, this for the innovative technology, the incumbent technology, and part of the background system. To see how these changes could influence the results of the LCA, three scenarios where developed and assessed. All scenarios showed favourable results for using size separation on Class F fly ash before using the fly ash in concrete mixes. This was mainly due to the contribution of the fine fly ash fraction, which allows for more UHPC to be produced, which in turn can replace a large amount of CC when used in constructions.

When comparing the scenarios, it became clear how much the ultra-fine fraction and the amount of cement substituted by UHPC had an effect on the results. Despite the increased energy efficiency and lower land and material use of the industrial scale DCS, the environmental benefit of the fly ash treatment still decreased due to the DCS's slightly lower collection efficiency, compared to that of the pilot scale DCS. In scenario 3 a future marginal electricity mix was used, which had a slightly larger environmental impact than that of the current mix. This did not substantially increase the environmental impact of the innovative fly ash treatment, which uses electricity to operate the DCS and produce UHPC. Instead it induced an environmental benefit. This was because the amount of electricity used to produce and construct the UHPC bridge was far lower than the amount that would have need to be used if the bridge was instead made out of CC. The environmental benefit of the ultra-fine fraction is so high that even at a collection efficiency of 0.007 ton ultra-fine fly ash per ton fly ash treated, the DCS treatment is still an environmentally friendly route compared to untreated fly ash.

Landfilling the coarse fraction did have a noticeable effect on several environmental indicators such as toxicity. Currently the developers are performing tests to see if they can use the coarse fraction to substitute cement by first grinding this fraction. This research has shown promising results. Future work will assess this potential route and determine if the environmental benefit of avoiding landfill and substituting cement outweigh the environmental impact of grinding the coarse fraction.

When looking at potential changes to the background system, this study focused on the use of electricity, as it is the sole consumption product of the DCS. The evolution of the electricity's marginal mix had a relatively low influence on the LCA results. This was expected as only a 5-year period was taken between the current and future situation and because the contribution of electricity use to the environmental impact of the system is fairly small compared to the burning of fuels to produce heat for the clinker process and the CO_2 released during the calcination process. What was not expected was the increase in certain environmental impact categories for electricity production, in the future scenario. This could be caused by a lower increase in renewable energies, reducing their market share in a marginal mix. It could also be the results of a nuclear phase out. Some countries like Belgium are planning to phase out nuclear plants in the near future. As solar and wind plant capacity is not yet big enough to take over the energy production from nuclear plants, a different energy source will be needed, which most likely will be natural gas (European Commision, 2018a; Sutrisno and Alkemade, 2020). This will negatively affect the environmental impact of energy production in categories such as global warming. Future work may need extend the studied time period for the LCA. Changes that are happening in the short term may not be a good reflection of the long-term changes. Examples of this are the short-term plans for a nuclear phase out but also the introduction of novel technologies such as carbon capture, which is expected to take of close after 2030.

Results have shown however that the environmental impact of the fly ash treatment is mostly influenced by the amount of cement that can be substituted by the UHPC, as can be seen in Fig. 3. Future work should therefore focus on expanding the background system to include the potential changes that may occur to cement and how this would affect an LCA.

There is a large uncertainty on any projection used though. The EU is trying to reach carbon neutrality by 2050 (European Commision, 2018b). This target is far removed from where we are now. This can be seen in the projection used in this study (Carpos et al., 2016), which assumed that no further policy changes would be implemented past 2016. While there are still efforts being made in this projection to lower the greenhouse gas emissions, there is still more than 2700 Mt CO_2 equivalents emitted per year (Potsdam Institute for Climate Impact Research, 2020). The EU's climate goal can have a substantial effect on the technologies studied here. Cement may adopt novel technologies such as electric kilns and carbon capture in order to lower its environmental impact (Material Economics, 2019). The electricity sector may start a phase out for some, or all of its fossil fuel plants, use hydrogen to produce electricity and adopt carbon capture in order to lower the environmental impact of combustion power plants (CLIMACT, 2018). These changes can substantially affect the results for both the current practice and the DCS and may increase the influence of electricity changes on the results, as cement starts to use electric kilns more and more. While it is unsure if and even how the EU's target will be reached, it does show that large changes could potentially take place, casting a large amount of uncertainty on any projection made. In order to take this uncertainty into account, roadmaps should be investigated which strife to reach the climate goal set by the EU (Cembureau, 2020; CLIMACT, 2018; Material Economics, 2019). By assessing not one, but multiple possible routes which the EU can take, a clearer picture can be formed on how the innovative technology could perform in the future.

The scope for this study was the treatment of fly ash in the EU. However, as literature shows the amount of fly ash available can decrease in the EU in the coming years thanks to coal power plants shutting down (Favier et al., 2018; Material Economics, 2019). However not all countries are planning to lower their coal use, with some parts of Africa and Asia even planning to build new coal power plants in the future (Evans, 2020). It may be interesting to see how the DCS would perform in these places as this is where the demand for the technology could be highest.

5. Conclusions

The DCS can assist the EU in reaching their climate goal by changing the way fly ash is used in cement. Results have shown that the pretreatment results in a higher environmental benefit for fly ash, though more work is needed to refine the results. This work includes incorporating cement into the projections and by incorporating not one but multiple plausible future pathways into the assessment to deal with the highly uncertain future. It is expected that as these changes are incorporated the environmental benefit of using the DCS will become smaller, as the cement that is avoided becomes less damaging to the environment. The same will also happen to the direct use of fly ash, which also gets its environmental benefit from substituting cement. It seems unlikely though that the DCS would become an environmentally worse alternative to the direct use of fly ash, as the main environmental impact of the DCS is electricity consumption, which is currently lower than the electricity saved by the substitution of CC by UHPC and in the future this difference will only become larger as electric kilns are installed in cement plants.

The results showed that not only the foreground system can have a large influence on the results but also the background system, and that potential future changes to either of the two should be accounted for when assessing technologies that are planned to be released in the future. For this specific case study, it was shown that the environmental impact is almost fully decided by the amount of ultra-fine fly ash that is collected and the environmental benefit it can deliver by producing UHPC which can substitute cement. Further development of the DCS should therefore be steered towards improving the collection efficiency of the ultra-fine fly ash. For this research, future work should see if the potential collection efficiency of the industrial scale plant could be determined. Literature has shown various methods that are already being used in ex-ante LCA, which may prove applicable to this case study (Buyle et al., 2019). In terms of the background system, various parties such as Cembureau and the European Climate Foundation have shown a large interest in how the EU's climate goal may be obtained and have drawn out roadmaps to get to this goal (Cembureau, 2020; Material Economics, 2019). These roadmaps and pathways could be used to integrate any potential changes to cement production, as well as electricity, into the LCA.

As the environmental benefit of the ultra-fine fly ash heavily outweighs the environmental burden of using the DCS, an additional route for this study may be to see how the DCS would perform on fly ashes that fall outside of the standard (EN 450-1, 2012) and need to be landfilled due to containing too many coarse particles. The ultra-fine fraction that is gained with these fly ashes may be quite small, but this may still result in an environmental benefit compared to landfilling.

To conclude, this study has shown the environmental benefit a DCS treatment could provide to fly ash with the use of ex-ante LCA. To refine the results from this study, further research will need to focus on how cement production may change in the coming years. Optimization of the collection efficiency of the DCS is advised as this parameter has by far the most influence on the environmental benefit of the technology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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