



Ecological comparison of wastewater pipe rehabilitation with glass fiber liners compared to replacement with new concrete pipes in Germany

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ABSTRACT

In Germany hundreds of thousands of kilometers of wastewater pipes will need to be modernized in the near future. Two upkeeping approaches are compared by using a cradle-to-grave life cycle assessment: trenchless rehabilitation with cured-in-place glass fiber liners versus open-trench replacement with concrete or reinforced concrete pipes. Due to the very long service life of over 50 years, estimates are made for end-of-life treatment. Thermal recycling in a cement plant is assumed optimal for the disposal of glass-fiber liners. However, the end-of-life treatment of the liners is of minor environmental importance compared to the installation efforts of concrete pipes. The analysis shows some environmental advantages for glass liners in the production stage but major advantages in the installation stage, depending on the actual installation conditions. Overall, the rehabilitation by liners shows obvious environmental advantages over the replacement of wastewater pipes.

1. Introduction

Many thousands of kilometers of the German sewage system, as in numerous other countries, will need to be refurbished in the years to come. Many pipes have reached or even exceeded their lifespan (Berger et al., 2020). The most obvious method is to replace such pipes with new ones using open trench methods (open cut pipe installation - OCPI), which causes the destruction of surface structures, disrupting daily life and resulting in further environmental and social impacts (Kaushal and Najafi, 2020). However, in recent years, many different methods have been developed to refurbish pipes using trenchless methods (TLMs). Widely used methods are cured-in-place pipes (CIPP), pipe bursting systems, pipe ramming, resin transfer molding slip lining, and horizontal auger boring (Chin and Lee, 2005; Hicks et al., 2022; Zhu et al., 2021).

The general advantages of these methods include fewer activities, decreased surface disturbance, reduced time consumption, less impact on surface structures (such as pavements and buildings), and cost savings. In addition to these benefits, environmental considerations are becoming increasingly important to local authorities when renewing infrastructure.

Three main strategies for upkeeping of pipes can be distinguished: repair, rehabilitation or replacement. Various repair methods are available in cases where the pipe structure is still mostly intact, such as spot repair for defective areas (e.g. joints, cracks) by applying resin or

sealing leaks with injection resins. Spot repair is carried out for half of the pipe lengths in Germany that require upkeeping. Rehabilitation describes the construction of a new pipe within the old one using liners. Replacement refers to replacing pipes entirely. Replacement is done mostly with the open trench method while TLMs are also applied. In Germany, rehabilitation and replacement each account for approximately a quarter of the total upkeeping activities, and repair activities account for half. However, rehabilitation by liners has shown the largest growth rate in recent years (Berger et al., 2020).

To quantify the environmental advantages or disadvantages of rehabilitating instead of replacing wastewater pipes at their end-of-life (EoL), we carry out a life cycle assessment (LCA) of CIPP liners based on glass fibers and unsaturated polyester resin (glass fiber reinforced plastic - GFRP) and compare them to the replacement of no longer functional wastewater pipes with new pipes.

To our knowledge, in Germany, there is no comprehensive life cycle assessment that compares wastewater pipe rehabilitation using GFRP-based CIPP linings to the replacement of concrete pipes. An overview of the current state of knowledge on the ecological assessment of pipe upkeeping methods is given in supplementary material A.

We chose concrete wastewater pipes as a reference material because they tend to have a lower environmental impact than plastic pipes, particularly for larger pipe diameters and when considering the EoL stage (Morera et al., 2016). In addition, primary data were collected

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from German glass liner manufacturers and German concrete pipe producers, and a comparative cradle-to-grave LCA study was carried out. For better interpretation, the LCA results were normalized, weighted and aggregated into a single score using the PEF3.1 method.

2. Methods

2.1. Goal and scope

The goal of this LCA study is to assess and compare the environmental impacts of the upkeeping of wastewater pipes in Germany either by rehabilitating them on site using glass liners or by replacing them with new concrete pipes.

2.1.1. System boundaries

The system boundaries are defined as “from cradle-to-grave” (Fig. 1), except for the use stage; the latter plays a subordinate role from an environmental perspective and is assumed to be similar for both alternatives. In addition to the production of pipes or rather liners, the installation aspect is of particular importance.

The environmental burden of installing a new pipe can easily account for a significant proportion of the total environmental impact. However, the installation situation for open trench pipe renewals greatly varies from case to case. We have therefore defined a typical installation situation, including excavation work, transport of soil, refilling with sand and the renewal of the surface structure (asphalt).

Liners require an almost negligible amount of installation effort.

Before installing a liner, the old pipe must be cleaned and straightened, if necessary, and after installation, branches may have to be milled and re-laminated. This additional work is not considered in the system boundaries. Similarly, the cost incurred by manufacturing the connections to branches is also excluded for concrete pipes.

During the open construction method, the overlying traffic infrastructure is likely to be obstructed for a long time, leading to further impacts by traffic jams, detours and inconvenience of people living near the construction site, whereas CIPP methods can often be realized within 1 or 2 days only. These indirect effects are not considered in this study.

2.1.2. Functional unit

The main function of wastewater pipes is to provide a specified wastewater transport capacity for a certain period of time. The service life of the liner and the replaced concrete pipes is usually >50 years (Allouche et al., 2014; Alzraiee et al., 2015; ASTM, 2022) and is assumed to be identical in both cases. However, in both cases, the choice of material, the chemical environment, mechanical loads, the installation quality, and ongoing maintenance strongly influence the service life.

The reference flow of the functional unit (FU) equals a segment of a pipe with a certain length and a certain (identical) inner diameter. Here, a length of 50 m is selected, and the calculation is carried out for three typical diameters (400, 800 and 1200 mm). In addition, the functional unit considers the EoL stage, which is important because both methods have different EoL processes. However, as the EoL stage is >50 years ahead, only indicative estimates based on current technologies and trends can be made. The EoL impact assessment results are therefore

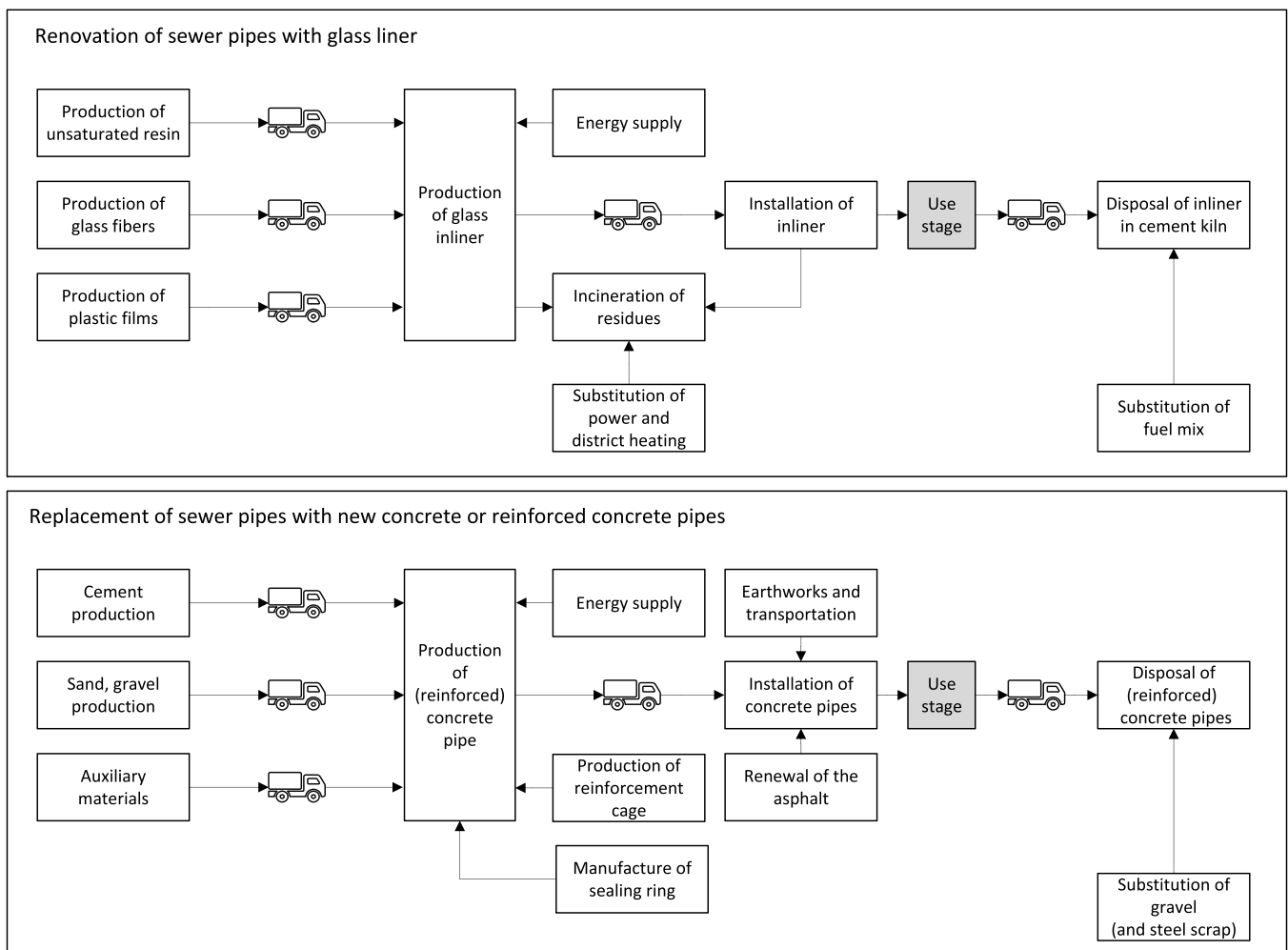


Fig. 1. System boundaries of renovating sewer pipes with glass liners (top) and of replacing sewer pipes with concrete or reinforced concrete pipes (bottom).

shown separately from impact results of the other life cycle stages.

To summarize, we define the functional unit as the provision and disposal of a 50-meter-long sewer pipe with three typical diameters (400, 800 and 1200 mm) for a period of over 50 years.

2.1.3. Data collection and data quality

For the glass liner technology, primary data were collected from two companies located in Germany (Reline Europe GmbH, Rohrbach, and IMPREG GmbH, Ammerbuch). Primary data of energy and material consumption were collected in 2023 covering a period of one year and half a year, respectively. Despite minor technical differences between the companies, material and energy demands were very similar, indicating a high level of robustness of the data. The products are used in central Europe, i.e. Germany, Switzerland, Austria, France, Belgium, and the Netherlands, and an average delivery distance is calculated based on the customer databases.

The data for concrete pipes come from a current Environmental Product Declaration (EPD), which uses primary data from German concrete pipe manufacturers. The study was conducted by Fraunhofer UMSICHT and was published in the Ökobaudat (BMWSB, 2024) database after reviewing (ift Rosenheim GmbH, 2023).

In all cases, background data were selected to reflect the German situation. As background database, Sphera Managed LCA Content (MLC), version 2025.1, was used, which applies Sphera's modelling principles (Sphera, 2024). Datasets of fossil-based plastics in MLC already consider present data on upstream methane emissions from crude oil production and transport.

Apart from small quantities of waste, no by-products are generated in the main production process. Waste treatment is modelled using system expansion, i.e. credits are awarded for recovered energy and materials.

2.1.4. Sensitivity assessment

For the EoL of glass liners, combustion in a cement kiln is assumed to be the best technology. The GFRP wall material is completely recycled at the cement plant. The glass fibers melt and are incorporated in the cement as a valuable component, and the energy is also fully used in the process. However, the cement industry has transformation plans to reduce emissions, too, for example by switching fuels (Barbhuiya et al., 2024). The consequences of a future greener fuel mix are investigated as a sensitivity analysis.

The composition of the liners can have an influence on their environmental impact, too. Therefore, the sensitivity of the results with respect to the minimum and maximum polyester resin content is examined.

2.1.5. Choice of impact assessment methods

The environmental impacts are assessed using the life cycle impact assessment (LCIA) methods of the Product Environmental Footprint (PEF), version 3.1 (European Commission, 2022). Furthermore, factors for normalization and weighting of the impact categories are provided in this method (European Commission, 2022).

2.2. Systems under study

2.2.1. Glass liner method

The liner wall material examined is glass fiber reinforced plastic, which consists of glass fibers and unsaturated polyester resin. The glass content of the liners varies between 43 % and 54 %, and an average of 50 % is set as base case. The inner and outer sides of the liner are covered with several layers of thermoplastic films.

Fig. 2 shows a simplified representation of a liner. Different films made from different thermoplastic materials like LDPE, PA, PVC, PP, or PET are applied to fulfill different requirements such as mechanical stability, abrasion resistance, diffusion barrier, or adhesion. Sometimes even films are used with an internal multilayer setup.

Depending on the pipe diameter, the material requirements in terms

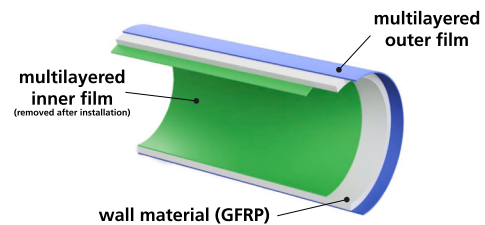


Fig. 2. Sample structure of the glass liner.

of glass fibers, unsaturated polyester resin, and LDPE, PA, PVC, PP, and PET films vary per functional unit (50-meter-pipe). The wall material accounts for approximately 88 to 95 % of the mass and its thickness varies between 4, 6 and 10 mm, depending on the pipe diameters of 400, 800 and 1200 mm, respectively.

In addition, liner production requires electricity and thermal energy. Depending on the diameter of the wastewater pipe, the production of the liner requires electrical power between 45 and 318 kWh and thermal energy between 181 and 1288 MJ. For the delivery of the liners produced, an average distance of 723 km is estimated based on the companies' customer databases. After transport, the non-expanded, non-cured liners are pulled into the damaged pipe and then unfolded by internal air pressure so that they fit tightly and crease-free inside the existing pipe. The wall material is cured with UV lamps mounted on a carriage slowly travelling through the pipe. The velocity varies from 55 to 120 cm/min depending on the power of the lamps and the wall thickness to be cured. The slowest velocity of 55 cm/min is considered as a conservative assumption. Additionally, there is a holding time of 60 s before and after curing. The curing process begins with an initial start time of 120 s. The energy for these processes (compressed air and electricity) is generated with a diesel-powered generator. Diesel consumption is 17.8 L/h in case of FU1 and FU2, and 13.3 L/h in case of FU3.

The polymer material is a styrene-based unsaturated polyester. During curing of the material in situ, styrene fumes may be released into the atmosphere (up to 2 % of the weight of the liner has been reported), especially in case of steam curing, which requires open release to the atmosphere (Purdue University, 2022; Teimouri Sendesi et al., 2017; USA Today, 2023). The liners considered in this study are cured exclusively by UV light, without any media such as steam flowing through the pipe. Furthermore, they are coated inside and outside with polymer films made of polyolefins or PVC, which form a good barrier against styrene and cause significantly lower styrene emissions during installation. As a conservative assumption, it has nevertheless been assumed that 2 % of the polymer is released as styrene, of which 1 % is emitted into the atmosphere and 1 % into the water.

A detailed table of the material and energy requirements for liner production, including the selected background datasets, is provided in the Supplementary Material (SM) B, Table B-1. Inventory data for liner installation is given in SM B, Table B-2.

After its service life, the liner must be disposed of. This study assumes that it will be used as a substitute fuel in a cement plant. The heating value of the resin is 27 MJ/kg, and the average heating value of the wall material is 13.5 MJ/kg since the average resin share is 50 %. CO₂ emissions are calculated stoichiometrically, whereas further emissions are calculated based on the average emissions reported in the Best Available Techniques (BAT) Reference Document for the Production of Cement, Lime and Magnesium Oxide (Schorcht et al., 2013).

Disposal in a waste incineration plant is problematic due to the high glass fiber content and the lower combustion temperatures at which the fibers do not melt and end up in the filters, causing quick filter clogging (Milek and Fuhrmann, 2024; Qureshi, 2022; Tao et al., 2023). However, it is uncertain which fuel mix will be used in cement plants in the future, after a liner service life of 50 years.

The current fuel mix of cement plants in Germany consists of 32.5 %

primary fuels and 67.5 % secondary fuels (Bulach et al., 2022). The average heating value of the fuel mix is 23.5 MJ/kg, whereas the CO₂ emission factor is 1.78 kg CO₂/kg fuel mix. The replacement of fuels was modelled following the assumptions regarding composition of the fuel mix, heating values of the fuels, carbon content and the biogenic share of carbon following Bulach et al. (2022). The composition of the current and future fuel mix is provided in SM B, Table B-3.

2.2.2. Replacement with (reinforced) concrete pipes

Primary data were collected as part of an Environmental Product Declaration (EPD) for the German Federal Association of Concrete Sewer Systems (FBS). The data show a representative average for Germany, taking into account both large and small pipe manufacturers (ift Roseenheim GmbH, 2023).

Wastewater pipes made of concrete and reinforced concrete with a compressive strength class of C40/50, immediately demolded, were examined. The average density of concrete is 2.35 g/cm³ (2.25–2.45). The average degree of reinforcement for the reinforced concrete pipes is 1.9 %. The average pipe length is usually between 2.5 and 3.5 m and covers diameters between DN300 and DN 4000. The necessary polymer-based seals were also taken into account. Different cements were considered depending on the manufacturer. The weight of the (reinforced) concrete pipes is provided in SM B in Table B-4. The average fuel input is provided in SM B in Table B-5, and the average material composition of concrete in SM B in Table B-6.

While the installation effort is almost negligible for the liner system, the installation phase of concrete pipes contributes significantly to the total environmental burden. Installation of concrete pipes entails excavation work, transport activities, refilling with sand, and asphalt replacement. However, the installation effort heavily depends on the specific situation. This study therefore makes assumptions about the average situation. Key assumptions are summarized in SM B in Table B-7. Table B-8 in SM B also shows the material and energy requirements as well as the background data used.

3. Results and discussion

3.1. Environmental impacts of glass liner

To identify the most relevant environmental impacts, the results of the impact assessment were normalized and weighted with PEF3.1 recommended person-equivalent-based normalization factors and weights (European Commission, 2022). The following impact categories account for >90 % of the environmental impacts: climate change, resource use (fossils), ecotoxicity (freshwater), particulate matter, photochemical ozone formation and acidification. The raw data can be found in SM C in tables C4 to C6.

As shown in Fig. 3, around 40 % of the environmental impacts can be attributed to climate change and a further 40 % to the consumption of

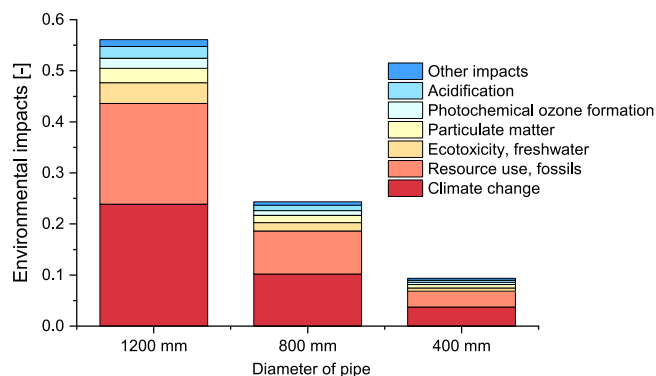


Fig. 3. Normalized and weighted impacts of glass liner per FU for 1200, 800, 400 mm pipe diameters.

fossil resources. Ecotoxicity (freshwater), particulate matter, photochemical ozone formation and acidification contribute only slightly to the environmental impact, while all other impact categories are nearly neglectable. The proportion of the individual environmental impact categories in the total environmental impact varies only slightly between the three diameters due to the different wall thickness and the changed surface/volume ratio.

The two main impact categories, climate change and resource use (fossils), are therefore examined in more detail. Depending on the diameter of the wastewater pipe, the carbon footprint is between 1342 and 8561 kg CO₂-eq. per 50 m (FU). The net fossil resource use is between 24,067 and 153,991 MJ per FU (Fig. 4). Depending on the pipe diameter, between 70 % (400 mm) and 82 % (1200 mm) of the global warming impact is caused by the upstream processes involved in producing the resin and glass fibers for the wall material (red color). In the case of fossil resource use, the wall material contributes between 80 % (400 mm) and 94 % (1200 mm) to the total impact.

The impact of the films covering both liner surfaces makes the second largest contribution. Its importance increases with smaller diameters, as the ratio of surface area to volume increases with smaller wall thickness and the films are identical for all wall thicknesses. For global warming, the contribution increases from 6 % (1200 mm) to 13 % (400 mm) and for the use of fossil resources, which is influenced by the production of the films, the contribution increases from 8 % (1200 mm) to 18 % (400 mm). In the fossil resource use impact category, the thermal utilization of glass liners leads to a credit. This results from the fact that the refuse-derived fuel substitutes approximately one-third-of fossil fuels in the cement kiln.

The energy required to manufacture the glass liners, and the disposal of production waste plays a minor role. The transportation of raw materials as well as the transportation of the liners to the construction site and back to the cement plant at the end of their lifetime cause around 5 % of greenhouse gas emissions and contribute 3 % to the consumption of fossil resources. The installation of the glass liner causes between 1 % (1200 mm) and 7 % (400 mm) of the climate impact. In terms of fossil resource consumption, 1 % (1200 mm) to 5 % (400 mm) are caused by the installation.

Wall material production almost always dominates the environmental impacts as shown in Figure C-1 in SM C for all investigated impact categories. Only in some cases, however, the substitution of fuels in the cement plant has a greater impact: for example, human toxicity is positively influenced by the substitution of the fuel mix with glass liners. As described before, the installation of the liners hardly contributes to climate change or the use of fossil fuels, but it does make a notable contribution to ecotoxicity, human toxicity, particulate matter and ozone formation. The contributions to ecotoxicity and human toxicity are mainly due to the assumed styrene emissions. The net contribution (impacts minus credits) becomes negative for human toxicity due to high credits. This result shows a well-known problem with the avoided burden approach, namely that an increase in material consumption due to the award of credits leads to a reduction in environmental burdens and should therefore be interpreted with caution. A comparison of the contribution analysis for the different diameters shows that liner installation becomes more relevant as the pipe diameter decreases. This means that the environmental impact of the installation increases in relative terms compared to the environmental impact of manufacturing the liners.

3.1.1. Sensitivity to wall material composition

Due to the high contribution of the wall material to the environmental impacts, the extent to which the ratio of glass fibers to resin has an influence on its environmental impact is being examined. The influence on the impact results is shown in Fig. 4 as an uncertainty bar: The variation of resin share from 46 % to 57 % has hardly any impact on global warming, fossil resource use or the normalized and weighted environmental score. The total environmental impact (for a fixed wall

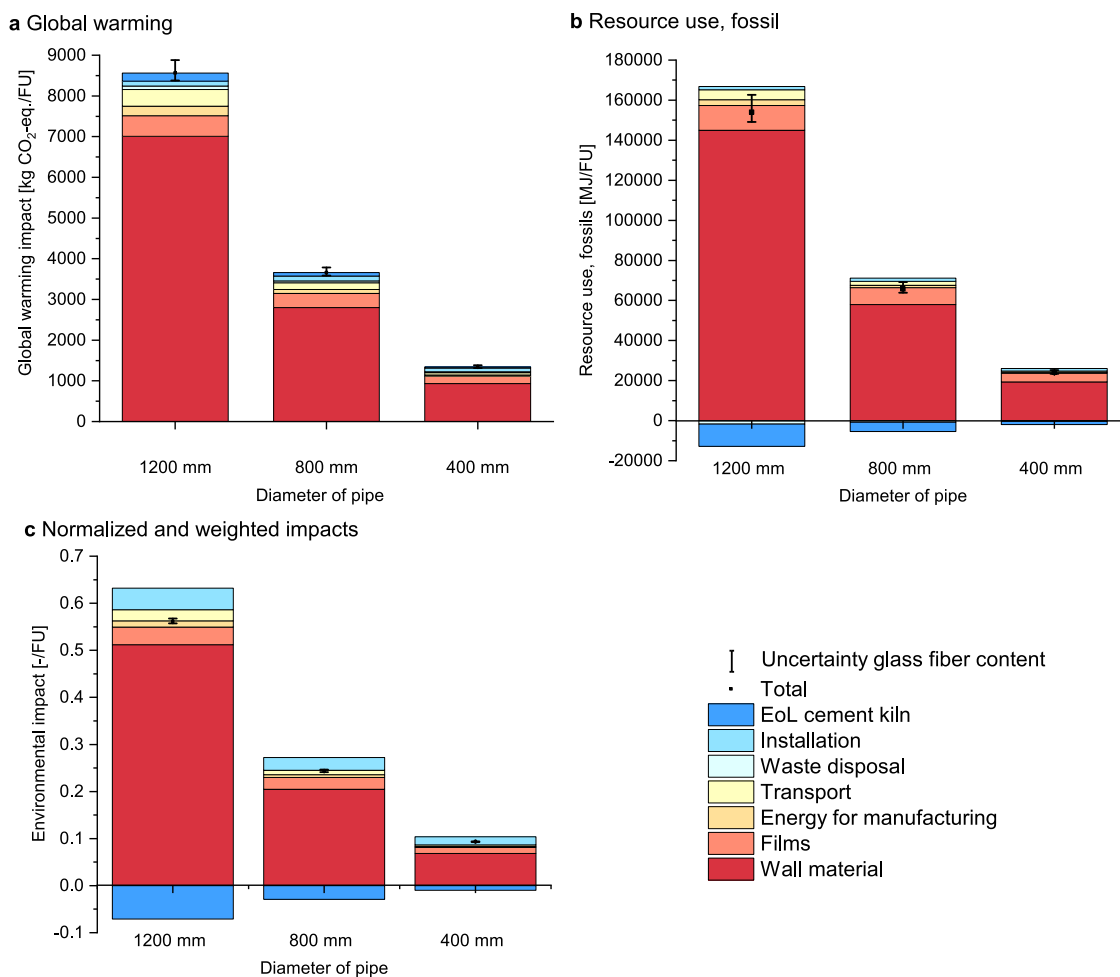


Fig. 4. (a) Global warming impact, (b) fossil resource use, and (c) total environmental impact of glass liners (per 50 m) with various diameters: 1200 mm, 800 mm, 400 mm; uncertainty bars reflect the uncertainty according to the glass fiber content of the wall material, which varies between 43 and 54 %.

thickness) increases with the increase of the glass portion, although it is the material with the lower environmental impact, because this positive effect is overcompensated by the higher density.

3.1.2. Sensitivity regarding end-of-life treatment of liners

Waste treatment at the EoL has an influence on some environmental categories. A sensitivity analysis is therefore carried out regarding the future fuel mix in cement plants. In the future, cement plants will increasingly use alternative fuels to reduce greenhouse gas emissions. In terms of the energy content of fuels, an increase in alternative fuels in cement plants to 90 % is forecast for 2050 (45 % biomass, 45 % wind-driven hydrolysis) and only a remaining share of 10 % hard coal. By mass this equals 8.7 % coal, 9.5 % hydrogen, and 81.7 % wood (Georgiades et al., 2023).

Assuming this future fuel mix of cement plants, the total carbon footprint of the liners will increase from 8561 to 11,010 (1200 mm), from 3658 to 4662 (800 mm), and from 1342 to 1687 (400 mm) kg CO₂-eq./FU as shown in Figure C-2 in the SM C. The reduction of credits granted causes an increase in greenhouse gas emissions per FU between 20 % (400 mm) and 22 % (1200 mm). With regard to the use of fossil resources, these will only increase slightly by 2 %.

Furthermore, the carbon footprint of cement plants might be further reduced by implementing Carbon Capture and Use (CCU). For example, the company Holcim is already integrating CCU technologies to reach a carbon-free cement plant (HOLCIM, 2025). Such options were not investigated in this study.

3.2. Environmental impacts of (reinforced) concrete pipes

The global warming impact of concrete pipes varies between 5736 (400 mm) and 18,798 kg (1200 mm) CO₂-eq./FU and the fossil resource use between 134,134 (400 mm) and 268,748 (1200 mm) MJ/FU (see Fig. 5). No credits for the decarbonization (CO₂ uptake) of concrete were taken into account in the end-of-life stage, as the exchange of CO₂ and concrete in road construction is very limited. All LCIA results for (reinforced) concrete pipes are provided in SM C in tables C-7 to C-12.

To identify the most relevant environmental impacts for (reinforced) concrete pipes, the LCIA results were also normalized and weighted. The normalized and weighted environmental impacts of (reinforced) concrete pipes are provided in SM C in table C-13 and are shown in Fig. 5 (concrete pipes) and Figure C-3 in the SM C (reinforced concrete pipes). The environmental impact of (reinforced) concrete pipes is also influenced primarily by the impact on the climate and the consumption of fossil raw materials. In contrast to the glass liners, the installation of concrete and reinforced concrete pipes accounts for a significant proportion of the environmental impact of around 43 % in case of huge pipes with a diameter of 1200 mm and 78 % in the case of smaller pipes with a diameter of 400 mm. This is mainly since the asphalt surface has to be opened up and, above all, reinstalled after the construction work. This road construction work is not required in the case of the glass liner. As a conservative assumption, only the excavation work for the trench, the transportation of the excavated material, the provision of sand and the production of the asphalt were taken into account in this study. Diesel requirements for pipe extraction and pipe laying, diesel for

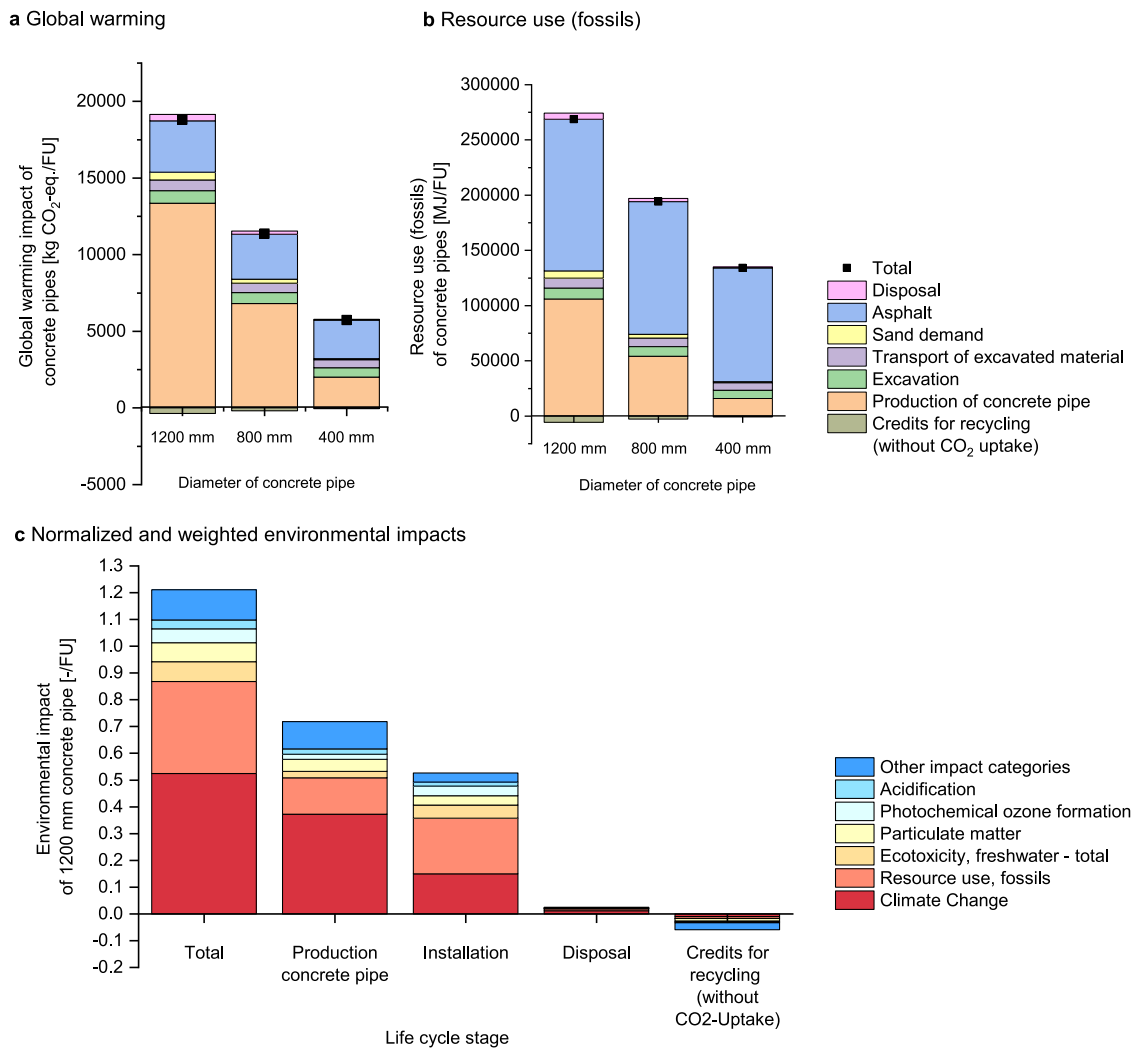


Fig. 5. Contribution analyses from cradle-to-grave of a) processes to the global warming impact, b) processes to the fossil resource use, and c) normalized and weighted impact results for concrete pipes with a diameter of 1200 mm.

installing the asphalt, disposal of the old asphalt and other transportation costs were not considered.

For validation, due to the high environmental relevance of the installation stage, we used the Excel® tool provided by Morera et al. (2016) to determine the material and energy requirements. To allow a consistent comparison, we modelled the impacts of installation based on the foreground data provided by Morera et al. (2016) in combination with Sphera MLC datasets. The inventories can be found in SM B Table B-9. A comparison of the environmental impact of replacing wastewater pipes based on the LCA tool created by Morera et al. (2016) shows that we tend to underestimate the environmental impact of replacing sewer pipes. This is particularly due to the additional diesel required for pipe extraction and pipe laying. On the other hand, Morera et al. (2016) assume trenches that are narrower and less deep, thus taking into account a smaller amount of asphalt. Life cycle impact assessment results for the installation of concrete pipes based on Morera et al. (2016) are provided in the SM in tables C-14 to C-16. In summary, it can be said that different assumptions about the installation situation also lead to a similar interpretation of the results.

The end-of-life disposal of concrete pipes and the credits for the substitution of gravel in the road substructure by broken pipes only have weak influence on the environmental impact. The environmental significance of the installation tends to increase with smaller pipe diameters in most of the impact categories investigated (see Figure C-4

and Figure C-5 in SM C).

3.3. Comparison of glass liners to concrete pipes

The carbon footprint of glass liners is 54 % (1200 mm diameter) to 77 % (400 mm diameter) smaller than that of concrete pipes (see Figure C-6 in SM C). The reduction of fossil resource use is between 43 % (1200 mm diameter) and 82 % (400 mm diameter) compared to concrete pipes. Similar savings are also achieved in the other relevant impact categories of ecotoxicity, freshwater, particulate matter, photochemical ozone formation, and acidification. In general, relative savings are greater with smaller pipe diameters, as the proportion of pipe production decreases in comparison to the installation efforts.

Similar to the comparison of the midpoint indicators, the comparison of the total normalized and weighted environmental impacts shows that the environmental impacts of glass liners are between 54 % (1200 mm) and 80 % (400 mm) lower than those of concrete pipes (Fig. 6). The difference between concrete and reinforced concrete pipes is very small. Although the footprint per kilogram of reinforced concrete pipes is higher than that of concrete pipes, the material requirement per meter of pipe for reinforced concrete pipes is lower than that of concrete pipes. These opposing effects mean that the overall footprint per meter of pipe is similar.

Taking into account a future fuel mix in cement plants leads only to a

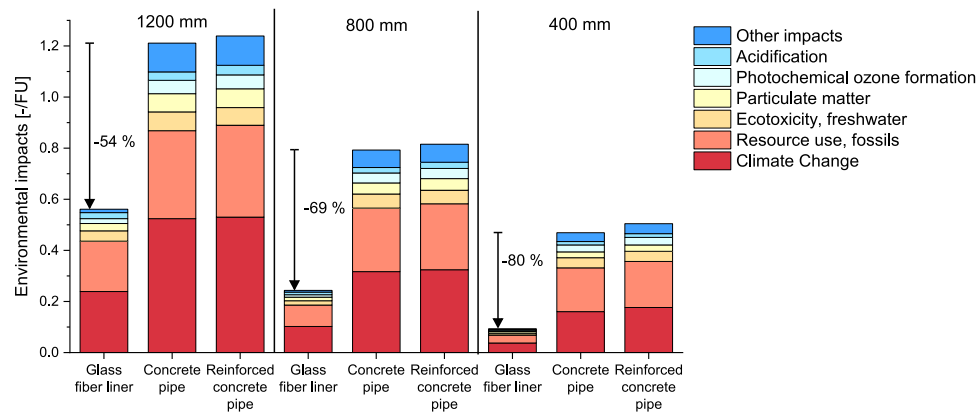


Fig. 6. Comparison of the normalized and weighted impact results for glass liners, concrete pipes and reinforced concrete pipes from cradle-to-grave.

slight decrease in the environmental advantages of glass liners compared to replacement with concrete pipes. When comparing the normalized and weighted results for glass liners and concrete pipes, there are still advantages of between 48 % (1200 mm) and 78 % (400 mm). The interpretation is therefore not influenced by a greener cement plant fuel mix in the future.

4. Limitations

A key assumption is that the service life of glass liners is comparable to that of concrete and reinforced concrete pipes. The actual service life of glass liners and (reinforced) concrete pipes depends on many factors such as material quality, material composition, chemical stress (pH value, exposure to solvents and disinfectants, acid and sulphate attack, chlorides, carbonation), mechanical stress (e.g. traffic loads, earth and building loads), temperature and humidity changes (e.g. freeze/thaw cycles), abrasion/wear due to the transport of solids (sand, gravel, etc.), and the degree to which the surface has been exposed to the effects of weathering. The service lifetime of both technologies may vary due to different regional conditions. As the service life is included in the assessment on a linear basis, the results presented can easily be transferred to other service lives of glass liners and concrete pipes. The service life of a concrete pipe would need to be 2.1 times longer than that of a glass liner in order to achieve the same total environmental impact.

It is also conceivable that, in the distant future, glass liners may no longer be accepted for co-processing in cement plants, for instance, due to regulatory reasons or availability of new recycling methods. In these cases, the glass liners would have to be disposed of in a different way. There are therefore uncertainties regarding the environmental impact of the end-of-life. Furthermore, the possibility that a liner at its end-of-life could be rehabilitated by a second liner has not been considered in this study.

In addition, the use of glass liners may be restricted or technically not possible depending on e.g. the slope or the curvature of the wastewater pipes. These special cases have not been considered in this study.

The environmental burdens of concrete pipes depend not only on the pipes themselves but are strongly influenced by the efforts required for the trenching and restoration of surface structures. In this study, only a typical situation could be assumed, which might be very different from other situations either causing higher or lower environmental impacts.

5. Conclusion

The comparison of the glass liner method with the replacement of concrete pipes has shown that the rehabilitation with the liner can reduce the environmental impact by 54 % to 80 % depending on the pipe diameter. Greenhouse gas (GHG) emissions are reduced by 54 % (for a 1200 mm diameter pipe) to 77 % (for a 400 mm diameter pipe). Similar

findings were obtained by [Chorazy et al. \(2024\)](#) who found a 59.2 % reduction in GHG emissions in a case study in the Czech Republic. Therefore, from a climate perspective, it is advantageous to use the glass liner method for upkeeping of sewage pipes instead of replacing them with new ones, if technically possible. Furthermore, the comparison of the total normalized and weighted environmental impacts shows that the environmental impacts of glass liners are between 54 % (1200 mm) and 80 % (400 mm) lower than those of concrete pipes. Therefore, it also makes sense from an ecological point of view to favor the glass liner method.

In addition to the impact of fossil resources on the climate, their consumption in particular contributes to the environmental impact of the glass liners. The use of fossil resources also leads to greenhouse gas emissions produced at the end-of-life during incineration of the plastics. The use of bio-based plastics instead of fossil-based plastics could potentially contribute to a further reduction in the environmental impact of liners.

The sensitivity analyses have shown that the variation in glass fiber content of the wall material within the typical range has only a minimal impact on the environmental performance. The end-of-life situation has a greater influence on the environmental impact of the glass liner but does not affect the advantageousness of the glass liner. Even framework conditions other than those assumed for the installation of concrete pipes do not change the advantages of glass liners compared to the replacement by (reinforced) concrete pipes.

The relative advantage of the liner method tends to increase with smaller pipe diameters, while the absolute environmental benefits decrease with decreasing diameter. When comparing only the environmental impacts of the production phase there is a slight advantage of <30 % for glass liners compared to (reinforced) concrete pipes. The main difference only comes into play during installation and disposal. Particularly during installation, the glass liner method can avoid breaking up the road surface, excavation work, transportation and replacement of the asphalt while the energy costs of installing the glass liners are minimal. In rare cases, sewage pipes may have to be reconstructed in places where there is no asphalt road. In such situations, the effort to replace an old pipe with a new concrete pipe would be reduced.

(Reinforced) concrete pipes have advantages when it comes to disposal, as concrete can be crushed and used as a gravel substitute in road substructures. The steel can also be recycled. Glass liners, on the other hand, must probably be thermally treated. With an increasingly greener fuel mix in cement plants in the future, the benefit from the calorific value of the glass liner will decrease. However, the sensitivity analysis shows that the environmental benefit of glass liner remains even in the case of a future green fuel mix. Ultimately, it should be noted that, in addition to glass liners, there are several other trenchless methods available for the rehabilitation of wastewater pipes that were not investigated in this study.

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CRedit authorship contribution statement

Jan Blömer: Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Daniel Maga:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.resconrec.2025.108748](https://doi.org/10.1016/j.resconrec.2025.108748).

Supplementary Material A: Literature Review

Supplementary Material B: Life cycle inventory of glass fiber liner and (reinforced) concrete pipes

Supplementary Material C: Environmental impacts of glass fiber liner and (reinforced) concrete pipes

Data availability

All relevant data are included in the article and supplementary information.

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