Interreg North-West Europe
RAWFILL
European Regional Development Fund
Co-funded by the Walloon region

Deliverable WP T3.2.3.
Preliminary environmental and social impact assessment report

Date: December, 2020

spaque · OVAM · Liège université · British Geological Survey · atrasol · BAV · Les Champs Jouault · Cleantech Flanders

SUBJECT:	Deliverable WP T3.2.3. Preliminary environmental and social impact assessment report						
☒	report	☐	information	☐	consideration	☐	decision
To:	…			From:	SPAQuE, Atrasol, BAV.		

Introduction

The first part of the report is devoted to assess the environmental and social benefits/negative impacts of the landfill mining project that could be launched on the RAWFILL pilot sites. For that purpose, we have considered two types of scenarios:

(1) “BAU” – business as usual, so without landfill mining operations. Site remains as it is in its current state;
(2) A landfill mining project is launched, some waste are removed and site is rehabilitated.

For the scenario without landfill mining operations, we analyse the effects on the environment and the population on short-term (5 years) and on long-term (>50 years). The scenarios discussed in the following are based on the scientific literature and experience knowledge.

For the assessment of the social benefits, several methods exists such as the contingent valuation method (Marella and Raga, 2014), the hedonic price method (e.g., Avayon *et al.,* 2006), the travel cost method (e.g., Avayon *et al.,* 2006) among others. Most of these methods are based on surveys and/or require intensive research studies. For this preliminary social impact assessment report, the survey on site was not an option. The main reason was that the presence of landfill (that might be a danger for the human health) is not always known by the residents. Revealing the presence of waste deposits is a sensitive topic that could induce stress and anxiety among the local community. As the other social assessment methodologies necessitate years of research study and the social benefit assessment was not the main target of the RAWFILL project, we decided to assess the global social benefits of landfill mining project based on the existing literature.

The second part of the report is dedicated to the analysis of the environmental impacts of existing landfill mining project. The analysis is based on the results of an environmental survey sent to landfill mining project managers and RAWFILL Stakeholders.

Greenhouse gases emissions from waste extracted from landfills

The question of greenhouse gases emissions produced by Refuse Derived Fuels[1] coming from mined waste is quite complex and will not be developed in detail here. On one hand, a part of the carbon is biogenic and therefore must not be considered as a source of greenhouse gases emissions, as it participates to the natural carbon cycle[2]. Waste composition studies show that fresh unsorted domestic waste contains at least 50 to 65% of biogenic carbon. After landfilling, and depending on the age of the waste deposits, this proportion should decrease but cannot be easily evaluated except by performing carbon-14 dating to assess the ratio “fossil carbon/biogenic carbon”. On the other hand, combustion of fossil carbon will indeed release CO_2 and contribute to greenhouse gases emissions, but this will also lead to avoid the generation of new greenhouse gases which are difficult to quantify without comparing to substitute combustion sources. Moreover, by not performing any waste valorisation, a large part of carbon (whatever its origin, biogenic or fossil), will be ultimately released in the air when

[1] Fuel produced from various types of waste such as municipal solid waste, industrial waste or commercial waste.
[2] Biogenic Carbon is excluded from Kyoto Protocol.

landfill capping and slopes are not waterproof, which is very often the case for all old landfills. So, in first approach, we can consider that combustion of Refuse Derived Fuels produced with mined waste will not lead to additional greenhouse gases emissions.

1. Les Champs Jouault (France)

The sanitary landfill site of Les Champs Jouault (48°43'17" N, 1°05'25" O) is located close to Cuves in Normandy. The landfill site is located at 60 m above sea level and lies on a thick clay layer. A small river (La Sée) is flowing in the south of the site but the site is not currently situated in a flooding area.

The landfill site opened in 2009 and is still under operations. It is a non-hazardous municipal solid waste landfill equipped with a leachate recirculation system and operated as a bioreactor. An exploitation permit is running until 2029 when its maximum storage capacity is expected to be reached. The composition of incoming waste is approximately 50% municipal solid waste and 50% non-hazardous industrial waste. The landfill is divided in several cells (100 m x 50 m x 15m). The waste deposits are covered by a 1 m topsoil and sealed with HDPE geomembranes. The bottom of the landfill consists of 0.5 m layer of draining materials, a clay layer, and an HDPE geomembrane.

1.1. Scenario without landfill mining project

a. Short-term Scenario (5 years)

In 5 years, the landfill site of Les Champs Jouault will still be under operations as the end of the operation are planned for 2029*.* Therefore, the constant monitoring of the site will ensure the environment safety from a leachate and biogas production point of view. The presence of geomembrane at the bottom and at the top of the landfill will preserve the waste deposits from external factors and so no risk for groundwater, air, soil or human health has to be expected. As the "zero" risk does not exist, there will be low probability risks of explosion and/or fire related to the presence of biogas or/and leachate leakage despite the safety engineering system present on site, but the risk is really low.

b. Long-term Scenario (> 50 years)

Regarding the long-term future (> 50 years) of les Champs Jouault landfill site, the site will be monitored for aftercare for 30 years. During the aftercare period, the biogas and the residual leachate production will be collected and monitored, minimizing the risks of air and water contamination. However, it is still unclear if the aftercare will be stopped after 30 years or will be extended.

The main issue in this case will be the low degradation of the waste material in this confined environment. Moreover, there is also no guarantee that the geomembrane located at the bottom will stay waterproof over a long period of time even if the product had a 100-years guarantee. The impossibility to have access to the geomembrane lead to the difficulty to predict its long-term behaviour. The degradation of the geomembrane over time may lead to the release of leachates in the environment. The residual leachates will potentially contaminate agriculture parcels located around the landfill site as well as the surface water. Several studies (e.g., He *et al.,* 2019 ; van Praagh *et al.,* 2018) demonstrated that the leachates produced by landfill is a significant source of microplastics. In the case of les Champs Jouault site, these microplastics will be transported by the Sée river into the Channel (~32 km far from the site) and will directly contribute to the microplastics pollution of the Channel and its ecosystem. The impact on marine ecosystems is described in details in section 3.1.a.

Regarding the natural hazards, the flooding risk is currently relatively low in the area. Even with the worst sea level rise scenario, the area will not be flooded. The presence of the Sée River in the south will not represent a threat for the site according to the regional flooding map. The seismicity of the region is relatively low and therefore, no large magnitude earthquake will be expected in the area. No large landslide will be expected as the landfill was designed to have gentle slopes and therefore to be stable.
The change of precipitation pattern (increase of heavy rain events) will potentially lead to the erosion of the topsoil in the following decades. However, the landfill will still be protected by the geomembrane and the waste will not be affected.

1.2. Scenario with landfill mining project

The direct benefit of the implementation of a landfill mining project at les Champs Jouault landfill site is the gain of void space and prolongation of the landfilled activities. By recycling waste and creating new voice space, it will avoid the use of new green field for the establishment of a new landfill site in the region. Moreover, the landfill of les Champs Jouault is a source of employment in the area and it currently employs 30 persons.

The landfill mining operations will ensure the revalorization of metal scraps contained within the landfill. The recycling of metal will avoid the production of CO_2 emissions and therefore will be directly benefit for the climate. However, the removing of the entire landfill would only be done if the recycling and waste revalorization facilities as well as the waste management in France evolves.

A summary of the environmental and social impacts of the landfill of Les Champs Jouault (with and without LFM project) is presented in **Table 1**.

	Human health/Social aspect	Soil	Air	Water (groundwater)	Natural hazards	Impact on the landscape	Climate
Scenario without LFM 5 years	• (-) Person Accident. • (-) Lower land value surrounding the LF. • (+) Source of employment.	• (+) Protected by landfill liner system and landfill monitoring program.	• (+) Valorization of landfill gas. • (-) Low risk of fire/explosion. • (-) Dust emissions.	• (-) Low risk of leakage.		• (-) Small amounts of waste lost by waste logistics.	• (+) Valorization of landfill gas → Substituting fossil fuels.
Scenario without LFM 50 years	• (-) Lower land value surrounding the LF.	• (-) Potential contamination of the surrounding areas by leachates.	• (-) Risk of fire/explosion.	• (-) Risk of leakage. • (-) Microplastic pollution, contamination of the Channel.		• (-) Waste material eroded → can affect the well-being of the inhabitants and increase anxiety; → Encourage the new deposition of illegal waste; → Attract vermin.	• (-) Biogas emission → contribution to the greenhouse effect.
Scenario with LFM	<u>During LFM operations :</u> • (+) Increase employment opportunities. • (-) Increased noise, odor and transport. <u>After LFM operations (*if total excavation of the waste deposits*):</u> • (-) Unemployment • (+) Increase of land value surrounding the LF.	<u>After LFM operations (*only for gain of void space*):</u> • (+) Limitation of Greenfield use. • *See Scenario 5-yr without LFM project for the other impacts.*	<u>During LFM operations :</u> • (-) Risk of fire/explosion. • (-) Dust emission. <u>After LFM operations (*if total excavation of the waste deposits*) :</u> • (+) No more gas emission.	<u>After LFM operations (*only for gain of void space*):</u> • *See Scenario 5-yr without LFM project for the other impacts.*	<u>During LFM operations :</u> • (-) Risk of scattering waste and ashes/dust at heavy storms. • (-) Risk of landslides and collapse.	<u>After LFM operations (*if total excavation of the waste deposits*) :</u> • (+) Positive impact on the landscape. <u>After LFM operations (*only for gain of void space*):</u> • *See Scenario 5-yr without LFM project for the other impacts.*	• (+) Metal recycling avoids CO_2 emissions. + *See Scenario 5-yr without LFM project for the other impacts* <u>*(only for gain of void space).*</u>

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	After LFM operations (*only for gain of void space*): • *See Scenario 5-yr without LFM project for the other impacts.*		After LFM operations (*only for gain of void space*): • *See Scenario 5-yr without LFM project for the other impacts.*				

Table 1 – Summary of the environmental and social impact of les Champs Jouault landfill mining project.

2. Meerhout (Flanders, Belgium)

The landfill of Meerhout (51°06'11"N, 5°03'00"E) is a landfill located in Meerhout (Flanders, Belgium). The landfill was exploited from sixties to nineties. In total, more than 1,315,000 m^3 of municipal solid waste and industrial solid waste were landfilled on site. The waste materials directly lie on Quaternary sand. The site is characterized by a mound shape with a maximum elevation of 20 m above ground level. The landfill site can be divided into two areas: (1) the north-eastern part of the site which corresponds to the oldest part of the landfill dated back to the sixties and is characterized by 10 m of waste deposits and equipped with a drainage system; (2) the southern part which is also the highest part (20 meters of waste materials) and most recent one (dated from the eighties) which have been sealed properly. The site is currently monitoring for leachates and biogas. Biogas is only monitored and not valorized, because the production is too low (the gas installation is only on the oldest part of the landfill).

Two small streams (the Kleine Laak and the Halfwegloop) are flowing nearby the landfill site. From an ecological point of view, there is no valuable biodiversity on site.

2.1. Scenario without landfill mining project

a. Short-term Scenario (5 years)

In five years, the site will still be under aftercare. Therefore, the production of biogas and leachates will be controlled limiting the risk of ground water contamination and air pollution. Nevertheless, due to the absence of impermeable layer at the bottom of the waste deposits, the risk of groundwater contamination is still significant. Regarding the biogas production, even if it remains relatively low, it will directly contribute to the greenhouse effect and to global warming. However, Gebert *et al.* (2016) pointed out that gas transport through a landfill cover is diffusive with quite often complete methane oxidation and subsequently no emissions. Quantification of this effect was not part of this investigation.

The landfill is currently revegetated with trees and scrubs. In five years, the site will potentially be the natural habitat for specific flora and fauna. As the landfill site is mostly revegetated, it will not constitute a visual treat. In fact, except for air emissions, the landfill site will directly contribute to the well-being of the surrounding inhabitants as the landfill, due to its elevation, block the noise from the highway N126.

The investigations revealed traces of asbestos on site (cement). No pockets with high asbestos cement content nor free fiber asbestos was detected. The presence of asbestos on site is not expected to represent a threat in the next five years as the waste deposits are sealed with a geomembrane (for the newest part) and a cover layer (for the oldest part).

Regarding the flooding hazard, the two streams flowing nearby (the Kleine Laak and the Halfwegloop) will not be a treat in the near-future.

b. Long-term Scenario (> 50 years)

The sealing of the landfill is only guaranteed for a maximum of 100 years. However, it is difficult to predict the long-term behavior of the material. For the not geomembrane covered part, water will still be able to infiltrate through the waste mass, increasing the production of leachates until the complete mineralization of the waste materials. As there is no protection at the bottom of the landfill, the leachates will potentially impact the groundwater and the surface water. As mentioned above, leachates can be a significant source of microplastics (He *et al*., 2019; van Praagh *et al*., 2018) indirectly contributing to increase the pollution of the river and the North Sea ecosystem.

In the long-term, the climate change will induce a change in the precipitation pattern by increasing the number of short heavy rain episodes (IPCC, 2012), which will directly contribute to increase the flooding hazard in the area as well as the leachate production. The two streams flowing nearby will potentially affect the landfill. Currently, the Halfwegloop stream has a water buffering area just ±100 meters upstream of the landfill. However, it will probably change in the future. As the thickness of the waste deposits in the southern part of the site is relatively important, the landfilled waste deposits will not be flooded entirely. However, the waste located at foot of the landfill slope will potentially be saturated with waste which will lead problems of mechanical stability, potentially causing shear and sliding fractures into the waste pile. The vegetation cover which has developed for decades will mitigate these effects to a large extent. In addition to the flooding risks, the change of precipitation intensity will result in (i) a significant increase of the infiltrate leaking increasing the risk of accidental leakage of contaminants from the Meerhout landfill to the surroundings; (ii) increase of surface runoffs progressively leading to the erosion of the cover layer.

The cover layer (i.e. topsoil) of the older part of the landfill will erode with time, making the waste material visible. This risk is very low due to the vegetation cover. The presence of eroded waste will increase the risk of direct contact with waste material such as accidental cuts and inhalation (especially in the presence of asbestos). The free part of the asbestos contained in the landfill could potentially be blew away by the wind or washed out by the surface runoff water. The released asbestos in the air will potentially affect the people living nearby the landfill or the people having access to it. This risks is neglectable due to the matrix conditions (asbestos cement) and its presence (traces). The presence of eroded waste may encourage the new deposition of illegal waste. The current activities of the former landfill operator on the adjacent site and the fences lowers this risk of dumping.

2.2. Scenario with landfill mining project

Due to the large volume of the landfill (i.e. >1,315,000 m^3 of waste), the landfill mining of the entire site will probably take several years, generating dust, odor, noise, and lorry trucks that will be potentially an issue for local residents. The landfill mining project will increase the employment opportunities in the area for several years as well as the land value of the surroundings. The site is located close to the highway which is a good location for economical redevelopment project. Redevelopment project on site (such as implementation of private companies and industries) will also create job opportunities.

The highway and its traffic generate a lot of noises and vibrations which is not suitable for residential redevelopment project. By removing the waste deposits and therefore flatten the site, the local habitants will not be protected anymore by the landfill which acts like a sound barrier. The increase of the intensity of the noise generated by the highway will directly affect the well-being of the residents. It will also negatively impact the landscape as the highway will be more visible.

During the landfill mining operations, extra measures should be taken to protect the workers and the inhabitants living around the site. Moreover, there will be a potential risk of leakage resulting in the contamination of the surface water and groundwater. The topography of the site, which is characterized by relatively steep slopes, will increase the risks of slope failure and waste mass collapse. Protection of the excavated waste should be taken during the storm events to avoid the scattering of waste in the environment.

The landfilled waste excavation will stop the production of biogas, which will directly contribute to an improvement of the air quality and the reduction of the greenhouse effect. The revalorization of the industrial waste retrieved from the landfill will avoid the production of CO_2. The carbon footprint of the latter is currently difficult to assess. All the risks related to the stability of the waste pile and the production of leachates will be eliminated with the landfill mining operations. The water quality will also be improved.

The content and geometry of the Meerhout landfill is not offering favorable conditions for landfill mining. The volume/surface ratio is rather high (average 17) and the mineral content ranges between 75 and 90%. Metals represent a minor fraction (average 3%) and plastics reveal an average of 15%.

A summary of the environmental and social impacts of the landfill of Meerhout (with and without LFM project) is presented in **Table 2**.

	Human health/Social aspect	Soil	Air	Water	Natural hazards	Impact on the landscape	Climate
Scenario without LFM 5 years	• (+) Soundproof (LF blocks the noise from the highway).	• (-) Leachates production (on site leachate treatment plant).	• (-) Biogas (low concentration).	• (-) Risk for groundwater and surface water contamination.		• (+) Revegetation and hiding the highway.	• (-) Negative contribution to the Greenhouse effect.
Scenario without LFM 50 years	• (+) Soundproof (LF blocks the noise from the highway). • (-) Waste direct contact : accidental cuts (related to eroded waste) and inhalation (asbestos).	• (-) Leachates production?	• No more biogas production.	• (-) Risks for groundwater contamination. • (-) Microplastic pollution.	• (-) Flooding hazard can increase with the climate change. • (-) Slope destabilization due to the increase of surface runoff and to the erosion of the foot of the waste mass by flood.	• (-) Waste material eroded (negative visual impact). → can affect the well-being of the inhabitants and increase anxiety; → Encourage the new deposition of illegal waste; → Attract vermin.	
Scenario with LFM	<u>During LFM operations:</u> • (-) Increased noise, odor and transport. • (-) Health risks for workers. • (+) Increase of employment opportunities.		• (+) Improvement of the air quality.	<u>During LFM operations:</u> • (-) Risk of leakage. <u>After LFM operations:</u> • (+) No more risk of leakage of contaminants directly to the groundwater and the surface water	<u>During LFM operations:</u> • (-) Risk of landslides and collapse. • (-) Risk of scattering waste and ashes/dust at heavy storms. <u>After LFM operations:</u> • No more risk of collapse.	• (-) Negative → direct view to the highway. • (+) Positive → Clean site without eroded waste. • (+) Increase of the land value surrounding the site.	• (+) Avoids methane emissions → Reduce greenhouse effect. • (+) Revalorisation of the industrial waste → Avoid CO_2 production.

	After LFM operations: • (-) Increase of the noise related to the highway. • (+) Possibility of redevelopment projects increasing the employment opportunities.			• (+) Improvement of the groundwater quality.			

Table 2 – Summary of the environmental and social impact of Meerhout landfill mining project.

3. La Samaritaine, Lingreville (France)

The landfill of La Samaritaine (48°56'22.8"N, 1°32'49.3"W) has a surface area of 4,320 m^2 and is located along the French coast in Lingreville, Normandy (France). The elevation of the site is +8 m above sea level. Due to its proximity to the sea, the edge of the landfill is regularly eroded during storm events. The landfill mainly contains municipal solid waste deposits, landfilled between 1965 and the eighties. However, the precise composition of the municipal solid waste deposits is unknown. Based on the scientific literature, we assume that the landfill contain hazardous material including, among others, waste electrical and electronic equipment (e.g., mercury in fluorescent tubes, heavy metals, CFC, and brominated flame retardants in plastics), pharmaceuticals, pesticides, oils and fats, paints, batteries (heavy metals) (Slack *et al*., 2004; Slack *et al*., 2005; Brant *et al.*, 2017). In addition, asbestos, wood, metal, granulate and plastic have been described (BURGEAP, 2018).

The site of La Samaritaine is probably the most problematic RAWFILL pilot site in terms of environmental issues because of its location along the shore and the coastal erosion of the Normandy coast. Due to its potential treat for the environment, the landfill of La Samaritaine was excavated in 2017-2018. Before the landfill mining operations, the investigation study showed that the soil was contaminated with heavy metals and hydrocarbon. The presence of leachates was identified in the groundwater.

The case of La Samaritaine landfill is representative of the thousands of landfills located along the shores in North-west Europe. In the past, these low-lying estuarine and coastal areas were commonly chosen to install landfill due to the low value of the land caused by the important flood risks (Brand *et al*., 2017). In the United Kingdom, Brand *et al.* (2017) calculated that without intervention at least 345 coastal landfills are expected to start to erode into the sea in the short-term (i.e. 79 LFs by 2025), medium-term (i.e. 122 LFs by 2055) and long-term (i.e. 144 LFs by 2105), respectively. Therefore, the two scenarios developed for the landfill of La Samaritaine (i.e. short-term and long-term evolution of the site with and without landfill mining) presented below is representative of what expected in the future for historical coastal landfills.

Due to the high risk for the environment and the human health, the emergency landfill mining operations were performed in 2018. A part of the waste were valorized, and the non valorisable part was relandfilled in Les Champs Jouault and other Class II and Class III landfill facilities.

3.1. Scenario without landfill mining project

This scenario and the following one remain speculative as the waste have been removed, however it is presented as example of “BAU” situation.

a. Short-term Scenario (5 years)

A part of the 18,000 tonnes of waste deposits and their related contaminants would be physically remobilized from the landfill by the wave actions and transported directly into the sea. The eroded waste material would potentially harm the fauna and the flora by physically and chemically altering the supratidal and intertidal environment. For instance, eroded waste material would potentially increase the suspended particulate matter concentration and nutrient loads, reducing dissolved oxygen concentrations (Brand *et al*., 2017), and physically damage benthos in the supratidal and intertidal zone by crushing them. Moreover, the marine organisms would be physically injured by the release of plastic material from the Samaritaine landfill. Several studies have demonstrated the impact of the plastic on marine life. The most common impact plastics on the marine fauna are starvation, suffocation, injury due to ingestion (internal injuries, gastrointestinal blockages, etc.) as well as death (Gregory, 2009).

Regarding the impact of the landfill on human health, humans would be exposed to eroded waste material through bathing in polluted water and be in contact with debris, leading to accidental cuts and inhalation (e.g., asbestos) (Brand *et al*., 2017). Brand & Spencer (2020) demonstrated that the infiltration of seawater within a landfill tends to release more heavy metals than in case of fresh water. Therefore, the leachates produced would be potentially more dangerous for human health. The inhalation of hydrocarbons and other highly volatile compounds present in the soil would potentially be toxic for the human and the animals. The presence of eroded landfill waste would also impact the visual aspect of the landscape and the well-being of the residents. Moreover, it would cause anxiety and stress on people living nearby. The erosion of the landfill waste would also attract vermin.

b. Long-term Scenario (> 50 years)

In the future, climate change is expected to trigger higher sea levels, more frequent and intense storm events as well as higher storm surges and increased coastal flooding (Lowe *et al*., 2009; IPCC, 2012) resulting in an increase of the coastal erosion. In this long-term scenario (> 50 years), the potential consequence of climate change are taken into account to assess the environmental impact of the Samaritaine landfill.

The negative impacts of the landfill on the environment described above in the scenario (in five years) would be amplified in the future as most of the 18,000 tonnes of waste deposits would be remobilized and transported directly into the sea. In addition to these impacts, new environmental issues would appear in the future.

The Samaritaine landfill was not equipped with liner or leachate management systems. Due to the absence of sanitary equipment, the landfill would be susceptible to release dissolved nitrogen, other pollutants and metals to groundwater and to surrounded sediments (Njue *et al*., 2012; O'Shea *et al*., 2018). Contaminants contained in the solid waste and leachate would be assimilated by flora through their roots or ingested by filter feeding fauna. This assimilation would either provoke direct toxicity or cause biomagnification and/or bioaccumulation leading to toxicity. It would result in trophic transfer of pollution through the food web (Pope *et al*., 1999; Kvesitadze *et al.,* 2009). Moreover, several studies (e.g., Van Praagh *et al*., 2018; He *et al*., 2019) demonstrated that leachates would be a significant source of microplastic pollution.

The drift of plastic debris far away from the landfill is a possible pathway for the invasion of exotic species (Derraik, 2002). At sea, the floating plastic would become the habitat of various encrusting organisms such as bacteria, diatoms, algae, barnacles (e.g., Clark, 1997). As the plastic materials would be able to drift over long distance, the introduction of invasive species would destabilize the fragile marine ecosystems equilibrium (Grassle *et al.,* 1991).

In long-term, the rise of the sea water level and the increase of frequency and intensity of storm events will regularly flood the Normandy coastal area and the Samaritaine landfill. The increase of precipitation intensity and the flooding of the landfill by storm surge would cause an increase in the volume of leachate contained in the landfill due to the water percolation triggering an increase of the leachate leakage (Bagchi, 1994). The water saturation of the waste would potentially lead to mass failure (e.g., Blight and Fourie, 2005). The leachate migration and the eroded landfill waste would contaminate the surrounding sediments (Cooper *et al*., 2013) which would be transported by wave action and redeposited far from the landfill, indirectly contaminating a new area (e.g., Cooper *et al*., 2013).

Before the total erosion and transport of the landfilled waste material into the sea, the waste deposits could generate greenhouse gases such as carbon dioxide, contributing to increasing the greenhouse effect and directly affecting the climate change.

3.2. Scenario with landfill mining project

In the case of the Samaritaine landfill, the landfill mining was the only lasting solution. Therefore in 2018 after a major storm event, urgent landfill mining operations started. With this solution, there was no more environmental hazards due to the removal of waste deposits and contaminated sand and soil. Moreover, the quality of the estuary water and the air will improve. However, during the excavation, the residents and workers could have been exposed to VOCs which can be potentially toxic in case of inhalation. We estimated that the risk of inhalation was very limited due to the low density of the population living nearby and the safety measures taken during works (as explosimeter, pressurized cabins…). Except during the excavation operations, the landfill mining of La Samaritaine landfill site was a benefit for the environment as well as for the human health. Moreover, the direct plastic pollution of the sea was limited and the quality of the groundwater increased. With sea level rise and the increase in storm event frequency and intensity, the landfill site will be regularly affected by floods. The edge of the site situated along the coast will continue to be eroded by the sea and the storm surge. The sediments will be remobilized, transport and redeposited. However, as most of contaminated sediments and waste material has been removed, the landfilled waste are no longer a major treat for the coastal environment.

Another positive effect of the landfill mining project is the source of employment for the region. During the excavation and sorting work, local companies were involved. The site rehabilitation into a natural dune complex increased the well-being of the residents and attracted more tourists along the coast which is benefic for the local economy.
A summary of the environmental and social impacts of the landfill of La Samaritaine (with and without LFM project) is showed in **Table 3**.

	Human health/ Social impact	Air	Water (groundwater, surface water)	Fauna and flora (estuary/intertidal/supratidal zone)	Flood hazard	Sea and Marine Ecosystem	Impact on the landscape	Climate
Scenario without LFM 5 years	• (-) Exposition to eroded landfill waste. • (-) Waste Direct contact : accidental cuts and inhalation (e.g., asbestos). • (-) Contamination by bathing/touching leachates. • (-) Inhalation of VOCs.	• Gas emission	• Contamination by leachate.	• Chemical alteration of the supratidal/intertidal environment. • Physical damage of fauna and flora. • Microplastic pollution.	• Landfill erosion. • Increase the leachate content of the landfill : → Risk of leakage; → Risk of slope destabilization.	• Remobilization and transport of tonnes of eroded landfilled waste directly into the sea. • Plastic pollution: - Starvation of sea bird, cetaceans, fishes, turtles; - Suffocation of seabirds; - External and internal injuries of sea bird, cetaceans, fishes, turtles; - Animal deaths; - Microplastic pollution. • Debris Drift and possible pathway for the invasion of alien species.	• (-) Presence of waste deposits along the coast: → Can affect the well-being of the residents and increase anxiety; → Visual impact; → Attract vermin.	• (-) Contribution to the Greenhouse effect.
Scenario without LFM >50 years	• (-) Exposition to eroded landfill waste. • (-) Waste direct contact: accidental cuts and inhalation (e.g., asbestos). • (-) Contamination by bathing/touching leachates.		• Contamination by leachate.	• Chemical alteration of the estuary, supratidal and intertidal environments. • Physical damage of fauna and flora. • Microplastic pollution.	• Landfill erosion. • Increase the leachate content of the landfill: → Risk of leakage; → Risk of slope destabilization.	• Remobilization and transport of tonnes of eroded landfill waste directly into the sea. • Plastic pollution: - Starvation of sea bird, cetaceans, fishes, turtles; - Suffocation of seabirds; - External and internal injuries of sea bird, cetaceans, fishes, turtles; - Animal deaths; - Microplastic pollution.	• (-) Presence of waste deposits along the coast: → Can affect the well-being of the residents and increase anxiety; → Visual impact; → Attract vermin.	• (-) Contribution to the Greenhouse effect.

	• (-) Inhalation of biogas.							
Scenario with LFM	During LFM operations: • (+) Increase employment opportunities. • (-) VOCs generate during excavation. • (-) Health risks for workers. After LFM operations: • (+) Conservation area. • Attract tourists.	During LFM operations: • (-) Gas emissions generate during excavation. After LFM operations: • Improvement of air quality.	• (+) Improvement of water quality.	• (+) Creation of a protected natural area.	During LFM operations: • (-) Risk of scattering waste during heavy storms (storm surge). After LFM operations: • The area will be regularly affected by flood and the coastal erosion will progress.		• (+) Restoration of a natural dune complex.	• (+) Avoids methane emissions → Reduce greenhouse effect.

Table 3 – Summary of the environmental and social impacts of La Samaritaine landfill mining project.

4. Onoz (Wallonia, Belgium)

The landfill site (50°29'23'' N, 4°40'12'' E) is located in Onoz, province of Namur, Walloon Region, Belgium. The geology of the site consists of massive carboniferous limestone and dolomite. The site was a former limestone quarry equipped with lime kilns. From 1967 to 1976, the quarry was used as landfill where industrial waste (approximatively 210,000 m^3 of lime and fly ashes) were illegally dumped, filling progressively the pit. Since the eighties, the landfill of Onoz has been revegetated, providing an important ecological added value to the site, which was partially classified as a protected area (i.e. Natura 2000 network). On the eastern part of the landfill, a calcareous grassland and its related fauna and flora growth. The rock walls surrounding the site constitute a natural habitat for rare and threatened species such as Eagle Owls. European Badgers are also present on site, living in burrows on the steep slopes shaped by waste deposits.

The landfill site is in an extended groundwater source protection zone and a pumping station is situated at ~500 m downstream from the site. In the lowest part of the site, the groundwater table is located around four meters below the subsurface and is in contact with the waste deposits.

4.1. Scenario without landfill mining project

a. Short-term Scenario (5 years)

Despite the presence of a fence, the site is easily accessible to the residents. One major health risk will related to the direct contact with the waste deposits, which can provoke accidental cut. Moreover, the well-being of inhabitants living nearby the landfill site will be potentially negatively impacted by the presence of the landfill and new illegal waste deposits (causing stress and anxiety). The presence of barrels (which can potentially contain hazardous liquid waste) has been assessed during the investigation study. If one barrel leaks, it will contaminate the groundwater and therefore will directly pollute the exploited aquifer and the river nearby. Due to precipitation and water surface runoffs, the landfill will erode and fly ashes will potentially be released at the surface generating dust.

Moreover, the site shelters specific fauna (e.g., Eagle Owls, Badgers) and flora (e.g., calcareous grassland). The fauna will be directly physically damage by the waste deposits (cuts or internal injuries related to the ingestion of waste materials). Soon, the calcareous grassland and its related ecosystem will disappear due to the propagation of the Japanese knotweed and other invasive plants.

b. Long-term Scenario (> 50 years)

In the long-term scenario, the risks described above in the short-term scenario section will be still present and will potentially increase becoming more problematic. The change of precipitation patterns related to climate change in the NWE area (i.e. more heavy rain events) will lead to the erosion of the landfill slope. More landfill waste materials will be eroded and accidents related to waste contact will increase. Additionally, the increase of the heavy rains episodes will potentially trigger landslides and the destabilization of the steep slopes. The slope destabilization will have three direct effects: (i) It will destroy the natural habitat of the badgers and potentially decimate the badger population living on site; (ii) the dust released during the landslide will potentially affect the fauna on site and the residents living nearby.

4.2. Scenario with landfill mining project

The landfill mining of the site will have direct benefits on several aspects. The site rehabilitation will be a good way to manage invasive species on site, such as the Japanese knotweed and protect the calcareous grassland. The reshaping of the site will be done to avoid slope destabilization. On the upper part of the site, a natural forest, consisting of native species such as nerprun, crab-apple tree, fusain will be recreated (IRCO, pers. comm.). The cleaning of the cliff will increase the habitat space of the Eagle Owls. In the future, the site will continue to shelter threatened species. The current site redevelopment project is to create meadows for horses and a natural observatory for Eagle owls. These two redevelopment projects integrate the nature protection of the site. Some studies show an increase of biodiversity in the following years/decade after the removal of waste materials. We can expect a similar situation. The excavation of the barrels will ensure the quality of the groundwater and thus the safety of the environment.

As mentioned above, the landfill of Onoz mainly contained industrial waste materials (slaked lime and fly ashes). As the slaked lime and fly ashes will be directly reused in industrial processing, it will indirectly avoid the emission of CO_2 related to the production of lime and therefore reduce the carbon footprint.

From a social point of view, the landfill mining operations conducted by local companies and the site redevelopment project will increase employment opportunities in the area. The presence of the natural observatory and green space will promote nature awareness and increase the well-being of the neighbors. The nature observatory will attract tourists in the area leading to the development of the local economy. Moreover, the site will be safe from eroded waste materials and the cleaning of the site will help to avoid the new deposition of illegal waste deposits. The land value surrounding the site is also expected to rise.

The environmental and social impacts of the landfill of Onoz (with and without LFM project) are summarized in **Table 4**.

	Human health /Social impact	Air	Water (groundwater)	Fauna and flora on site	Natural hazards	Impact on the landscape	Climate
Scenario without LFM 5 years	• (-) Waste Direct contact: accidental cuts • (-) Well-being of the residents impacted by the LF.		• (-) Contamination by hazardous waste deposits (presence of barrels).	• (+) Presence of specific fauna (Eagle Owls, Badgers, etc.). • (+) Presence of calcareous grassland. • (-) Invasion of Japanese knotweed. • (-) Physical damage of fauna and flora.	• (-) Landfill erosion triggered by surface runoff.	• (-) Presence of illegal waste deposits on site → Negative visual impact.	
Scenario without LFM 50 years >50 years	• (-) Exposition to eroded landfill waste materials. • (-) Waste direct contact: accidental cuts. • (-) Well-being of the residents impacted by the LF.	• (-) Dust.	• (-) Contamination by hazardous waste deposits (presence of barrels).	• (+) Presence of specific fauna (Eagle Owls, Badgers, etc.). • (-) Invasion of Japanese knotweed and disappearance of the calcareous grassland. • (-) Physical damage of fauna by exposed waste materials.	• (-) Increase of the heavy rains episodes triggering destabilization of the steep slopes and landslides. • (-) Landfill erosion triggered by surface runoff.	• (-) Presence of illegal waste deposits on site. • (-) Negative visual impact.	

Scenario with LFM	During LFM operations : • (+) Increase employment opportunities. • (-) Increased noise, dust and transport. After LFM operations : • (+) Increase employment opportunities. • (+) Increase well-being of the neighbors. • (+) Redevelopment project (Nature observatory) will attract tourists in the area → Development of the local economy.	During LFM operations : • Emission of dust during excavation.	During LFM operations : • (-) Risk of leakage. After LFM operations : • (+) Improvement of the groundwater quality.	During LFM operations : • (-) Disturbance of the fauna and flora. After LFM operations : • (+) Restoration of the calcareous grassland. • (+) Restoration of natural habitats for the Badgers and the Eagle Owls. • (+) Eradication of the Japanese Knotweed. • (+) Diversification and increasing of the biodiversity on site.	During LFM operations : • (-) Risk of scattering waste and ashes/dust at heavy storms. • (-) Slope destabilization. After LFM operations : • (+) Reshaping of the site and slope stabilization.	• (+) Positive visual impact. • (+) Eradication of illegal waste deposits. • (+) Increase of the land value surrounding the site.	• (+) Reduction of the carbon footprint as slaked lime and fly ashes will be directly reused in industrial processes.

Table 4 – Summary of the environmental and social impact of Onoz landfill mining project.

5. Emerson's Green

The Emerson's green landfill site (51°29'41.0"N, 2°27'34.1"W) is located in the eastern suburbs of Bristol (Gloucestershire), UK. The landfill site was implemented on a valley feature with an ephemeral stream running through it. Progressively, from 1984 to 1991, the valley was filled with inert and industrial/commercial waste deposits. Historical records suggested that the landfill was filled with the following types of waste: (1) Excavation, demolition and construction waste; (2) Concrete glass and ceramic waste; (3) General shop and office waste; (4) Foundry sands; (5) Paper and cardboard; (6) Plastic and polythene; (7) Timber and sawdust waste; (8) Fabric waste; (9) Ferrous scrap metal (Coles and Hocker, 2014). The stream is assumed to be diverted (there are currently no record to prove it). In total, the landfill site has a surface area of 23,000m^2. The thickness of the waste deposits varies between 3 and 5 m depth. The landfill site was not equipped with no engineered leachate or gas management system. At the end of the landfilling operations, the waste deposits were recovered by inert soils and topsoil. The site is currently occupied by open grassland. The host rocks are composed of alluvial deposits, mudstone and sandstone. Aquifers are present locally but the landfill site is located within a ground water source protection zone (Coles and Hocker, 2014).

The site is drained by several minor tributaries, flowing north to south, to the Folly Brook. The site lies within a low risk flood area (Flood zone 1 on the UK flood hazard map). However, areas characterized by hydrophilic vegetation and waterlogged ground were observed on site (Coles and Hocker, 2014).

5.1. Scenario without landfill mining project

a. Short-term Scenario (5 years)

On the short term scenario, the major issues will be related to the presence of the waste deposits and the lack of engineering protective system. The presence of leachate at the surface, will directly contaminate the watercourses flowing on the site. The absence of impermeable layer at the bottom of the landfill will also problematic for the aquifers (which is currently not exploited for drinking water). Ephemeral streams and watercourse will progressively erode the capping of the landfill which only consists of topsoil. The erosion of the capping will continue and will be probably increase in the long-term.

b. Long-term Scenario (> 50 years)

As mentioned above in the short-term scenario section, the watercourses and ephemeral streams flowing on site will contribute to the erosion of the capping. Moreover, the increase of heavy rains events in the future and the related surface runoffs will participate to the erosion of the topsoil, making the landfilled waste deposits visible. The exposed landfilled waste will potentially attract vermin, will encourage the deposition of new illegal waste and will directly impact the landscape as well as the well-being of the inhabitants living nearby.

Even though the site is currently mapped as low flood risks, the future change in precipitations patterns and the presence of hydrophilic vegetation and waterlogged ground suggest that the site will be prone to flooding in the future. The erosion of landfilled material and the release of pollutants from flooded landfills are well documented (e.g. Geller *et al*., 2004; Clevers *et al*., 2004). The inundated Emerson's green landfill will release a flow of pollutants (heavy metals and organic pollutant into the floodplain soils and river sediments.

The environmental issues related to the lack of landfill engineering design (*see description 5-year scenario*) will remain until the landfilled waste material become inert.

5.2. Scenario with landfill mining project

The major environmental issue will occur during the landfilled waste excavation where the risk of explosion and fire related to the presence of biogas, the risk of groundwater and surface water contamination and the dust emission are significant. Like during the other landfill mining operations, the excavated waste material should be properly protected to minimize the risk of scattering waste during heavy storms.

The landfill mining work will generate employment opportunities. The building of school and other facilities will ensure new employment opportunities after the end of the landfill mining operations.

From a long-term point of view, the removal of the landfill and the site rehabilitation will eliminate all the risks related to the presence of waste deposits. Moreover, the implementation of the redevelopment project on this brownfield site will limit the urban sprawl on greenfield by avoiding the building on land suitable for agriculture or nature conservation. The land value surrounding will probably increase after the landfill mining project as well as the price of the houses. Several studies demonstrated the impact of landfill mining on the housing price, which is either negative (e.g., Du Preez, 2009; Nelson et al., 1992) or neutral. The presence of a landfill can have a negative impact of the housing price in a radius up to 6 km. However, the most important fall price (between 21 and 30% of the price) have been observed for the houses located within a radius of 400 m – 800 m of the landfill. The direct consequence of an increase of land value or house price is the gentrification process leading to an increasing of the housing price. As results, the neighborhood will be too expensive to live for the poor and lower middle classes.

From a climate point of view, the recycling of metal scraps will avoid the production of CO_2 related to the primary production of metal.
The environmental and social impacts of the landfill of Emerson's green (with and without LFM project) are listed in **Table 5**.

	Human health/ Social impact	Air	Water	Natural hazards	Impact on the landscape	Climate
Scenario without LFM 5 years	• (-) Direct contact, ingestion or inhalation of soil bound contaminants/dust.	• (-) Biogas emission.	• (-) Risk of water contamination (landfill producing leachates).	• (-) low flood risk.	• (+) Open green space.	
Scenario without LFM 50 years >50 years	• (-) Direct contact, ingestion or inhalation of soil bound contaminants/dust.	• (-) Biogas emission.	• (-) Risk of water contamination (landfill producing leachates). • (-) Microplastic pollution.	• (-) Increase of surface runoffs and flood. → Transport of contaminants.	• (-) Waste material eroded (negative visual impact) → can affect the well-being of the inhabitants and increase anxiety; → Encourage the deposition of illegal waste; →Attract vermin.	
Scenario with LFM 5 years	During LFM operations : • (+) Employment opportunities. • (-) Increased noise, odor and transport. • (-) Health risks for workers. After LFM operations : • (+) Employment opportunities. • (+) Limitation of the urban sprawl. • (+) Building of houses and school. • (+-) Increase of the land value surrounding the LF.	During LFM operations: • (-) Emission of dust during excavation. • (-) Risk of explosion/fire.	During LFM operations: • (-) Risk of leakage. • After LFM operations: • (+) Improvement of the groundwater quality.	During LFM operations: • (-) Risk of scattering waste at heavy storms.		• (+) Metal recycling avoids CO_2 emissions.

Table 5 – Summary of the environmental and social impact of the Emerson's Green landfill mining project.

6. Stockley Park

The landfill site (51°29'58.5"N; 0°26'59.6"W) is located in Stockley Park near Heathrow airport. The site is relatively large (12 ha) and consists of a former sand, gravel and clay quarry, which was utilised as a solid waste landfill from the 1940s. The landfill was progressively filled with domestic and commercial waste, reaching a peak in its activity in the late 1960s and 1970s. Since the landfill has ceased to operate, the site is now relatively flat, covered by grass and used for horse grazing. At the bottom of the landfill lies the Londay clay, which constitutes an impermeable layer. In the south and east part of the site, an underlying Principal Aquifer (River Terrace Deposits) is directly present.

6.1. Scenario without landfill mining project

a. Short-term Scenario (5 years)

As mentioned above, the landfill site is currently occupied by meadows for horses. As all the waste are recovered by soil and the site is relatively flat, the landfill site does not impact the landscape. Most of the people passing nearby probably ignore that the site is a former landfill. However, the walkers will potentially be in direct contact or ingest/inhale soil bound contaminants/dust. On-site analysis showed that the landfill site contains asbestos (WPS/Parsons Brinckerhoff, 2015), which can be problematic. The horses will probably ingest polluted plants, concentrating heavy metals. We don't know if the horses are aimed to be eat by humans. If it is the case, the horse meat could indirectly contaminate humans.

Another recurrent problem with landfill is the production of leachates. The leachates produced by the Stockley Park landfill will directly impact the groundwater or the surface water, contaminating indirectly the inhabitants. We are currently missing information about the thickness of the London Clay located at the bottom of landfill. We ignore if the thickness of the clay will be enough to protect the groundwater of the site.

The aquifer present in the River Terrace deposits in the south and east part of the site will be directly affected by the landfilled waste materials. The surface water of Stockley Lake and the Grand Canal Union will be impacted by the leachates. Regarding the production of biogas, soils laboratory analysis did not reveal elevated levels of hazardous volatile contaminants, considering that the vapour risks are considered negligible. Based on the biogas analysis, degradation process is expected to continue for a further 15 -20 years (WPS/Parsons Brinckerhoff, 2015), contributing to the greenhouse effect.

b. Long-term Scenario (> 50 years)

In the long-term scenario without landfill mining project, we can expect an aggravation of the issues described in the short-term scenario. The cover layer will probably be damaged by the erosion and the surface water run-off, exposing the waste material. The presence of visible waste deposits will affect the inhabitants, creating stress and anxiety. Person accident related to the direct exposition to waste will potentially increase as well as the inhalation of dust containing asbestos.

In 50 years, the degradation of the waste will be over and will no longer be a treat for the climate.

6.2. Scenario with landfill mining project

The landfill mining of the landfill site will contribute to stop the production of biogases and leachates. It will reduce the impact of the biogas on the greenhouse effect. Moreover, it will avoid a contamination of the groundwater and the surface water of Stockley Lake and the Grand Union Canal.

The landfill mining and the development of a project on site will be a source of employment in the area. It will avoid the use of new green field for the project redevelopment and limit the urban sprawl. As for Emerson’s green, the land value and the housing price will increase around the site, potentially leading to gentrification processes.

In **Table 6** are presented the environmental and social impacts of the landfill of Stockley Park (with and without LFM project).

	Human health/Social aspect	Air	Surface water and underground water	Natural hazards	Impact on the landscape	Climate
Scenario without LFM 5 years	• (-) Direct contact, ingestion or inhalation of soil bound contaminants/dust.		• (-) Risk of water contamination (landfill producing leachates). • (-) Microplastic pollution.			• (-) Production of greenhouse gases (limited amount) contributing to the greenhouse effect.
Scenario without LFM 50 years >50 years	• (-) Direct contact, ingestion or inhalation of soil bound contaminants/dust.		• (-) Risk of water contamination (landfill producing leachates). • (-) Microplastic pollution.		• (-) Waste material eroded (negative visual impact) → Can affect the well-being of the inhabitants and increase anxiety; → Encourage the deposition of illegal waste; → Attract vermin.	
Scenario with LFM	During LFM operations: • (-) Increased noise, odor and transport. • (+) Increase employment opportunities. • (-) Health risk for workers. After LFM operations: • (+) Redevelopment project: Increase employment opportunities.	During LFM operations: • (-) Emission of dust during excavation.	During LFM operations: • (-) Risk of leakage. After LFM operations: • Improvement of the surface and ground water quality.	During LFM operations: • (-) Risk of scattering waste and ashes/dust at heavy storms.	• (-) Reduce the “green space” in the area.	• (+) Avoids methane emissions → Reduce greenhouse effect.

	• (+-) Increase of the land value surrounding the site. • (+) Limitation of the urban sprawl on greenfield.					

Table 6 – Summary of the environmental and social impact of Stockley Park landfill mining project.

7. Leppe

The Leppe landfill (51°00'43.9"N, 7°25'13.7"E) is located in the North Rhine-Westphalia region, close to Lindar in Germany. It was initially a municipal solid waste landfill characterized by a waste disposal area of 39 hectares and a waste volume of 9 million m^3 forming a 350 m above the sea level dome. The landfilling operations started in 1982 and continue until today. However, in 2006, the project :metabolon was created converting the Leppe landfill into a modern waste management center, focusing on innovation, research and education supported by the European Regional Development Fund (COCOON, 2020). In order to sensitize the public to waste management and circular economy, educational and recreational activities were implemented on site, which change the social perception and the image of the landfill.

7.1. Scenario without landfill mining project

a. Short-term Scenario (5 years)

In 5 years, like the landfill of les Champs Jouault, the Leppe landfill site will still be under operations. The end of the landfilling operations was planned for the end of 2020, however negotiations with the regional authorities are in progress for a prolongation, since extending the landfilling operations on the Leppe landfill site is more sustainable than constructing a novel landfill site in the region. The project :metabolon and other related research projects funded by the EU will also continue on site. The site will stay a source of employment in the region for several fields: research, landfill and waste management, logistics. In total, approx. 150 people will continue to work there in the near future. The part of the landfill site will continue to be an educational and recreational area, bringing schools, locals and tourists. As the site will be still under operations and partially open to the public, there will remain a possible risk of person accident.

The constant monitoring of the site will ensure the environmental safety by minimizing the risks related to leachate and biogas production. The presence of a geomembrane at the bottom and at the top of the landfill will preserve the waste deposits from external factors. However, a small amount of waste will be potentially lost by the waste logistic which will directly impact the landscape and the well-being of people living nearby. The waste management and landfilling operations of ashes from MSW incineration will continue to generate dust emissions. On one side, the treatment of organic wastes in fermentation and composting plants on the landfill site will generate emission of biogas and ammonia, which will directly contribute to the greenhouse effect and to an increase of the risk of explosion on site. On the other side, the valorization of biogas on site will remain a good substitution to fossil fuels and, moreover, no external energy supply will be needed on site.

Concerning the impact of natural hazards, the flooding risk is relatively low and will remain minor in the near future. Due to its morphology (i.e. dome with steep slopes), the landfill can be prone to collapse in case of strong seismic shaking. However, the seismic hazard map of Germany (Tyagunov *et al*., 2006) shows that the region is characterized by a low to moderate seismic intensity ($V^{1/2}$ on the Modified Mercalli Intensity scale), which would not be strong enough to generate a waste landslide. The sealing of the waste with an appropriate surface capping will ensure the stability of the landfill in case of heavy rains associated with strong winds. Heavy storms will potentially destroy the surface capping. However, as the site will still be under operations, capping restoration will be performed directly.

b. Long-term Scenario (> 50 years).

The :metabolon landfill site is expected to have a life time of more than 50 years. The educational and recreational activities as well as the research center activities will remain on site. The research center, the landfill aftercare and the waste management for MSW and organic waste will continue to be a source of employment in the region.

After the completion of the aftercare, a reduced landfill monitoring will be implemented. Nevertheless, the risk of capping and liner failure will increase through time, which will increase the risks related to soil, water surface and groundwater contamination.

Regarding the natural hazards, the future expectations will be similar to the 5-year scenario except for the heavy storms. As already mentioned above, climate change will generate an increase of heavy rains associated with storm events in the future, which will potentially increase the failure of the surface capping and the triggering of a waste landslide.

7.2. Scenario with landfill mining project

In short-term, the landfill mining will not be an option as the site will remain under operations. Moreover, a modern research center for resource management and circular economy as well as recreational and educational activities for the public have been developed on site. The Leppe landfill has become a touristic attraction in the North Rhine-Westphalia region. Every year, since 2012 the site attracts more than 30.000 people. From a social point of view, the landfill mining of the site and thus the disappearance of the site will destroy a recreational and educational center dedicated to circular economy, which is and will continue to be an important educational topic to raise awareness among the junior community. On the one hand, it will increase the unemployment rate in the area (in landfill aftercare and touristic sectors). On the other hand, the removal of the landfill will create more land space to implement an industrial park or a new research facility and therefore will increase new job opportunities.

Due to its large volume of waste deposits, the Leppe landfill has a prominent shape, which blocks the view of the valley. Its removal will contribute to opening the landscape and reduce its anthropization. The stress generated among the local population by the presence of waste materials will also be reduced and the well-being of the inhabitants will increase.

The waste removal will minimize the long-term risk of soil contamination related to the potential failure of the geomembrane. Nevertheless, soil contamination will potentially occur during the landfill mining operations as old waste materials are excavated and will potentially be in contact with the surrounding soils. The environmental risks related to the presence of a landfill will be overall reduced as the waste materials will no longer represent a threat. The risk of surface and groundwater contamination by leachates will be minimized as well as the explosion risk due to the presence of biogas. During the landfill mining operations, extra caution will be taken to avoid fire, dust emissions and water contamination.

Regarding the climate, no more biogas will be produced as the waste materials have been removed which will reduce the greenhouse effects. The revalorization of the metal content will avoid the CO_2 emissions related to the extraction and treatment of primary metals. Additionally, the valorization of the combustible fraction will be a good substitute for fossil fuels. Overall, a large fraction of the excavated waste materials (i.e. metal, fly ashes, combustible fractions, organic material) will potentially be revalorized with the landfill mining project.

The environmental and social impacts of the landfill of Leppe (with and without LFM project) are summarized in **Table 7**.

	Human health/Social aspect	Soil	Air	Water	Natural hazards	Impact on the landscape	Climate
Scenario without LFM 5 years	• (+) Source of employment in the region (landfill management, waste management and logistics, and project :metabolon). • (+) Recreational and educational area on the landfill site. • (+) Research center. • (-) Risk of person accident.	• (+) Protected by landfill liner system and landfill monitoring program.	• (-) Landfill gas and biogas → risk of explosion/fire. • (+) Landfill gas collection and valorization. • (-) Emission of dust from deposition of ashes from MSW incineration. • (-) Emission of biogas and ammonia due to the treatment of organic wastes in fermentation and composting plants on the landfill site.	• (+) Protected by landfill liner system and landfill monitoring program.	• (-) Flooding risk (low). • (-) Landfill collapse (following high precipitation → low risk due to surface capping or seismic activity → low – medium risk. • (-) Failure of surface capping due to heavy storms → medium risk and will increase with climate change.	• (-) Small amounts of waste lost by waste logistics. • (-) Prominent shape of the landfill is visible from a distance to depict the outstanding objective of the project :metabolon → disruptive landscape.	• (-) Contribution to the Greenhouse effect. • (+) Valorization of landfill gas : → Substituting fossil fuels; → No external energy supply needed on site.
Scenario without LFM 50 years	• (+) Source of employment in the region (aftercare of landfill, waste management and logistics for MSW and organic waste, and project :metabolon or subsequent projects).	• (-) Risk of landfill liner failure. • With completion of the aftercare phase a reduced landfill monitoring program. • (-) Risk of soil contamination by landfill leachate.	• (-) Risk of landfill capping failure. • With completion of the aftercare phase a reduced landfill monitoring program. • No Landfill gas collection and valorization.	• (-) Risk of landfill liner failure. • With completion of the aftercare phase a reduced landfill monitoring program. • (-) Surface and groundwater contamination by landfill leachates.	• (-) Flooding risk (low). • (-) Landfill collapse (following high precipitation → low risk due to surface capping or seismic activity → low – medium risk. • (-) Failure of surface capping due to heavy storms → medium and will	• (-) Small amounts of waste lost by waste logistics. • (-) Prominent shape of the landfill is visible from a distance to depict the outstanding objective of the project :metabolon → disruptive landscape.	• (-) Contribution to the Greenhouse effect. • (-) With completion of the aftercare phase no valorization of landfill gas: → No substitution of fossil fuels; → External energy supply needed on site.

	• (+) Recreational and educational area on the landfill site. • (+) Research center. • (-) Risk of person accident. • (-) Risk of landfill liner failure. • (-) Risk of prolonged aftercare and unforeseen aftercare costs. • (-) Risk of a more severe legislation on landfill emissions.		• (-) Emission of biogas and ammonia due to the treatment of organic wastes in fermentation and composting plants. • (-) Biogas → risk of explosion/fire. • (-) Exposition to eroded asbestos.		increase with climate change		
Scenario with LFM	<u>During LFM operations:</u> • (-) Health risks for workers. • (-) Increased noise, odor and transport. <u>After LFM operations:</u> • (-) Unemployment in the sector of landfill aftercare. • (-) Reduction in the recreational and educational areas on the landfill site.	<u>During LFM operations:</u> • (-) Risk of soil contamination. <u>After LFM operations:</u> • (+) Minimization of long-term risk of soil contamination due to landfill liner failure.	<u>During LFM operations:</u> • (-) Risk of explosion or fire. • (-) Emission of dust during excavation. <u>After LFM operations:</u> • (+) No more landfill gas emission. • (+) Improvement of the air quality.	<u>During LFM operations:</u> • (-) Risk of surface and groundwater contamination. <u>After LFM operations:</u> • (+) Minimization of long-term risk for surface and groundwater contamination due to landfill liner failure.	<u>During LFM operations:</u> • (-) Risk of scattering waste and ashes/dust at heavy storms. <u>After LFM operations:</u> • (+) No more risks with respect to a landfill.	• (+) Reduced prominent shape of the landfill → less or no disruptive landscape.	• (+) Avoids methane emissions → Reduction of the greenhouse effect. • (-) With LFM project no valorization of landfill gas → external energy supply needed on site. • (+) Revalorization of the metal content → Avoid CO_2 production. • (+) Valorization of the combustible fraction → substitution of fossil fuels.

	• (+) More space for a research center or industrial park (new job opportunities). • (+) No risk of person accident due to aftercare of the landfill. • (+) Increase of the land value surrounding the site.						

Table 7 – Summary of the environmental and social impact of Leppe landfill mining project.

9. Results of the environmental survey

A questionnaire about the environmental impact of existing landfill mining project was sent to landfill mining project manager and RAWFILL Stakeholders. The idea behind the survey was to quantify the environmental benefits of LFM project on the development of the biodiversity the following years, the water, air and soil quality (up to 10 years). The questionnaire is available in the Appendix 1 of this report. An online version displayed in google form was also available online. We only receive two answers to this questionnaire, therefore it is impossible to draft conclusions and quantify the environmental benefits on LFM projet. The main reason to the lack of answers can be related to the fact that :

- LFM project to solve environmental issues are usally done in emergency. In that case, no environmental studies prior to the LFM project are generally conducted due to the lack of time.
- Most of the LFM project with environmental benefits are often quite recent and it is generally too early to quantify the long-term benefit of the project on the biodiversity.

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Appendix 1 – Environmental questionnaire

RAWFILL PROJECT - REQUEST FOR INFORMATION – LANDFILL MINING EXPERIENCES & ENVIRONMENTAL ASPECT

I. <u>Description of the RAWFILL project</u>

RAWFILL is EU-funded project supporting a new circular economy for RAW materials recovered from landFILLs. The ultimate goal of RAWFILL is to allow NWE public & private landfills owners & managers to implement profitable resource-recovery driven landfill mining projects. The landfill mining can be defined as the excavation and the revalorization of waste, which have previously been landfilled.
In order to reduce the economic risk related to the landfill mining project, RAWFILL develops three tools:

- A cost-effective standard landfill inventory framework (ELIF) based on existing inventories and experiences ;
- An innovative landfill characterization methodology combining geophysical imaging and guided waste sampling ;
- A two-level Decision Support Tool (DST) to allow smart landfill mining project prioritization.

RAWFILL considers the landfill mining from a more global perspective taking into account not only the financial aspect but also environmental and social impacts.
For more information:

EN – www.nweurope.eu/rawfill
FR - http://www.spaque.be/01288/fr/RAWFILL

Any question?
Please contact SPAQuE – Laura Lamair : l.lamair@spaque.be

II. <u>Request to landfill mining projects managers – Assessment of the landfill mining impact on the environment.</u>

Why do we ask you some information?
We contact you because you have started a landfill mining or
a landfill revalorization project. We believe that your experience can help us to assess the impacts of landfill mining project on the environment.

The Request
We would be pleased to receive from your organization any suitable information you agree to share related to the above topic. Please note that only aggregated results will be published, without mentioning any origin of the data nor specific project information. No information will be disclosed without your prior authorization. If you are interested, you will receive the results of this study at the end of the RAWFILL project.

May we ask you to send the questionnaire below completed at SPAQuE – l.lamair@spaque.be **before October 31, 2020.**

RAWFILL – Landfill mining and Environmental aspect

1. General information

- Are you working for?
  ☐ A local public authority
  ☐ A regional public authority
  ☐ A national public authority
  ☐ An international organization
  ☐ A NGO
  ☐ A private company
  ☐ Other (Please specify): ……

- Where is located your landfill mining project?
  ☐ In North-Western Europe
  ☐ Outside North-Western Europe

- When was the main period of landfilling activities on site?
  ☐ <1940
  ☐ 1940-1955
  ☐ 1955-1980
  ☐ 1980-1999
  ☐ >1999
  ☐ Unknown

2. Prior to the waste excavation

- What was the land-use of the site before you started your project?
  ☐ Commercial use
  ☐ Recreational use
  ☐ Natural reforestation
  ☐ Agriculture
  ☐ Use for renewable energies
  ☐ Other (Please specify): ……

- What was the former morphology of the landfill site?
  ☐ Depression/Quarry
  ☐ Mound

☐ Open dump
☐ Slope/along a valley
☐ Other (Please specify): ……

- Was the landfill located nearby a residential area? ☐ Yes ☐ No

  If yes, did you get support from the local authorities and the residents living around the landfill to start the waste excavation? ☐ Yes ☐ No

- How did the presence of the landfill affect visually the landscape?
  ☐ Positively (e.g., green space, forest, artificial topography)
  ☐ Neutral
  ☐ Negatively (e.g., presence of waste deposits)
  ☐ Unknown

- Is the landfill located in a Natura 2000 area/protected area? ☐ Yes ☐ No

- Were there some threatened/rare/endangered species (fauna and flora) on the site?
  ☐ Yes ☐ No

- Before you start the landfill revalorization, were there some environmental issues related to the presence of the waste deposits?
  ☐ Yes ☐ No ☐ Unknown

  If yes, what kind of environmental issue?
  ☐ Surface water contamination
  ☐ Groundwater contamination
  ☐ Air pollution
  ☐ Soil contamination
  ☐ Other (Please specify): ……

  Could you tell us more about the nature of the pollution?
  …………………………………………………………………………………………………
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- Why did you decide to start the project?
  ☐ Economic purpose (e.g., real estate)
  ☐ Waste revalorization
  ☐ Environmental issue
  ☐ Human health issue
  ☐ Negative visual aspect related to the presence of waste deposits
  ☐ Construction of infrastructure
  ☐ Safety issue (e.g., instability of the landfill)
  ☐ Natural hazard

☐ Other (Please specify): ……

Could you tell us more about the reasons why you started your project?
……………………………………………………………………………………………
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3. During the waste excavation phase

- When did the waste excavation start? ……

- What type(s) of waste did you excavate?
  ☐ Municipal solid waste
  ☐ Industrial waste
  ☐ Dredging materials
  ☐ Waste water treatment sludge
  ☐ Inert
  ☐ Fly ash
  ☐ Asbestos
  ☐ Metal slag
  ☐ Mining waste
  ☐ Military waste
  ☐ Hospital waste
  ☐ Mixed
  ☐ Other (Please specify): ……

- Did you take action to protect the residents living around the landfill from gas emanations during the waste excavation?
  ☐ Yes ☐ No ☐ Irrelevant

  If yes, could you tell us more about the actions taken?
  ……………………………………………………………………………………………
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- Did you take action to protect the biodiversity during the waste excavation phase?
  ☐ Yes ☐ No ☐ Irrelevant

  If yes, could you tell us more about the actions taken?
  ……………………………………………………………………………………………
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- Did you measure the environmental incidence of the waste excavation phase (e.g., groundwater analysis)? ☐ Yes ☐ No

  If yes, what were the impacts of the waste excavation on the environment?

☐ Surface water pollution
☐ Groundwater pollution
☐ Dust
☐ Emission of biogas
☐ Other (Please specify): ……
☐ Nothing

4. After the waste excavation

- What is/will be the current use of the site?
  ☐ Residential area
  ☐ Commercial area
  ☐ Industrial area
  ☐ Recreational area
  ☐ Green space
  ☐ Landfill
  ☐ Energy production
  ☐ Other (Please specify): ……

- Did you specifically recreate natural habitat for the fauna and flora?
  ☐ Yes ☐ No ☐ Irrelevant

- Can you assess the environmental benefits of your project (e.g., increase of the quality of water surface/groundwater, air, soil)?

  … After 1 year? ☐ Yes ☐ No ☐ Unknown ☐ Irrelevant
  If yes, on which aspect(s)?
  ☐ Surface water contamination
  ☐ Groundwater contamination
  ☐ Air pollution
  ☐ Soil contamination
  ☐ Other (Please specify): ……

  … After 2 years? ☐ Yes ☐ No ☐ Unknown ☐ Irrelevant
  If yes, on which aspect(s)?
  ☐ Surface water contamination
  ☐ Groundwater contamination
  ☐ Air pollution
  ☐ Soil contamination
  ☐ Other (Please specify): ……

  … After 5 years? ☐ Yes ☐ No ☐ Unknown ☐ Irrelevant
  If yes, on which aspect(s)?
  ☐ Surface water contamination
  ☐ Groundwater contamination
  ☐ Air pollution
  ☐ Soil contamination
  ☐ Other (Please specify): ……

  … After 10 years or more? ☐ Yes ☐ No ☐ Unknown ☐ Irrelevant
  If yes, on which aspect(s)?

☐ Surface water contamination
☐ Groundwater contamination
☐ Air pollution
☐ Soil contamination
☐ Other (Please specify): ……

Could you tell us more about the environmental benefits observed after the end of the project?
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Could you tell us more about the other benefits observed after the end of the project? (e.g., from a social, economical, technical point of view among others)
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Thank you for helping us to encourage landfill mining in NW Europe!

Contact

Feel free to contact us.

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