Life Cycle Assessment (LCA) & Total Cost of Ownership (TCO) analysis of residual streams from brine in Hengelo

Commissioned by Nobian

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Ecomatters B.V.
Weg der Verenigde Naties 1
3527 KT Utrecht
The Netherlands
W www.ecomatters.nl

Content

Executive summary

Nobian is an industrial chemicals company that, among other activities, extracts salt from subsoil through solution mining in Hengelo, the Netherlands. In the production process several residual flows are produced, originating from both the Nobian salt factory and the salt specialties plant of Salins. Two scenarios are studied:

1. The current situation, in which residual flows are partially pumped back into exhausted salt caverns to ensure stability of the underground spaces and/or extract additional brine from the caverns.
2. An alternative scenario where these flows would undergo waste treatment, and cavern stabilisation is achieved with an alternative stabilisation method.

To determine the environmental performance and total costs of this practice, a Life Cycle Assessment (LCA) and Total Cost of Ownership (TCO) study was conducted.

Data was collected from Nobian technical experts and the waste handling company Renewi in order to include all relevant inputs and outputs within the study. The results indicate that the TCO would increase 1369 times in the alternative scenario. Additionally, for all environmental categories studied, the alternative scenario has a higher environmental impact. The climate change impact, expressed in CO_2-eq emissions, was shown to be 318 times higher compared to the current practice. A weighted PEF score of several impact categories shows that the overall weighted impact is 173 times higher in the alternative treatment scenario. Finally, the eco-costs, an indicator translating the environmental impact into fictitious costs, show an increase of a factor 476 higher than the current situation.

	Unit	Current	Alternative	Change
Climate Change	ktCO2eq	0.07	21.43	x318
PEF Score	Pt.	12.4	2133.5	x173
TCO	€	€ 32,610	€ 44,650,109	x1369
Eco-costs	€	€ 15,334	€ 7,292,827	x476

Several sensitivity analyses on the data and assumptions were also performed, but the current practise remains favourable from an environmental and economic perspective. Therefore, based on this study, the LCA and TCO results clearly indicate the continuation of current practise where the residual streams are reinjected into the caverns for stabilisation and/or extraction of additional raw brine, instead of applying alternative waste treatment methods to the residual streams.

Nederlandse samenvatting

Nobian is een producent van industriële chemicaliën die, naast andere activiteiten, zout uit de ondergrond wint in Hengelo, Nederland. Bij het productieproces komen verscheidene stromen vrij, afkomstig van zowel de Nobian zoutfabriek als de specialistische zout fabriek van Salins. Twee scenario's zijn bestudeerd:

1. De huidige situatie, waarin de residustromen deels terug worden gevoerd naar gebruikte zoutcavernes ten behoeve van stabilisatie en/of het oppompen van nieuwe ruwe pekel.
2. Een alternatief scenario waar deze retourstromen als afvalstroom worden behandeld en de cavernes op een andere manier gestabiliseerd worden.

Om de milieu-impact en bijbehorende kosten van deze praktijk in kaart te brengen, is er een Levenscyclus Analyse (LCA) en een totale kostenberekening studie (Total Cost of Ownership, TCO) uitgevoerd.

Om alle relevante inputs en outputs mee te nemen in de studie, werden data verzameld bij Nobians technische experts en bij Renewi, een afvalverwerkingsbedrijf. De resultaten laten zien dat de totale kosten voor het alternatieve scenario 1369 keer hoger uitvallen. Daarbij is de milieu-impact over het algemeen ook hoger voor de bestudeerde impact categorieën. De impact op klimaatverandering, uitgedrukt in CO_2-equivalenten, zou 318 keer hoger uitvallen voor het alternatieve scenario. Een gewogen PEF score voor meerdere impact categorieën laat zien dat de algemene milieu impact 173 keer hoger is in het alternatieve scenario. Tot slot zijn ook de eco-kosten, de klimaatimpact omgerekend naar fictieve kosten, bekeken, waarbij het alternatief 476 keer hoger uitkomt dan het huidige scenario.

	Eenheid	Huidig	Alternatief	Verandering
Klimaatverandering	ktCO2eq	0.07	21.43	x318
PEF Score	Pt.	12.4	2133.5	x173
TCO	€	€ 32,610	€ 44,650,109	x1369
Eco-kosten	€	€ 15,334	€ 7,292,827	x476

Er zijn verschillende sensitiviteitsanalyses op de data en aannames in de studie uitgevoerd, maar de huidige situatie blijft gunstig vanuit zowel een milieu als economisch perspectief. Vanuit deze LCA en TCO studie kan dan ook geconcludeerd worden dat het gunstig is om de retourstromen terug te pompen naar de cavernes voor stabilisatie en/of het oppompen van nieuwe ruwe pekel, in plaats van alternatieve manieren van afvalverwerking toe te passen.

1 Background

Nobian operates several salt caverns in Twente, The Netherlands, where brine is extracted from underground salt deposits by solution mining. With this technology, water is pumped into the deposits which dissolves the salt into brine. The brine is pumped up and transported by pipeline to Nobian's salt production site in Hengelo. Here, the brine solution is purified and the water is evaporated to produce salt for industrial purposes. During this process, several residual flows from salt extraction are pumped back into exhausted salt caverns to ensure stability of these underground spaces. In addition, some of the flows are injected into production caverns to extract brine solution for salt production.

To operate these caverns and reinject the residual flows, Nobian has a permit from the Dutch ministry of "Economische Zaken en Klimaat (EZK)" and operated by the Staatstoezicht op de Mijnen (SodM). Nobian requested Ecomatters to analyse the environmental impact (via Life Cycle Assessment (LCA)) and economic performance (via a Total Cost of Ownership (TCO) calculation) of the residual streams of the salt production. This is an obligation from the revised permit (ref. PDGGO-DTDO / V-23189 d.d. 6th of July 2023). As the residual streams contain some subsoil-foreign material from the salt production, the current situation is compared with an alternative scenario. In this alternative scenario, the residual flows are treated as a waste stream at a waste facility and a different stabilisation method for the caverns is applied.

2 Goal of the study

The goal of the study is to evaluate the environmental performance and economic viability of the current treatment of the residual streams (injecting the streams back into the caverns) compared to alternative treatment options. This will allow for the completion of an integrated analysis where the cost effectiveness and environmental performance are evaluated within the same scope.

This report provides an overview of the outcomes using widely accepted LCA impact categories, with a particular focus on Global Warming Potential (GWP) within the interpretation. The study follows the calculation requirements and the methodological aspects described in ISO 14040/44 standards on LCA without aiming at full-compliance. This study can support Nobian and the competent authorities in the decision-making process.

3 Scope of the study

The LCA and TCO are conducted for nine different residual flows that originate in the salt production. For each flow, the current scenario and an alternative waste treatment scenario have been analysed. Part of the flows originate in the adjacent facility from Salins, formerly part of Nobian. As the permit for mining for both Nobian and Salins operations falls under Nobian, the residual streams from Salins are included in this study as well.

3.1 Declared unit

The function analysed in this study is the treatment of the residual streams produced by the Nobian and Salins salt factories in Hengelo. The environmental and economic performance of both scenarios is calculated using the declared unit defined as:

"the treatment of the average total annual volume of residual streams as produced by Nobian and Salins in Hengelo"

3.2 System boundaries

The LCA and TCO include the inputs and outputs from the moment the residual flows are exiting the salt production facility to storage into the caverns, or until alternative treatment has taken place. This can be considered a "cradle-to-grave" study, as it includes the generation of the residual stream up to the end-of-life, while excluding subsequent product systems (displaced brine or recycled waste). A more detailed overview of the different flows is provided in Section 4, while an overview of the system boundaries is shown in Figure 1 (current situation) and Figure 2 (alternative treatment).

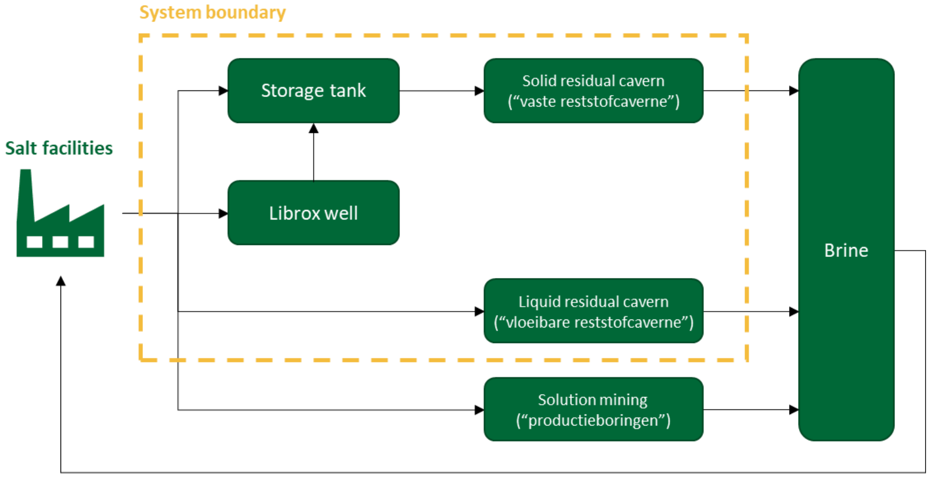


Figure 1: System boundaries for Scenario 1: the current situation, where residual streams are pumped into residual caverns, or used in solution mining.

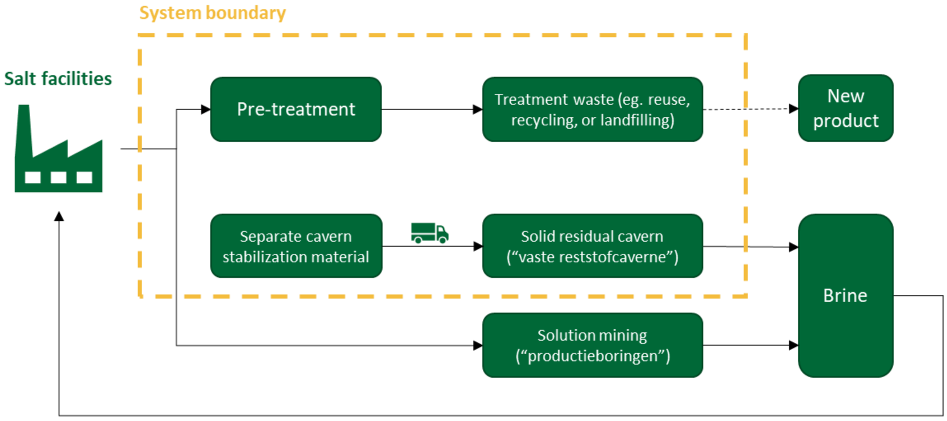


Figure 2: System boundaries for Scenario 2: alternative treatment of the residual streams

Eight residual flows are transported to the depleted caverns destined for solid residual streams ('vaste reststofcavernes') via a Nobian storage tank and one flow is pumped to a liquid residual cavern ('vloeibare reststofcaverne'). Within the scope of the study, the energy required for pumping, and the temporary storage in the tanks, is included. For the solid and liquid residual cavern, brine is displaced by the residual streams and transported to the salt factory for salt production. The transport and further purification of this displaced brine is outside the scope of the study. Lastly, several flows originate from Salins, which are first pumped into the Librox drain ('Libroxput') where they are dissolved in water and subsequently pumped via Nobian' storage tank to the solid residual caverns. This is included in the system boundaries.

For the residual streams that end up in the depleted caverns, this is deemed to be the final fate for the potentially subsoil foreign materials. It is assumed that no migration into other layers or groundwater takes place, therefore no further interaction of materials with the natural environment needs to be modelled. Moreover, this means that the origin of the components in the residual streams (whether subsoil-foreign or not) is not considered in this study.

For the alternative treatment of the residual flows, the preparation, transport, and waste treatment are included, as well as the cavern stabilisation of the solid residual cavern with an alternative material. The subsequent use of recycled or reused material after waste treatment is considered outside of the scope of this study. Furthermore, the main salt production facility is excluded. Important to note is that three flows that originate in the salt production are excluded from this study. These flows are not waste streams and are essential for the production of brine in the caverns which are currently operational. The flows concerned are the *'zoutoplossing zuren', 'proceswater'* and *'zoutoplossing natwassers (Librox)*', which consist of mostly water and make up to 50% of the water used for the conventional mining practices of Nobian. The streams are therefore used as raw materials to dissolve the underground salt for brine production. These flows (indicated by the arrow to solution mining *'productieboringen')* are therefore excluded from the system boundaries. Finally, one residual stream from Salins *('off spec overige zouten')* is currently sold as road salt and is therefore not considered to be part of the studied system.

3.3 Cut-off criteria

For the alternative treatment of the residual streams, a cut-off was applied for the construction of treatment facilities that would be required. Therefore, the environmental impact and CAPEX for the building of the treatment facilities and other infrastructure are excluded for the purposes of this study.

3.4 Allocation procedures

Within the system boundaries, the full impact has been allocated to the treatment of the residual streams as described above. In general, the residual streams are separated into separate product systems, so no allocation is needed.

Allocation for electricity use for pumping of the mixed stream of the Librox drain (flow 9, 10 and 11), has been allocated on the basis of flow volume (m3/hr). Similarly, electricity use for pumping of the output of the storage tank has also been allocated on the basis of flow volume (m3/hr).

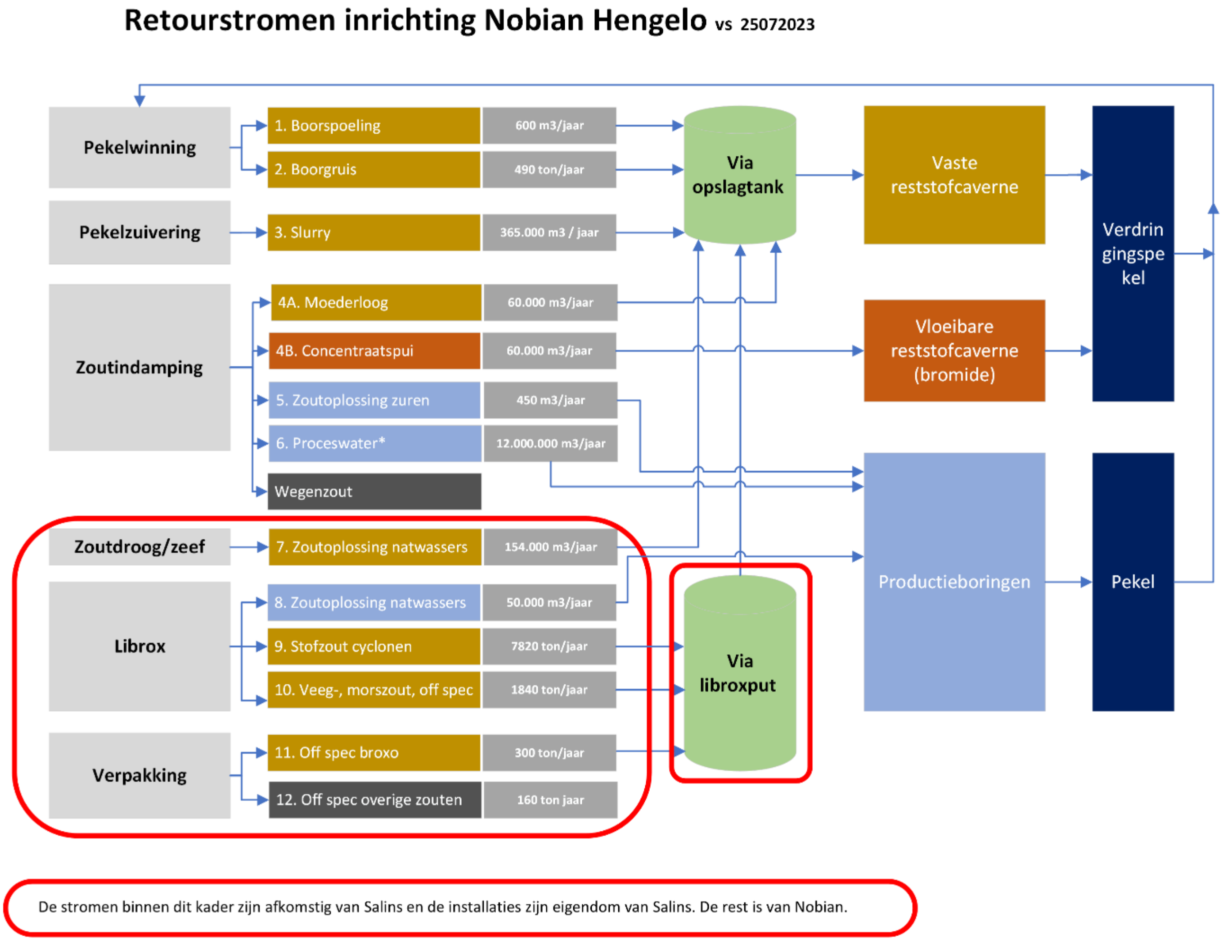
In the alternative scenario, the cavern stabilisation (consisting of the stabilisation material, transport & pumping) was allocated to the flows that are used for stabilisation in the main scenario (flow 1-3, 7, 9-11, Figure 3), again on the basis of flow volume in m3/hr.

Electricity mix

The electricity used in Hengelo is a mix of different sources (wind, biomass, municipal waste and natural gas-based). Part of the electricity is purchased from external suppliers and some electricity is derived from Nobian's own energy generation plants (also in Hengelo). The electricity allocation from different sources is done at a country level by Nobian's Energy team. The total electricity divided over the plants, and the share from each source, is provided in Annex C.1.

4 Model description

A short description of all residual streams analysed in this study is provided below, as well as the flows not studied. A more detailed overview of the components per stream is provided in Annex A. Additionally, a schematic overview of the residual streams is shown in Figure 3. As described in section 3.2, flow 5, 6 and 8 are excluded for this study as they are not waste flows but essential raw materials for salt production. Flow 12 and the flow indicated by "*wegenzout*" are sold as off-spec salt for road salt and not relevant for the residual flows to the caverns.



* Proceswater inclusief kanaalwaterinname (verhouding concentraat:kanaalwater = 50:50)

Figure 3: Overview of residual streams and their current treatment in the main scenario. Red borders indicate the operational control of Salins. Flows 5, 6 and 8, 12 and "wegenzout" were excluded from the study, as described in the text.

4.1 Description of Scenario 1: current situation

In the current scenario, the flows are pumped into the storage tank, or Librox drain, and then further pumped to the caverns. The Librox drain uses tap water to dissolve the input flows. No other inputs (e.g. chemicals) are required nor any outputs such as waste or emissions occur.

It is assumed that when the residual streams are stored in the caverns, no further exchanges with the surrounding environment take place. Therefore, no environmental impact or costs were included in the study for the long-term storage of the material in caverns. All inputs and process steps of the base scenario are provided in Figure 4.

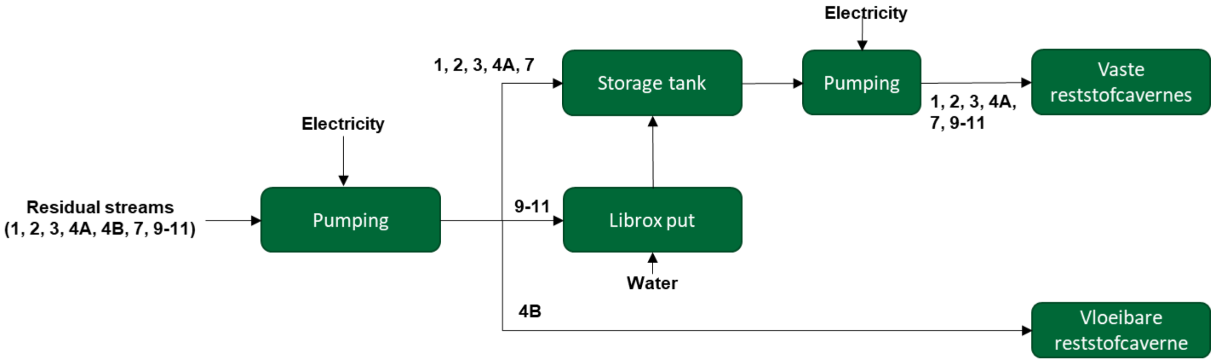


Figure 4: Overview of modelled process steps of Scenario 1: the current situation

It is important to note that the modelled residual streams have two different fates. The majority of the streams (1-3, 4A, 7 & 9-11) end up in the solid residual cavern ('vaste reststofcaverne'), a depleted salt cavern. The purpose of this is to both stabilise the cavern, as well as to displace any brine still left in the cavern which can be used for salt production. Stabilization is done for designated caverns only, i.e. caverns that have the classification 'potentially instable and not intrinsic safe'.

The 'concentraatspui' (flow 4B) is an exception: this flow has a high bromide concentration and is therefore not used in the solid residual caverns. This flow is used in a separate residual cavern (the liquid residual cavern or 'vloeibare reststofcaverne'), with a similar purpose: to displace useful brine. The major difference is that the amount of dissolved solids in the 'concentraatspui' is lower, and therefore the liquid residual cavern is not stabilised with this practice.

4.2 Description of Scenario 2: alternative treatment

In the alternative scenario, the residual flows are treated by external waste handlers. Based on discussions with the waste handling company Renewi, alternative treatment was determined for each flow. For all flows going to waste treatment, transportation to the final treatment destination was included. In general, Renewi stated that the Netherlands and surrounding countries do not have the capacity to handle the large volumes that Nobian produces. Despite these limitations, if alternative treatment would be required, water evaporation would reduce the volume and thus be the first step for most flows. To be able to process the large volume of flows for evaporation, the construction of a new facility would be required, using for instance Mechanical Vapor Recompression (MVR) technology to evaporate the solution. The amount of electricity needed for evaporation is based on data of MVR evaporators in Hengelo.

The amount of remaining solids, which can be calculated based on composition analysis, should subsequently be landfilled. The environmental impact of landfilling was modelled with a dataset for landfilling of salt residues from mining. This dataset assumes that all salt will over time leak into groundwater. Renewi indicated that this leaching would not take place in the realistic scenario, as this leaching into groundwater is strictly prohibited. Therefore, the model was adapted to exclude this long-term leaching into groundwater. As a sensitivity analysis, the results for a leaching rate of 5% of salt was included.

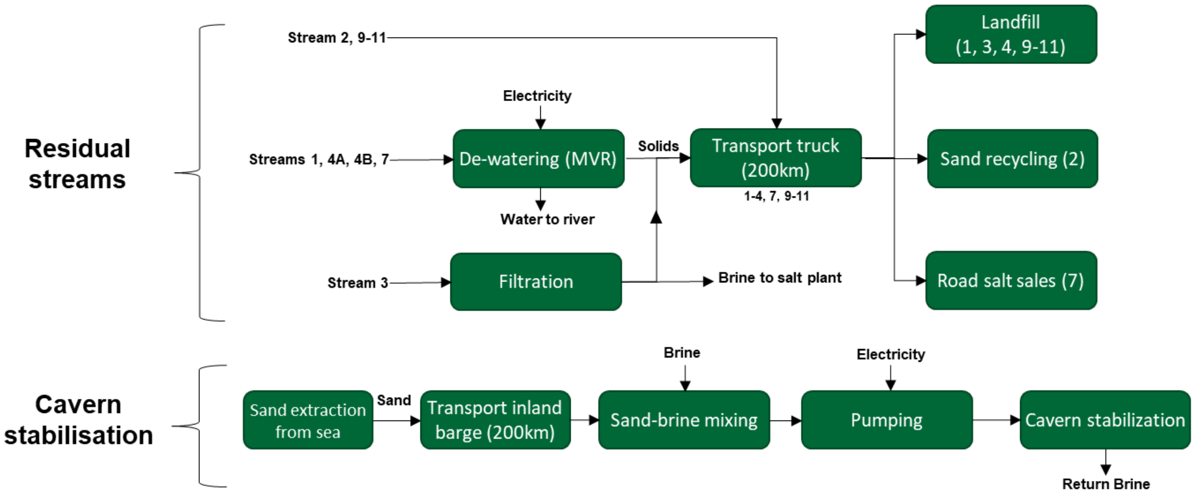


Figure 5: Overview of process steps of Scenario 2: alternative treatment

For three flows, a different alternative treatment was provided by Renewi and Nobian

- Flow 2. 'boorgruis' contains salt and other solids, and can be recycled as sand. The environmental impact and costs of sand cleaning were included.
- Flow 3. 'slurry' is a relatively clean flow with a lot of solids. Therefore, after applying a filtration technology, the filtration residue (amount calculated based on composition) can be landfilled, while the filtrate can be re-used in the salt production plant.
- Flow 7. is a salty water stream. After an evaporation step, the remaining salt can be sold as road salt. For this, the revenue (margin of profit) of road salt sales was included in the TCO. Additionally, a credit is applied for avoiding the production of 'virgin' road salt. Transport of sold salt is not included as this would instead be part of the next product system and is usually collected by the customer.

For the Librox flows (9-11), which in the current scenario are mixed with water in the Librox drain, it is assumed that they would not be mixed with water in the alternative case. Instead, they are transported directly to a landfilling site.

All steps related to the alternative treatment are depicted in Figure 5. A detailed description of the alternative treatment per flow, including costs, is provided in the Annex B.

Alternative stabilisation of caverns

In the alternative scenario where the residual streams are not used for cavern stabilisation in the solid residual cavern, another material would be required for cavern filling. Sand from the North Sea is seen by Nobian as the most promising option as filling material, due to its availability in large quantities and easy transportation by inland barges. This sand is transported with an inland barge to the Hengelo site, and subsequently mixed with brine from salt production (1m^3 material : 4m^3 brine). Doing this allows for it to be pumped into the caverns.

The environmental impact of the brine was based on the internal Nobian LCA models (2021 data). Costs for the brine are not included as these are internal flows and the salt production facility is considered out of scope. The displaced brine coming out of the solid residual cavern is considered sufficiently clean for re-use during brine purification in the factory. Any environmental impact and costs/revenues of the displacement brine are considered to be outside the system boundaries. An overview of the process steps is again provided in Figure 5.

5 Life cycle inventory analysis

5.1 Life cycle inventory and data quality

All inputs and outputs crossing the system boundary were included. Data on inputs/outputs and costs were collected for the year 2022 through a data questionnaire from Nobian process engineers who have experience with the residual streams in Hengelo. Primary data on the alternative treatment options was collected from Renewi. Data collected includes:

- For all residual streams, the amount, composition and fraction of solids;
- Volume and electricity use for pumps;
- Type, amount, costs, and pre-treatment of material for alternative cavern stabilisation;
- Electricity mix and costs per MWh;
- Average costs for transport, and profit margin for road salt; and
- Most viable alternative treatment option and costs for all residual streams (Renewi).

Data on the environmental impact of dry salt and brine (used for alternative cavern stabilisation), and road salt (for assigning a credit for salt sale), is taken from the Nobian internal LCA models. In case that primary foreground data was unavailable, background datasets from the widely supported database ecoinvent 3.9.1 are used. These include:

- Raw material extraction and production of materials for cavern stabilisation;
- Transport in trucks, inland barges and bulk sea transport;
- Upstream electricity production and transmission; and
- Handling of waste destined for landfill and recycling.

An overview of all inputs and outputs, including background datasets used, is provided in Annex C and Annex D respectively.

5.2 Summary of assumptions for calculation and modelling

To summarise previous chapters and the collected data, the following key assumptions were made:

- It is assumed that when the residual streams are stored in the caverns, no further exchanges with the surrounding subsoil or groundwater take place.
- The salt production process and the displaced brine coming out of the residual caverns were considered out of scope for the study.
- The residual flows sold as road salt in the current situation were excluded, since these have a useful purpose and are not injected into the subsoil.
- The residual flows used in solution mining are excluded, since these are used as essential raw materials in the mining process.
- The electricity costs for both the current situation and the alternative treatment is assumed to be 73 €/MWh. This is provided by Nobian as a probable estimate and taken from the "Klimaat- en Energieverkenning" (PBL, 2022).
- Electricity use for de-watering was based on amount of electricity needed for brine crystallization at the Hengelo salt factory.
- Recycling of sand is modelled as a proxy for the treatment of 'boorgruis', which can be treated as "steekvast materiaal". The costs of this treatment were estimated to be 45-200 €/t. The lower end is used in the comparison, while the effect of 200 €/t is discussed in a sensitivity analysis.
- For landfilling, a proxy of the landfilling of salt mining tailings is taken, adapted to exclude leaching to the soil. A leaching rate of 5% was studied in a sensitivity analysis.
- The costs for landfilling were assumed to be 100 €/t, as provided by Renewi. This price might be even higher in the future.
- Transport distance in the alternative scenario for transporting solids to waste treatment was set at 200 km by truck as the final location is unknown. Costs were estimated to be €15 per ton, which would be a price of €0.08 per ton-kilometre assuming 200km per journey.
- Profits from the sale of road salt were assumed to be 35 €/t, an estimated margin of profit.
- For the alternative stabilisation of the caverns, sand extracted from the North Sea is used as filling material. The costs were assumed to be 10 €/t. In the models, a proxy is taken, which is the extraction from sand from river bedding. This proxy includes primarily electricity use for pumping.

6 Environmental effects and costs

This chapter looks at the results of both the LCA modelling and the TCO calculation. This is discussed on the site-level, since many of the flows are treated together. All considered impact categories and the full results are provided in Annex E.

6.1 Life cycle impact assessment (LCIA)

The LCA model has been created using the software 'LCA for Experts' (formerly GaBi), version 10.7.0.183, developed by Sphera. For the impact assessment, the environmental exchanges are translated into environmental impacts by using the characterisation models that define a selected set of impact categories. The characterisation factors from the EF 3.1 method were used.

The main environmental impact category studied was Climate Change expressed as CO2-eq emissions. For the current situation (Scenario 1), the models resulted in 0.07 ktCO2eq annually, while for alternative treatment, the impact would be 21.43 ktCO2eq/yr. This would mean that the climate change impact of the residual streams is 318 times higher in the alternative scenario.

The additional impact is mainly caused by the waste transport, as shown in Figure 6. The alternative cavern stabilisation is a secondary impact, which consists of sand extraction (31%), sand transport by barge (61%), brine for dissolving (6%) and electricity for pumping (1%). Waste treatment (landfilling) and electricity for evaporation and pumping make up the remainder of the impacts.

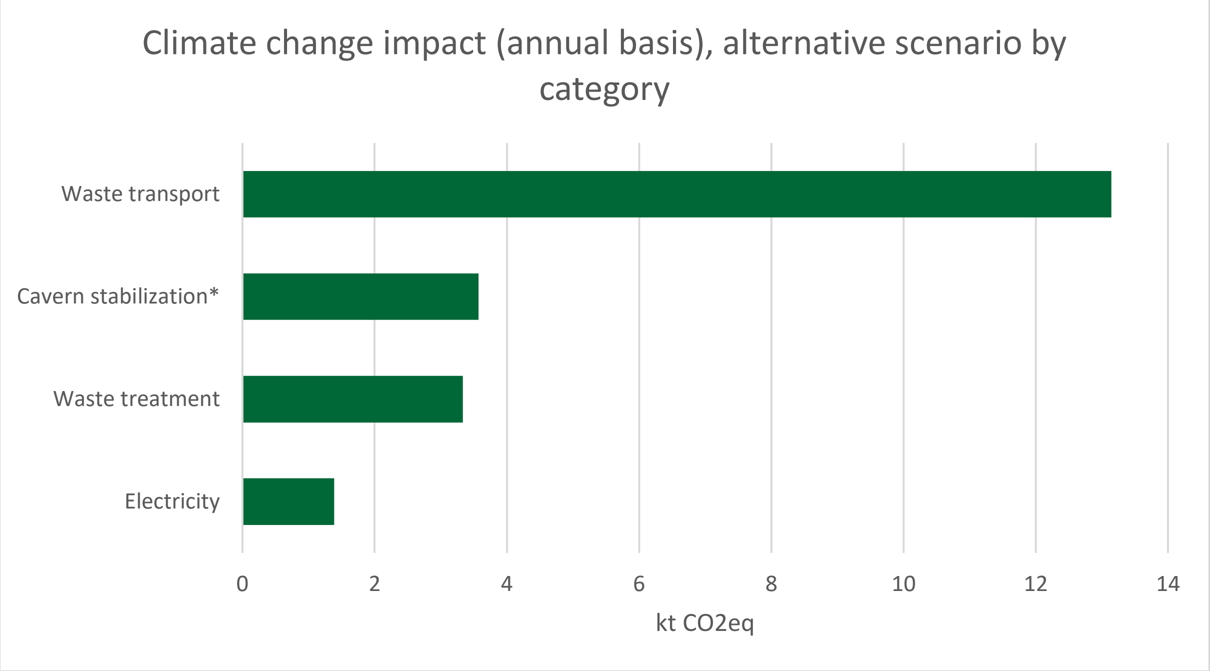


*Figure 6: Contribution analysis of alternative treatment to CO2-eq emissions. *Cavern stabilisation includes impacts from the sand extraction, transport, dissolving and pumping into the caverns.*

For the other impact categories, the alternative treatment also has a similarly higher effect, between 91 – 721x higher compared to the current situation. In 14 out of 16 impact categories, transport is the main driver of the higher impact in the alternative scenario. For land use, the sand extraction from sea bedding accounted for the high difference, while for water use, the waste treatment had the highest impact. The biggest difference between the scenarios is seen in the effect on Ecotoxicity-freshwater, which is 1336x higher in the alternative treatment, mostly due to transport. Additionally, the increase of 'Water use' is only minimal (9x) in the alternative scenario as some of the water is recovered by evaporation and fed back into surface water.

Table 1: Results for all impact categories for both scenarios

		Unit	Scenario 1 (current)	Scenario 2 (alternative)	Change
Climate change	Climate Change	kg CO2 eq.	6.75E+04	2.14E+07	x318
Ozone layer	Ozone depletion	kg CFC-11 eq.	7.11E-03	6.45E-01	x91
Air quality & health	Human toxicity, cancer	CTUh	5.53E-05	1.01E-02	x184
	Human toxicity, non-cancer	CTUh	9.04E-04	1.65E-01	x183
	Ionising radiation, human health	kBq U235 eq.	3.21E+03	4.23E+05	x132
	Particulate matter	Disease incidences	2.33E-03	1.68E+00	x721
	Photochemical ozone formation, human health	kg NMVOC eq.	2.10E+02	1.59E+05	x756
Effects on nature	Acidification	Mole of H+ eq.	2.30E+02	1.12E+05	x489
	Ecotoxicity, freshwater	CTUe	1.15E+05	1.54E+08	x1336
	Eutrophication, freshwater	kg P eq.	7.30E+00	1.62E+03	x222
	Eutrophication, marine	kg N eq.	6.56E+01	4.39E+04	x669
	Eutrophication, terrestrial	Mole of N eq.	9.02E+02	4.76E+05	x527
Resource use	Land Use	Pt.	2.58E+06	1.06E+09	x412
	Resource use, fossils	MJ	1.29E+06	3.56E+08	x276
	Resource use, mineral and metals	kg Sb eq.	2.07E-01	5.59E+01	x270
	Water use	m^3 world equiv.	9.14E+05	7.87E+06	x9

In addition to the comparison of individual impact categories, a Product Environmental Footprint (PEF) score is calculated. This is a methodology developed by the European Commission, which applies normalisation and weighting to the impacts shown in Table 1. The normalisation is done by dividing the impact by the annual impact of an average European citizen. In weighting, the normalised result is multiplied with a weighting factor defined per impact category. Weighting and normalisation factors are taken from the Environmental Footprint reference package 3.1.

While normalisation and weighting do have several underlying assumptions, this is a suitable method for assessing multiple impact categories in a single score. This makes it possible to compare the scenarios from a total environmental perspective, instead of comparing each individual impact category.

For the PEF Score, the alternative treatment of residual streams also showed a much higher impact. This was reflected by a PEF score of 2133.5 pt. in the alternative scenario as opposed to 12.4 pt. in the current scenario, an increase of 173x. The main cause of this is the transport of residues to landfill (Figure 7). This transport had a large effect on the impact categories of climate change, fossil resource use and particulate matter. The impacts from waste treatment (landfilling) and cavern stabilisation (sand extraction and transport) had the second largest impact.

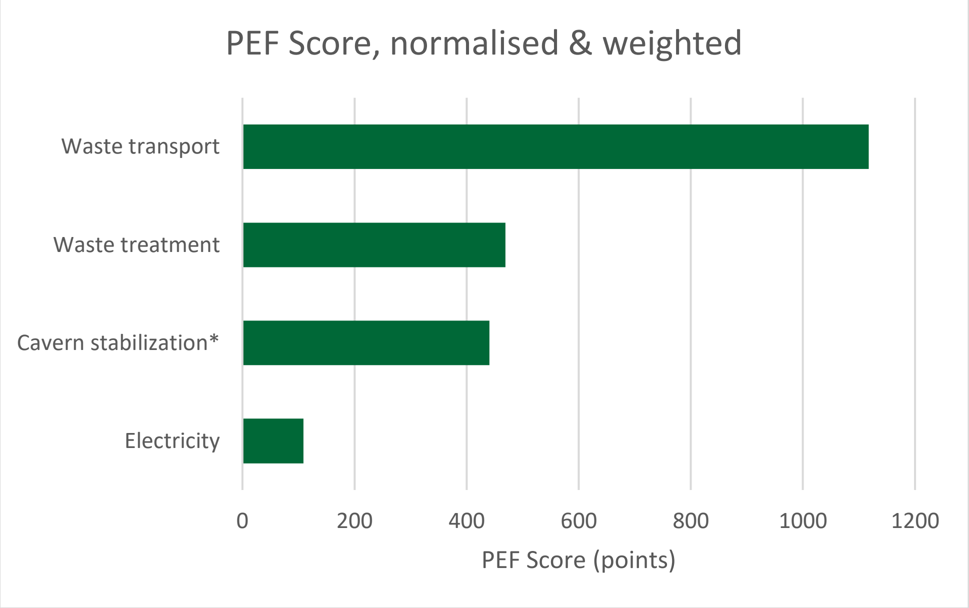


*Figure 7: Contribution analysis of processes to the PEF score of the alternative treatment scenario. *Cavern stabilisation includes impacts from the sand extraction, transport, dissolving and pumping into the caverns.*

6.2 Total cost of ownership

To calculate the total costs for the current and alternative treatment of the residual streams, all costs related to electricity use, transportation, landfilling/sand cleaning were included as well as revenues of the road salt sales of flow 7. The results are provided in Annex E.3. The TCO for the current situation were calculated to be €32,610 annually, while in the alternative treatment scenario the costs were €44,650,109, around 1369x higher. The costs in the current situation are from pumping the flows into the depleted caverns and the water for dissolving flow 9-11.

The main costs for the alternative scenario are from landfilling of the residues and the sand for stabilisation, as shown in Figure 8. Cavern stabilisation (consisting of primarily costs for sand and costs for the transport of sand) and waste transport make up other large costs. Although the salt sales from flow 7 provide some revenue, the costs of construction of an MVR for water evaporation are not included and would make the transformation of this flow to road salt not profitable; separate MVR construction would be required as this flow cannot be included in the available MVR in Hengelo due to it contaminating the salt production.

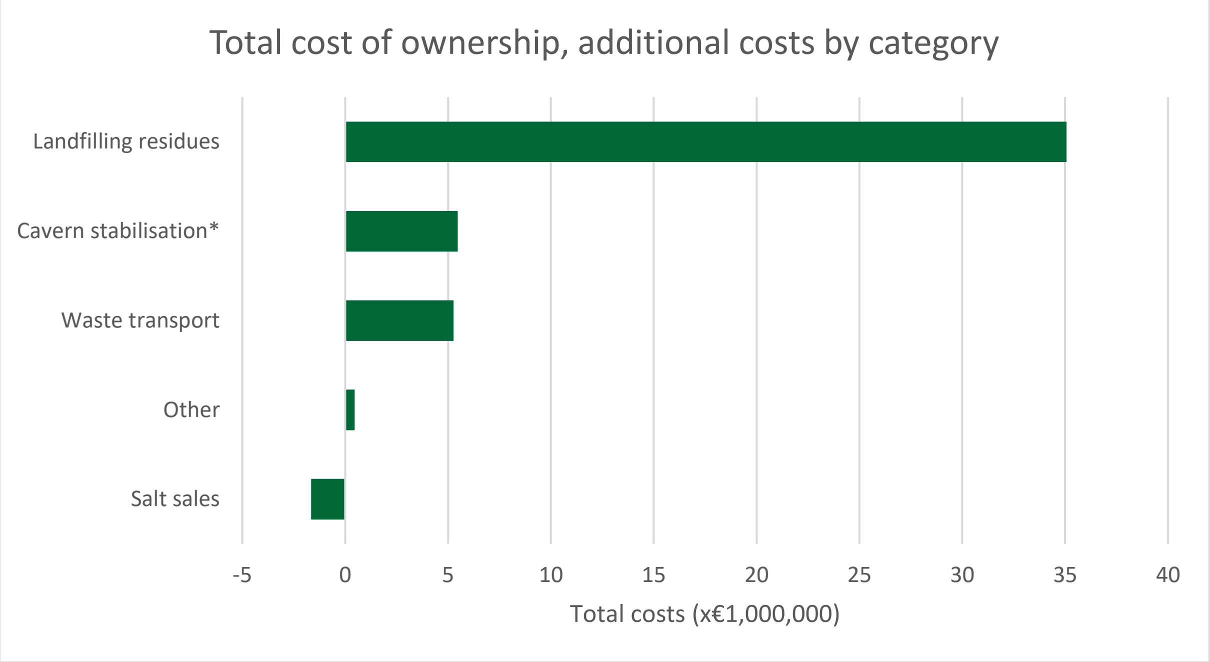


Figure 8: Contribution of processes to total costs in alternative treatment scenario as compared to the current situation. Cavern stabilisation includes costs for the extraction of sand, sand transport, and electricity for pumping.

6.3 Contribution by flow

In Table 2, the contributions to the climate change impact, PEF score and TCO are shown per flow, where the impact of alternative cavern stabilisation is divided over the relevant flows by their annual volume.

Table 2: Contribution analysis of the residual streams to climate change, PEF score and TCO in Scenario 1 and 2

	1	2	3	04a	04b	7	9	10	11	TOT
Climate change, Scenario 1	5.98E+01	2.55E+01	3.65E+04	5.61E+03	1.20E+03	1.49E+04	7.16E+03	1.68E+03	2.75E+02	6.75E+04
	0.1%	0.0%	54.1%	8.3%	1.8%	22.1%	10.6%	2.5%	0.4%	100.0%
Climate change, Scenario 2	1.97E+04	2.20E+04	1.47E+07	2.44E+06	1.91E+06	1.67E+06	4.89E+05	1.15E+05	1.87E+04	2.14E+07
	0.1%	0.1%	68.7%	11.4%	8.9%	7.8%	2.3%	0.5%	0.1%	100.0%
PEF Score, Scenario 1	0.00	0.00	2.91	0.45	0.1	1.19	6.06	1.43	0.23	12.36
	0.0%	0.0%	23.5%	3.6%	0.8%	9.6%	49.0%	11.6%	1.9%	100.0%
PEF Score, Scenario 2	1.93	2.32	1477.02	238.77	178.51	170.9	50.31	11.84	1.93	2133.52
	0.1%	0.1%	69.2%	11.2%	8.4%	8.0%	2.4%	0.6%	0.1%	100.0%
TCO, Scenario 1	€ 20	€ 9	€ 12,346	€ 1,893	€ 406	€ 5,031	€ 10,133	€ 2,384	€ 389	€ 32,610
	0.1%	0.0%	37.9%	5.8%	1.2%	15.4%	31.1%	7.3%	1.2%	100.0%
TCO, Scenario 2	€ 38,612	€ 31,787	€ 34,148,556	€ 5,008,398	€ 4,042,967	€ -2,900	€ 1,085,606	€ 255,437	€ 41,647	€ 44,650,109
	0.1%	0.1%	76.5%	11.2%	9.1%	0.0%	2.4%	0.6%	0.1%	100.0%

Flow 01. Boorspoeling, flow 02. Boorgruis, flow 03. Slurry, flow 04a. Moederloog, flow 04b. Concentraatspui, flow 07. Zoutoplossing natwassers, zoutdroog/zeef, flow 09. Stofzout 17yclone, flow 10. Veeg-, morszout, offspec, flow 11. Off spec broxo

In the climate change impact, PEF score & TCO, the slurry has the highest contribution. This can be explained by the fact that this is the highest volume of the residual streams. Moreover, it also has the highest contribution to cavern stabilisation, for which the alternative filling with sand was allocated based on flow volumes. Other streams, in particular stream 4a, 4b and 7, also show a higher impact and costs, related to their larger annual volumes.

In Scenario 1, it can be noted that flow 9-11 (the Librox flows) have a relatively high contribution to the PEF score. This is because they are mixed with water in the Librox drain before they are suitable for re-injection. Fresh water use is one of the indicators included in the calculation of the PEF score.

For flow *'7. Zoutoplossing natwassers (zoutdroog/zeef)'* it can be noted that the contribution to the TCO is negative in Scenario 2: alternative stabilisation. This is because a profit was included for the sale of road salt in this scenario for flow 7. Still, this method of evaporation and sale of this flow is considered to be economically infeasible since CAPEX for MVR construction were not included in the scenario.

In general, it can be seen that scenario 2 is disadvantageous for every individual stream, since all streams show an increase in environmental impact as well as costs.

6.4 Sensitivity analyses

Several sensitivity analyses were performed for the largest impacts to investigate the robustness of the data and assumptions used in this study. A total overview of the environmental results per impact category for each sensitivity analysis is provided in Annex E.1 and Annex E.2. For the sensitivity analysis on the costs, the results are provided in Annex E.3. Specific results per sensitivity analysis are highlighted below.

Landfill leaching

It is unlikely that large amounts of salt would leach to groundwater, since most salt has been extracted from the streams during salt production. Moreover, waste treatment companies will maximally limit the leaching. For these reasons, a leaching rate of 0% was assumed in the main scenarios. As the environmental impact of leaching is expected to be significant, a sensitivity analysis was performed assuming 5% of salt leaching. To this end, the dataset used for modelling was adapted accordingly. Table 3 shows that even with a leaching rate of only 5%, the ecotoxicity impact increases by a factor 5.9, and thereby the PEF score increases by 12% .

Table 3: Comparison of 100% and 1% salt leakage of landfill on Ecotoxicity and the PEF score

	Unit	Scenario 1 (current)	Scenario 2 (alternative)	Change
Ecotoxicity, freshwater, 0% leakage	CTUe	1.15E+05	1.54E+08	x1336
Ecotoxicity, freshwater, 5% leakage	**CTUe**	**1.15E+05**	**9.07E+08**	**x7893**
PEF Score, 0% leakage	Pt.	12.4	2133.5	x173
PEF Score, 5% leakage	**Pt.**	**12.4**	**2388.7**	**x193**

Transport distance

The transportation distance of all solids in the alternative treatment scenario was assumed to be 200 km. This distance is assumed because the location of treatment is unknown, as currently no capacity for the annual amount of residual streams is available. Since the impact of transport is significant, the effect of a lower transport distance of 50km was modelled as a sensitivity analysis. Table 4 shows that the Global Warming Potential and PEF scores of the alternative treatment decrease significantly, a trend that is also mirrored across the other impact categories (see Annex E.1 and Annex E.2). However, despite this reduction, the difference between the current situation and alternative treatment remains significant. Moreover, the reduction in costs is even smaller, with an 8.9% decrease in the total TCO.

Table 4: Comparison of 200km and 50km transportation distance in current situation and alternative treatment

	Unit	Scenario 1 (current)	Scenario 2 (alternative)	Change
Climate Change	ktCO2eq	0.07	21.43	x318
Climate Change, 50km TP	**ktCO2eq**	**0.07**	**11.57**	**x172**
PEF Score	Pt.	12.4	2133.5	x173
PEF Score, 50km TP	**Pt.**	**12.4**	**1295.7**	**x105**
TCO	€	€ 32,610	€ 44,650,109	x1369
TCO, 50km TP	**€**	**€ 32,610**	**€ 40,698,812**	**x1248**

Granulite

Granulite, a co-product from granite production, is studied as a secondary option for stabilisation in this sensitivity analysis. In the Netherlands, granulite is commonly produced as a co-product of granite from Norway. As a co-product, an allocation must be chosen. Currently, granulite is a low to zero value co-product. Therefore, an economic allocation is chosen, and the upstream impact of mining, crushing, and transport of granite are fully allocated to the other products.

Because the value of products and materials can change, an alternative allocation is studied where granulite would have a roughly similar value to granite and therefore a physical allocation would make sense: in this case, mass allocation is chosen. The total mass of granulite is estimated to be ~5% of the total granite mass. Therefore, 5% of the impact of the mining, crushing and sea transport of the granite would be allocated to the granulite. The mining of limestone can be used as a proxy, for which the dataset includes mining, washing and crushing of the limestone. The distance for sea transport from Norway to Amsterdam is estimated to be 1120 km.

Independent of the chosen allocation for granulite production, the subsequent steps after the production of granulite are modelled similar to sand. Firstly, the cleaning of the granulite is modelled by including the production of a cleaning agent (note: the cleaning agent does not end up in the granulite, but in the waste water from the granite producer). Transport by inland barge from Amsterdam to Hengelo is included as well. The water in granulite is fresh water, as opposed to the water in North Sea sand which is salt water. Therefore, dry salt must be dissolved into the granulite, to prevent the filling material from dissolving more salt in the salt cavern. After the saturation of the water in the granulite with dry salt, the granulite has to be mixed with brine (1:5 ratio) to make it suitable for injection into the caverns. However, the environmental impact of the brine and dry salt were based on the internal Nobian LCA models (2021 data). Costs for the brine and dry salt are not included.

The LCA results, as shown in Table 5, show that in the alternative scenario, the climate change impact was 1.4% lower and the PEF score was 4.6% lower when using granulite compared to sand. While slightly lower than using sand as filler material, there is still a significant impact due to transport of large volumes of granulite by inland barge to the Nobian site. When mass allocation is applied, the impact is higher than the case with sand, since a part of the mining and transport from Norway is included in the impact. Granulite is however cheaper than sand (€5/t as opposed to €10/t for sand), resulting in a total cost for alternative treatment of € 40,352,944 which is 9.6% lower than in the case using sand. Nevertheless, the alternative treatment with granulite would still have a higher environmental impact and TCO compared to the current scenario.

Table 5: Comparison of sand and granulite as cavern stabilisation material in current situation and alternative treatment

	Unit	**Scenario 1 (current)**	**Scenario 2 (alternative)**	**Change**
Climate Change	ktCO2eq	0.07	21.43	x318
Climate Change, granulite (economic)	**ktCO2eq**	**0.07**	**21.14**	**x313**
Climate Change, granulite (mass)*	*ktCO2eq*	*0.07*	*23.71*	*x351*
PEF Score	Pt.	12.4	2133.5	x173
PEF Score, granulite (economic)	**Pt.**	**12.4**	**2035.9**	**x165**
PEF Score, granulite (mass)*	*Pt.*	*12.4*	*2407.7*	*x195*
TCO	€	€ 32,610	€ 44,650,109	x1369
TCO, granulite	**€**	**€ 32,610**	**€ 40,352,944**	**x1237**

** mass allocation is not reasonable as granulite is a low to zero by-product, but the results are presented as a sensitivity since the value might change in the future*

Treatment of boorgruis

The cleaning of 'boorgruis' (flow 2) to recycle as sand was estimated between €45 and €200. The former was included in the main TCO calculations. To check the upper boundary of the additional costs, €200 was taken in this sensitivity analysis, of which the results are shown in Annex E.3. The results show that this would increase the TCO by 0.17%, since the costs for the treatment of this flow only make up a small part of the total costs.

The recycling of 'boorgruis' is uncertain, as noted by Renewi (see Annex B). Therefore, the model was adapted to see the results of landfilling this flow instead of recycling. From the results only marginal differences can be seen: the climate change impact increases by 0.012%, and the PEF score increases by 0.004%. This can be explained by the fact that the flow only makes up a small share of the annual amount of residual streams. The increase in costs of landfilling instead of recycling would be 0.06%.

6.5 Eco-costs

As an additional check, the eco-costs were calculated for several impact categories. Eco-costs are defined as the societal costs related to the environmental impact. Per impact category, these costs have been developed, however, it should be noted that an eco-cost value was not available for all impact categories. The environmental costs calculated by CE Delft (*Handboek milieuprijzen 2023, CE Delft*) were used, which are based on the PEF impact scores for 2021. These are generally used within a Dutch context and are applicable for the EF 3.1 impact assessment method of the LCA study. The results are shown in Table 6.

It is clear that Climate Change (kg CO2-eq) and Particulate Matter have the highest environmental costs in this study. Similar to the LCIA results (Table 1), the alternative treatment showed a higher costs overview for all considered impact categories.

Table 6: Eco-cost for environmental impact categories and change of alternative treatment versus current situation

Impact category	Unit	Costs / unit	Scenario 1 (current)	Scenario 2 (alternative)	Change
Climate Change	kg CO2 eq.	€ 0.13	€ 8,770	€ 2,785,784	x318
Ozone depletion	kg CFC-11 eq.	€ 29.10	€ 0	€ 19	x91
Ionising radiation, human health	kBq U235 eq.	€ 0.00	€ 2	€ 301	x132
Particulate matter	Disease incidences	€ 1,937,047	€ 4,520	€ 3,260,807	x721
Photochemical ozone formation, human health	kg NMVOC eq.	€ 1.40	€ 294	€ 222,218	x756
Acidification	Mole of H+ eq.	€ 2.01	€ 462	€ 225,889	x489
Eutrophication, freshwater	kg P eq.	€ 5.53	€ 40	€ 8,969	x222
Eutrophication, marine	kg N eq.	€ 14.25	€ 935	€ 625,167	x669
Eutrophication, terrestrial	Mole of N eq.	€ 0.34	€ 310	€ 163,673	x527
		Total eco-costs	**€ 15,334**	**€ 7,292,827**	**x476**

The total eco-costs in the current situation were calculated to be €15,334, while the alternative treatment showed a much higher cost of €7,292,827. These costs are hypothetical costs and therefore it is not advisable to add them to the TCO results. However, it provides an indication of the impact categories that would lead to the highest costs for abatement of the environmental damage.

6.6 Limitations

In this study, the current situation was compared to a theoretical, possible, alternative scenario of waste treatment. As this brings many uncertainties, not every relevant factor or detail can be captured in the models. This study therefore has several limitations related to the simplification of the models.

A thorough investigation into alternative treatments was performed to clearly understand the possibilities and limitations. Although the alternative treatments are theoretically possible, several limitations are raised:

- Treatment capacity for the volume of Nobian's streams is not available and new treatment facilities (MVR technology) would need to be constructed. These costs are not included in the TCO, but CAPEX costs are estimated to be around €100-200 / t residue, vastly increasing the total costs.
- Landfilling capacity in the Netherlands is likely to reduce in the coming years, while costs increase. This has not been taken into consideration in the current TCO calculations. Additionally, the option of exporting the solid residues to landfill sites abroad has not been considered. However, the additional costs, possible higher transport distances and the process of obtaining an export permit are expected to negatively affect the impact of alternative treatment.
- Currently the business of sand recycling in the Netherlands is under pressure as, in many (non-Nobian) streams, PFAS contamination hampers sand cleaning and recycling. Also, although there is capacity to clean the 'boorgruis' volumes of Nobian, not many projects for subsequent use of cleaned sand are available at the moment. Since sand processors will likely only take in the flow when sales are guaranteed, this treatment option is uncertain.
- For flow 7, the alternative was defined as selling the residue as road salt after evaporation. This seems economically beneficial, however, it should be noted that the CAPEX costs of a to-be-constructed MVR were not included. Although the Hengelo salt factory has an MVR for brine crystallization, flow 7 cannot be processed in this MVR due to contaminations that would hinder salt production.

For the alternative stabilisation materials of the caverns, the current suitable options were included in the study. Nobian has investigated several materials in their efforts for cavern stabilisations, including the use of granulite. Granulite, a relatively new option, may prove to be a useful material in the future. It is however still currently being investigated by Nobian. Despite this, it was decided that it would be included in the study in order to ensure the study is future-proof. However, it should be noted that it is not the goal of this study to compare options for cavern stabilisation. Therefore, the models for cavern stabilisation have limitations related to its simplification.

Several flows are excluded from this study, 5, 6, and 8, as these are not waste streams. In fact, these flows are essential for brine production in operational salt caverns to dissolve the underground salt. If these flows would be included for alternative treatment, the volume of these flows would need to be replaced with alternative clean water sources. This would increase the environmental impact (clean water production) and costs even more. The use of these flows in a continuous recycling loop from the caverns to salt production and back is a useful application.

7 Conclusion & Discussion

In this study, the environmental and economic performance of two scenarios were studied, concerning the fate of several residual output streams from the salt factories of Nobian and Salins in Hengelo. The scenarios studied were:

1. The current situation, in which the residual streams are injected back into the subsoil, in depleted salt caverns where they stabilise the depleted caverns (useful application).
2. Alternative treatment of the residual streams, in which they are not injected into the subsoil but treated as waste. Together with Renewi, a waste handler in the Netherlands, the alternative treatment options were defined (see Annex B). In this scenario, stabilisation of the depleted caverns was achieved with a different filling material, North Sea sand.

The scenarios were studied using LCA and TCO methodologies. Based on the results, the current situation of reinjection of residual streams for cavern stabilisation is favourable from both an environmental and economic perspective.

The environmental impact of alternative treatments increased significantly compared to the current scenario. Although the exact increase depends on the impact category, in order of magnitude, the effect of alternative treatment was ~100-800 times higher. In addition, the costs would increase 1369 times when alternative treatment would be performed. This is also the case when looking at individual streams in detail. For every single residual stream, the alternative treatment is disadvantageous from both a cost and environmental perspective.

Based on the results for both the LCA and TCO, several sensitivity analyses were performed to determine the robustness of the assumptions and data used. However, even with more advantageous conditions for the alternative treatment scenario (shorter transport distance and lower costs for cavern stabilisation material), the alternative treatment still showed a worse performance on the LCA and TCO results compared to the current situation.[1] This indicates that changing the underlying data and assumptions can alter the absolute outcomes, but do not change the relative higher impacts and costs of the alternative treatments. The eco-costs, in which environmental impacts are translated into fictitious societal costs, show a similar result.

Based on this study, the LCA and TCO results clearly indicate the benefits of continuing the current practise where the residual streams are reinjected into the caverns for stabilisation purposes.

Short comparison with previous study

Similar to this study, TNO (Netherlands Organisation for Applied Scientific Research) previously conducted an LCA and eco-efficiency study for alternative treatment of the Librox flows (flow 9-11 of this study), *"Eco-efficiency of injection of contaminated brine in caverns"* (TNO, 2004).

Besides re-injection into caverns, two alternative treatment options for these flows were discussed in their report:

- The filtration of soil-foreign materials, followed by landfill of the residue and reinjection of the filtrate into the caverns. The report concludes that even after filtration, the Librox flow still contains subsoil-foreign components. Re-injection into the caverns would therefore still be

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[1] In principle, to accelerate the stabilisation of the caverns, a scenario can be envisioned where the slurry is supplemented by additional filling material, therefore stabilising more of the suspended caverns. This would however result in a higher environmental burden and costs, as shown here. A detailed assessment of the acceleration of stabilising caverns is however outside of the scope for this study.

equal to Scenario 1, the current situation, with additional costs and environmental impact of the filtration step and the landfilling of the filtrate. Therefore, it does not add any additional considerations to the current study and was not included in this report.

- The immediate landfill of the Librox solids was studied in the TNO report, without dissolving the flows. This is similar to the alternative treatment approach for flow 9, 10 & 11 of the current study.

Although there were several methodological differences and assumptions, the TNO study also showed that the current situation was beneficial from an environmental and economic perspective as compared to the filtration scenario. The scenario of landfilling the Librox waste was considered disadvantageous in costs, while being similar in environmental performance.

The TNO report did include CAPEX, labour and maintenance costs, which are considered out-of-scope for this study. Labour costs did not change between scenarios in the report, while maintenance & machinery comprised €29,300 of the injection scenario. While this is a major share of the ''injection into caverns' scenario, it does not compare to the high costs for landfilling wastes & waste transport in the alternative treatment described in the current report.

The approach to the inclusion of electricity use, water and transport was similar to this study. A major difference is seen in the transport distance, which was assumed to be 2km in the TNO report. A local landfill in Hengelo was considered as a viable option. In the current study, Renewi noted that the availability of landfill capacity is much lower nowadays, especially for the volumes of waste included. Therefore, the assumption of larger transport in the current study is justified.

Finally, the TNO report also includes an incidental additional waste stream of sediment from the Librox drain, which was considered out-of-scope for this study. As the amount was low compared to the residual streams, 16 tonnes, this is not expected to change the results.

Annex A Residual streams

Annex A.1 Overview

An overview of all residual streams with given amounts is shown in Annex Table 1.

Annex Table 1: overview of residual streams + quantities

		Residual stream	Unit	Quantity
Nobian	Brine production	1. Boorspoeling	m3/a	597
		2. Boorgruis	t/a	492
	Brine purification	3. Slurry (brine purification)	m3/a	365,000
	Salt crystallization	4A. Moederloog	m3/a	60,000
		4B. Concentraatspui	m3/a	60,000
		5. Zoutoplossing zuren	m3/a	450
		6. Proceswater	m3/a	12,000,000
Salins	Salt drying/sieving	7. Zoutoplossing natwassers (zoutdroog)	m3/a	154,000
	Librox	8. Zoutoplossing natwassers (Librox)	t/a	50,000
		9. Stofzout cyclonen	m3/a	7,820
		10. Veeg-, morszout, off spec	t/a	1,840
	Packaging	11. Off spec broxo	t/a	300
		12. Off spec salt (road salt)	t/a	160

Annex A.2 Description and composition per stream

Annex A.2.1 Boorspoeling (flow 1)

This flow is mainly water with sodium chloride (~30%) and generally accepted auxiliary materials used to adapt the viscosity, pH and density. This flush circulates around the drilling hole to keep the drilling hole open and to bring drilling debris to the surface. The total volume of this stream is 597 m^3/year.

Annex Table 2: components of flow 1. Boorspoeling (input materials)

		Interval 1	Interval 2	Interval 3
	Unit	Silfor 1.12sg	Silfor 1.21sg	Silfor 1.35sg
Total boorspoeling	m3	285	167	145
Brine	kg per m3	201	472	472
soda ash		1	1	1
sodium silicate		54.964	54.964	54.964
chemstarch		10	10	10
chempac		4	4	4
chemvis		3	3	3
calcium carbonate		0	0	220

Annex A.2.2 Boorgruis (flow 2)

During drilling procedure, debris is formed similar to the composition of the formations. This mainly consists of salt, clay, limestone and marl. The total volume of this stream is 492 ton/year.

Annex A.2.3 Slurry (flow 3)

Slurry is a precipitated substance formed during brine purification. It mainly consists of water with precipitated salt and inorganic components (minerals such as magnesium, potassium, sulfates, etc.) from the brine solution. The water, slaked lime and anti-flocculation agent are the only components not originating from the underground salt layers. The total volume of this stream is 365,000 m^3/year.

Annex Table 3: components of flow 3. Slurry

Slurry Filtered liquid Analyses					
OH	31.1	meq/l	**Co**	<10	µg/l
CO3	<0.5	meq/l	**Cr**	<10	µg/l
HCO3/HZ		meq/l	**Cu**	<5	µg/l
Ca (meq/l)	24.8	meq/l	**Fe**	-	µg/l
K (meq/l)	23.755	meq/l	**K (mg/l)**		mg/l
SO4 (meq/l)	349	meq/l	**Li**	454	µg/l
Sr (meq/l)	0.1895	meq/l	**Mg(µg/l)**	212.5	µg/l
Mg (meq/l)		meq/l	**Mn**	4	µg/l
Cl	185.92	g/l	**Mo**	<10	µg/l
NaCl	306.5130708	g/l	**Ni**	<10	µg/l
NH3		mg/l	**P**	52	µg/l
NO2	0.272	mg/l	**Pb**	<50	µg/l
NO3	2.953	mg/l	**Ru**	<50	µg/l
Br	87.13	mg/l	**SO4 (mg/l)**		mg/l
I		mg/l	**Sb**	<60	µg/l
F	<0.1	mg/l	**Se**	<100	µg/l
Al	-	µg/l	**Si**	484	µg/l
As	<50	µg/l	**Sn**	<100	µg/l
B	4198	µg/l	**Sr (µg/l)**		µg/l
Ba	140.5	µg/l	**Ti**	<5	µg/l
Be	<1	µg/l	**V**	<5	µg/l
Ca (mg/l)		mg/l	**Zn**	<5	µg/l
Cd	<5	µg/l			

Annex A.2.4 Moederloog (flow 4a)

This is a residual flow from the evaporation step of the salt plant, which cannot be concentrated any further. The flow consists of water, sodium chloride (NaCl), and sodium bromide (NaBr), with the latter two originating from the salt caverns. Unlike the other minerals in the slurry, NaBr cannot be precipitated. The total volume of this flow is 60,000 m^3/year.

Annex Table 4: components of flow 4a. Moederloog

Moederloog Unfiltered liquid Analyses					
OH	11.485	meq/l	**Co**	<10	µg/l
CO3	10.385	meq/l	**Cr**	<10	µg/l
HCO3/HZ		meq/l	**Cu**	46	µg/l
Ca (meq/l)	0.911	meq/l	**Fe**	324	µg/l
K (meq/l)	46.02	meq/l	**K (mg/l)**		mg/l
SO4 (meq/l)	810.74	meq/l	**Li**	980	µg/l
Sr (meq/l)	0.0945	meq/l	**Mg (µg/l)**	21	µg/l
Mg (meq/l)		meq/l	**Mn**	-	µg/l
Cl	178.755	g/l	**Mo**	17.5	µg/l
NaCl	294.7006452	g/l	**Ni**	21	µg/l
NH3	0.1575	mg/l	**P**	<40	µg/l
NO2	1.465	mg/l	**Pb**	<50	µg/l
NO3	19.325	mg/l	**Ru**	<50	µg/l
Br	159.78	mg/l	**SO4 (mg/l)**		mg/l
I	0.95	mg/l	**Sb**	<60	µg/l
F	0.2715	mg/l	**Se**	<100	µg/l
Al	24	µg/l	**Si**	736.5	µg/l
As	<50	µg/l	**Sn**	<100	µg/l
B	9079.5	µg/l	**Sr (µg/l)**		µg/l
Ba	62.5	µg/l	**Ti**	<5	µg/l
Be	<2	µg/l	**V**	<5	µg/l
Ca (mg/l)		mg/l	**Zn**	-	µg/l
Cd	<5	µg/l			

Annex A.2.5 Concentraatspui (flow 4b)

This is a concentrated purge originating from the salt crystallization process that contains mainly NaCl. The total volume of this flow is 60,000 m^3/year.

Annex Table 5: components of flow 4b. concentraatspui

Concentraatspui Unfiltered liquid Analyses					
OH	61.45666667	meq/l	**Co**	<10	µg/l
CO3	49.7	meq/l	**Cr**	<10	µg/l
HCO3/HZ		meq/l	**Cu**	249.7333333	µg/l
Ca (meq/l)	1.593	meq/l	**Fe**	637.4666667	µg/l
K (meq/l)	238.5666667	meq/l	**K (mg/l)**		mg/l
SO4 (meq/l)	684.6333333	meq/l	**Li**	5122	µg/l
Sr (meq/l)	0.201	meq/l	**Mg (µg/l)**	31.89333333	µg/l
Mg (meq/l)		meq/l	**Mn**	9.983333333	µg/l
Cl	159.8	g/l	**Mo**	121.9666667	µg/l
NaCl	263.4508859	g/l	**Ni**	210.8666667	µg/l

NH3	0.773333333	mg/l	**P**	233.4333333	µg/l
NO2	5.9	mg/l	**Pb**	<50	µg/l
NO3	111	mg/l	**Ru**	<50	µg/l
Br	652.9666667	mg/l	**SO4 (mg/l)**		mg/l
I	5.417333333	mg/l	**Sb**	-	µg/l
F	0.451	mg/l	**Se**	<100	µg/l
Al	60.99333333	µg/l	**Si**	3864.333333	µg/l
As	<50	µg/l	**Sn**	<200	µg/l
B	50077.33333	µg/l	**Sr (µg/l)**		µg/l
Ba	182.0333333	µg/l	**Ti**	<5	µg/l
Be	<1	µg/l	**V**	10.22333333	µg/l
Ca (mg/l)		mg/l	**Zn**	-	µg/l
Cd	<5	µg/l	**Co**		

Annex A.2.6 Zoutoplossing zuren (flow 5)

This acidy salt solution is a small stream of sodium and calcium salts, originating from occasionally dissolving the calcium deposits in the installations. The stream is acidified with HCl (0.5%). Additional H+ and Cl- ions are negligible compared to the process water, flow 6. The total volume of this flow is 450 m^3/year.

Annex A.2.7 Process water (flow 6)

This flow is essential for salt mining. It contains purified water that remains after crystallization of the salt, which is reused in the production caverns to dissolve brine. Water losses during this process are supplemented with canal water from the Twentekanaal. The total volume of this flow is 12,000,000 m^3/year.

Annex Table 6: components of flow 6. Process water

Mengwater/proceswater unfiltered liquid Analyses					
OH		meq/l	**Co**	<6	µg/l
CO3	2.12	meq/l	**Cr**	<6	µg/l
HCO3/HZ		meq/l	**Cu**	14	µg/l
Ca (meq/l)		meq/l	**Fe**	106	µg/l
K (meq/l)		meq/l	**K (mg/l)**	3.793	mg/l
SO4 (meq/l)		meq/l	**Li**	2	µg/l
Sr (meq/l)		meq/l	**Mg (µg/l)**	2564.35	µg/l
Mg (meq/l)		meq/l	**Mn**	7.4	µg/l
Cl	0.89968	g/l	**Mo**	<6	µg/l
NaCl		g/l	**Ni**	<6	µg/l
NH3	<0.09	mg/l	**P**	42	µg/l
NO2	<0.1	mg/l	**Pb**	<50	µg/l
NO3	3.62	mg/l	**Ru**	<50	µg/l
Br	<1	mg/l	**SO4 (mg/l)**	21.73	mg/l
I		mg/l	**Sb**	<15	µg/l
F	0.12835	mg/l	**Se**	<30	µg/l
Al	-	µg/l	**Si**	1179	µg/l
As	<50	µg/l	**Sn**	<15	µg/l
B	22	µg/l	**Sr (µg/l)**	96.5	µg/l
Ba	17	µg/l	**Ti**	<5	µg/l
Be	<1	µg/l	**V**	<5	µg/l
Ca (mg/l)	19.185	mg/l	**Zn**	9	µg/l
Cd	<1	µg/l			

Annex A.2.8 Zoutoplossing natwassers, zoutdroog/zeef (flow 7)

A stream of salty water from Salins, originating from the process of drying and sieving of salt. In the handling and transport of the salt, dust & waste salt are formed. This salt dust is precipitated with water using wet washers. It contains a small amount of anti-caking agent ferrocyanide. The total volume of this flow is 154,000 m^3/year.

Annex Table 7: components of flow 7. Zoutoplossing natwassers (zoutdroog/zeef)

	Salt Analyses		
	Sample 1	Sample 2	
H2O	2.893333333	2.64	%
Br	21.95666667	22.22	mg/kg
Cl	591.1666667	594.5	gr/l
NH3	<0.09	<0.09	mg/kg
NO2	<0.1	<0.1	mg/kg
NO3	<1	<1	mg/kg
I	<0.1	<0.1	mg/kg
F	<0.1	<0.1	mg/kg
NaCl*	359		g/kg
Al	<15	<15	µg/kg
As	<150	<150	µg/kg
B	40.33333333	42	µg/kg
Ba	2.333333333	-	µg/kg
Be	<5	<5	µg/kg
Ca	2.053333333	2.26	mg/kg
Cd	<15	<15	µg/kg
Co	<30	<30	µg/kg
Cr	<30	<30	µg/kg
Cu	<15	<15	µg/kg
Fe	256.3333333	235.6666667	µg/kg
K	35.62333333	35.95666667	mg/kg
Li	3.666666667	4	µg/kg
Mg	-	9	µg/kg
Mn	<3	<3	µg/kg
Mo	<30	<30	µg/kg
Ni	<30	-	µg/kg
P	<140	<140	µg/kg
Pb	<150	<150	µg/kg
Ru	<150	<150	µg/kg
SO4	228.5	219.5666667	mg/kg
Sb	<60	<60	µg/kg
Se	<100	<100	µg/kg
Si	<60	<60	µg/kg
Sn	<100	<100	µg/kg
Sr	84.33333333	75.33333333	µg/kg
Ti	<15	<15	µg/kg
V	<15	<15	µg/kg
Zn	<15	<15	µg/kg
Fe(CN)6	<1	<1	mg/kg

Annex A.2.9 Zoutoplossing natwassers, Librox (flow 8)

Similarly to flow 7, this flow originates in the Librox process of Salins. This salt dust is extracted using waste gas washers. This stream is injected into the production caverns to dissolve brine (similar to flow 6, ‘proceswater’). The total volume of this flow is 50,000 m^3/year. 3 samples were analysed (A, B, C).

Annex Table 8: components of flow 8. Zoutoplossing natwassers, Librox

Analyte	Eenheid	20RL001-A	20RL001-B	20RL001-C
NaCl	g/l	12.4	0.56	3.36
Cu	mg/l	0.16	10.1	0.05
Zn	mg/l	0.35	46.7	0.22
Mg	mg/l	1.26	99.2	1.83
Ca	mg/l	1.03	45.8	2.37
Se	mg/l	<0,05	<0,05	<0,05
Fe	mg/l	0.05	19.5	0.24
Si	mg/l	0.37	9.7	0.26

Annex A.2.10 Librox flows

The Librox specific flows include:

- Stofzout 30yclone (flow 9): salty water stream from salt dust from cyclones in the installations of Salins. The total volume of this flow is 7,820 ton per year.
- Veeg-, morszout, off spec (flow 10): Salty water stream from spilled salt on the floors of the production installations of Salins that has been swept and rinsed. The total volume of this flow is 1,840 ton/year.
- off-spec broxo salt (flow 11): an off spec salty water stream from the Salins production site. The total volume of this flow is 300 ton/year.

These flows are going to the Librox drain, diluted and transported to Nobian’s storage tank in one flow. The composition of this combined flow is provided below.

Annex Table 9: components of flow 9-11. Librox flows

Overview flow from Librox drain to storage tank per month per mineral		
	Unit	**2022**
NaCl	kg	5682355
Cu2(OH)2CO3		1039.26
ZnO		1280.91
Mn2CO3		37.81
MgO		10843.1
Fe2O3		497.7
Na2SeO3		29.23
Ca(JO3)2		350
Total pumped	m3	22714
Totaal	kg	14078.01
Cu	mg/kg NaCl	99.67640177
Zn		179.8391684
Se		2.348747658
Concentration	NaCl (g/l)	250.1697191
Raw materials	mg/l	619.7943999
	g/kg NaCl	2.477495686

Annex A.2.11 Off-spec salts, for road salt (flow 12)

Off-spec salt from Nobian that can be used as road salt. This is not considered a residual flow and will not be included in the LCA and TCO. The total volume of this flow is 160 ton/year.

Off-spec salt (road salt)		
Composition	**Unit**	**2022**
NaCl	%	≥ 99.8
H2O	%	≤ 3
Insolubles	%	≤ 0.01
Sulphate (SO4)	%	≤ 0.1
Heavy metals + Arsenicum		
Aluminium (Al)	mg/kg	≤ 0.5
Arsenicum (As)	mg/kg	≤ 0.3
Cadmium (Cd)	mg/kg	≤ 0.1
Chromium (Cr)	mg/kg	≤ 0.1
Cobalt (Co)	mg/kg	≤ 0.1
Copper (Cu)	mg/kg	≤ 0.3
Mercury (Hg)	mg/kg	≤ 0.01
Lead (Pb)	mg/kg	≤ 0.2
Nickel (Ni)	mg/kg	≤ 0.1
Zinc (Zn)	mg/kg	≤ 0.1
Hydrocarbons (NPOC)	mg/kg	≤ 30
Additives		
Anticaking Agent – $Na_4FE(CN)_6$ calculated as $FE(CN)_6$	mg/kg	≥ 40 and ≤ 100
Grain size distribution		
Fraction ≥ 2 mm	%	≤ 2
Fraction ≤ 0.8 mm	%	≥ 25 and ≤ 100
Fraction ≤ 0.125 mm	%	≤ 5
Density + pH		
Density	Kg/m^3	1220 – 1235
pH in 10% solution (mass %)		5 – 10

Annex B Alternative treatment residual streams

For each of the residual streams under study, an alternative treatment was discussed with Renewi, a waste treatment company in The Netherlands. Their experience in waste treatment options, costs and capabilities provided sufficient data for the LCA and TCO. Below the alternative treatment options are described per residual stream, with a final overview given in Annex Table 10.

In general, for most streams, de-watering of the stream is required to reduce the volume and handle the solid residues as waste to landfill. For this, a new facility with a mechanical vapor recompression (MVR) technology would need to be constructed. In the study, the costs and environmental impact of the construction of the MVR plant are excluded, while the operation of the MVR is explicitly included.

Note: the streams “Zoutoplossing zuren”, “Proceswater” and “Zoutoplossing natwassers (Librox)” are not waste streams as they are used in the production caverns for brine production. Therefore, these streams are excluded from the analysis by Renewi.

Annex B.1 Description of treatment by residual stream

Annex B.1.1 Boorspoeling (1)

Salty water from the food industry is generally purified with biological treatment to remove fatty acids. However, the vast amount of this stream and the impurities present would interfere with the biological purification process. Moreover, the ‘boorspoeling’ does not contain fatty acids, and no capacity is available for treatment on a continuous basis. Therefore, evaporation of the water in the stream with MVR technology, followed by landfill of the remaining residue is identified as the required alternative treatment.

Annex B.1.2 Boorgruis (2)

As an alternative treatment, this flow can be offered as “steekvastmateriaal” (stackable material), cleaned and sold as sand. While this flow does not contain any PFAS contaminations, many other streams of “steekvast material” offered to a cleaning facility do. These contaminations cannot sufficiently be removed from streams, therefore many sand cleaning facilities are under regulatory pressure. In addition, although there is capacity to clean the sand, not many projects for sand use are available. Since sand processors will likely only take in the flow when sales are guaranteed, this treatment option is far from certain.

Annex B.1.3 Slurry (3)

No capacity exists for the large volume of slurry that is produced. Usually, sulphate streams can be treated at gypsum processing facilities, but the gypsum in the slurry is not sufficiently pure and would need to be landfilled afterwards. Therefore, the proposed treatment would be to evaporate the water with MVR technology. The remaining residue, mainly calcium sulphate and calcium carbonate, needs to be landfilled.

Annex B.1.4 Moederloog (4a)

The flow is similar to the Boorspoeling, so biological treatment is not feasible. Due to the large quantities, no capacity is currently available to process this stream. It is also not possible to de-water this stream and sell as road salt, due to the high concentrations of sulphate. The proposed treatment would thus be to evaporate the water with MVR technology. The remaining residue from solids present in the flow would be landfilled.

Annex B.1.5 Concentraatspui (4b)

Similar to the Moederloog, there is no capacity currently available to process this stream due to the large volume, nor is the salt suitable for road salt due to the high concentrations of sulphate. The proposed treatment would thus be to evaporate the water with MVR technology. The remaining residue from dissolved solids present in the flow would be landfilled.

Annex B.1.6 Zoutoplossing natwassers, zoutdroog/zeef (7)

There is currently no processing capacity for this amount. The only material that could be recovered is sodium chloride (salt) as this is a relatively concentrated flow. However, the stream contains ferrocyanide (hazard classification) which is the reason this stream cannot be fed back into the salt purification process. It could, however, be de-watered and used as road salt. This alternative scenario is analysed in the study.

Annex B.1.7 Stofzout cyclonen (9), Veeg-, morszout, off spec (10) & Off spec broxo (11)

At the moment, these streams are dissolved in water in the Librox drain. Treating the Librox drain output would require evaporation of water, which defeats the purpose of the dissolving step. Therefore, for the alternative treatment, it is assumed that the dissolving will not occur and the solids would be treated immediately by landfill.

Annex B.2 Costs

Renewi estimated that the landfilling of this type of dewatered residues would cost €100 per ton of landfilled material. This price is expected to increase to €200-300 per ton in the following decennia. The cleaning of the material as sand is expected to cost between €45 - €200.

Annex B.3 Summary

The alternative treatment of the majority of the residual streams is to de-water using MVR technology (electricity use) followed by landfill of the remaining solid residue (Annex Table 10). This is the alternative treatment scenario for flow 1 and 3-4.

Stream 2, the Boorgruis, can be cleaned as sand to be used in e.g. infrastructure projects. The demand this type of waste stream is however uncertain.

Streams 5, 6 and 8 are essential for the brine production, and therefore excluded from this study.

Stream 7 can be sold as road salt when the water is evaporated, therefore, de-watering with MVR will be the alternative treatment. Sales revenue is included in the TCO.

Finally, to stream 9-11 water is added in the current situation. Without adding water, only landfilling would be needed for these streams. Therefore it is similar to flow 1 & 3-5, without the evaporation step.

Annex B.4 Limitations

Renewi listed several additional limitations to the waste treatment as described above:

- Currently, no MVR facility is available for the purpose of treating residual streams, and would therefore need to be constructed. The costs are not included in the current TCO, however would add to the costs significantly.
- Another note is that the capacity for landfilling, which was already estimated to be insufficient by Renewi, is decreasing in the Netherlands since existing landfills will be scaled down in the future and no new landfills will be added.
- Landfilled waste which contains inorganic leachable solids (like NaCl) would possibly be classified as hazardous waste, which can bring additional complexities to the treatment of the evaporation residues.

- Finally only waste treatment possibilities in the Netherlands were considered. Exporting the waste was considered out-of-scope. Renewi stated that it is unlikely that export permits would be granted for this.

Annex Table 10: Overview alternative treatment options per residual stream

			Capacity available?	**Alternative treatment**
Nobian	Pekelwinning	1. Boorspoeling	No	De-water + landfilling residue
		2. Boorgruis	Yes*	Cleaned as sand
	Pekelzuivering	3. Slurry	No	Filtration + landfill residue, re-use brine
	Zoutindamping	4A. Moederloog	No	De-water + landfilling residue
		4B. Concentraatspui	No	De-water + landfilling residue
		5. Zoutoplossing zuren	Excluded from analysis, essential flow for production	
		6. Proceswater	Excluded from analysis, essential flow for production	
Salins	Zoutdroog /zeef	7. Zoutoplossing natwassers, zoutdroog/zeef	No	De-water + sold as road salt
	Librox	8. Zoutoplossing natwassers (Librox)	Excluded from analysis, essential flow for production	
		9. Stofzout cyclonen	No	Landfilling residue
		10. Veeg-, morszout, off spec	No	Landfilling residue
Nobian	Verpakking	11. Off spec broxo	No	Landfilling residue
		12. Off spec overige zouten	Excluded from analysis, sold as road salt	

**Capacity for sand cleaning is available, however, currently, not much infrastructure projects are available to use cleaned sand. Therefore, sand cleaning companies usually only take in material when selling of the sand can be guaranteed.*

Annex C Life cycle inventory

Annex C.1 General inputs

In this study, data for energy use, transport distances and costs of the different process steps were collected. A summary is provided in Annex Table 11.

Annex Table 11: General inputs for the LCA models

	Quantity	Unit	Source
Electricity de-watering	0.023279	MWh/m3	Brine crystallization in Hengelo
Electricity source	Hengelo electricity contract		Nobian Energy team
Amount of electricity	Dependent on the required pressure difference for pumping, see LCI by flow		Nobian experts
Transport distance for waste treatment	200	km	Nobian experts
Transport mode, waste treatment	Truck	-	Nobian experts
Transport distance sand	200	km	Nobian experts
Transport mode, sand	Barge, inland waterways	-	Nobian experts
Electricity	€ 73.00	€/MWh	PBL report ‘Klimaat- en Energieverkenning 2022’
Tap water	€ 0.56	€/t	Ecoinvent 3.9.1
Transport	€ 0.08	€/tkm	Renewi
Road salt (if sold)	€ -35.00	€/t	Nobian (value is profit value)
Treatment "steekvast materiaal" (sand cleaning)	€45.00	€/t	Renewi
Treatment landfill (residues)	€ 100.00	€/t	Renewi
Alternative stabilisation material (sand) for cavern stabilization	€ 10.00 (sand)	€/t	Nobian

Electricity grid mix

For the purchased electricity, background Ecoinvent datasets were used (see Annex D). For the environmental impact of Nobian’s own production, the LCA’s performed with 2021 data was used. In 2021, however, Nobian Rotterdam produced no net electricity, and the environmental performance for production in Nobian Delfzijl (Delesto 1) was taken as a proxy in this study.

Annex Table 12: Overview of all electricity sources used by Dutch Nobian sites

Purchased and own-produced electricity for Dutch sites		
Nobian Own Production (remaining after internal use of Energy plants)	**MWh**	**Share (%)**
Own production (natural gas-based)	788,461	48.9%
Total volumes for allocation of 'Renewable Production' (green)		
External production - Krammer/Bouwdokken (wind)	11,127	0.7%
External production - Eneco EU Wind	219,000	13.6%
External production - RWE biomass GvO's (Biomass)	318,750	19.8%
External production - BGR GVO's (Biomass Eneco)	158,608	9.8%
External production – municipal waste incineration	115,332	7.2%
Total volume for allocation of 'Vattenfall' supply (natural gas-based)		
External production – natural gas	567	0.04%
Total available electricity Dutch sites	1,611,845	100%

Annex C.2 Inputs and outputs by residual stream

Annex C.2.1 Boorspoeling

Annex Table 13: Inputs and outputs of flow 1. Boorspoeling

Current situation			
Inputs			
Name	**Quantity**	**Unit**	**Costs (€)**
Electricity (for pumping)	0.28	MWh	€ 20
Outputs			
N/A			
Alternative Treatment			
Inputs			
Name	**Quantity**	**Unit**	**Costs (€)**
Electricity (for pumping)	0.03	MWh	€ 2
Electricity (for evaporation)	13.90	MWh	€ 1,015
Outputs			
Name	**Quantity**	**Unit**	**Costs (€)**
Waste transport	56009	tkm	€ 4,201
Waste treatment, landfill	280	t	€ 28,004

Annex C.2.2 Boorgruis

Annex Table 14: Inputs and outputs of flow 2. Boorgruis

Current situation			
Inputs			
Name	**Quantity**	**Unit**	**Costs (€)**
Electricity (for pumping)	0.12	MWh	€ 9
Outputs			
N/A			
Alternative Treatment			
Inputs			
N/A			
Outputs			
Name	**Quantity**	**Unit**	**Costs (€)**
Waste transport	98314	tkm	€ 7,374
Sand cleaning	492	t	€ 22,121

Annex C.2.3 Slurry

Annex Table 15: Inputs and outputs of flow 3. Slurry

Current situation			
Inputs			
Name	**Quantity**	**Unit**	**Costs (€)**
Electricity (for pumping)	169.12	MWh	€ 12,346
Outputs			
N/A			
Alternative Treatment			
Inputs			
Name	**Quantity**	**Unit**	**Costs (€)**
Electricity (for pumping)	16.91	MWh	€ 1,235
Outputs			
Name	**Quantity**	**Unit**	**Costs (€)**
Waste transport	53655000	tkm	€ 4,024,125
Waste treatment, landfill	268275	t	€ 26,827,500

Annex C.2.4 Moederloog

Annex Table 16: Inputs and outputs of flow 4a. Moederloog

Current situation			
Inputs			
Name	**Quantity**	**Unit**	**Costs (€)**
Electricity (for pumping)	25.93	MWh	€ 1,893
Outputs			
N/A			
Alternative Treatment			
Inputs			
Name	**Quantity**	**Unit**	**Costs (€)**
Electricity (for pumping)	2.78	MWh	€ 203
Electricity (for evaporation)	1396.76	MWh	€ 101,964
Outputs			
Name	**Quantity**	**Unit**	**Costs (€)**
Waste transport	7590389	tkm	€ 569,279
Waste treatment, landfill	37952	t	€ 3,795,194

Annex C.2.5 Concentraatspui

Annex Table 17: Inputs and outputs of flow 4b. Concentraatspui

Current situation			
Inputs			
Name	**Quantity**	**Unit**	**Costs (€)**
Electricity (for pumping)	5.56	MWh	€ 406
Outputs			
N/A			
Alternative Treatment			
Inputs			
Name	**Quantity**	**Unit**	**Costs (€)**
Electricity (for pumping)	2.78	MWh	€ 203
Electricity (for evaporation)	1396.76	MWh	€ 101,964
Outputs			
Name	**Quantity**	**Unit**	**Costs (€)**
Waste transport	6853566	tkm	€ 514,017
Waste treatment, landfill	34268	t	€ 3,426,783

Annex C.2.6 Zoutoplossing natwassers, zoutdroog/zeef

Annex Table 18: Inputs and outputs of flow 7. Zoutoplossing natwassers, zoutdroog/zeef

Current situation			
Inputs			
Name	**Quantity**	**Unit**	**Costs (€)**
Electricity (for pumping)	68.92	MWh	€ 5,031
Outputs			
N/A			
Alternative Treatment			
Inputs			
Name	**Quantity**	**Unit**	**Costs (€)**
Electricity (for pumping)	7.13	MWh	€ 520
Electricity (for evaporation)	3585.02	MWh	€ 261,706
Outputs			
Name	**Quantity**	**Unit**	**Costs (€)**
Transport of salt	0	tkm	€ 0
Sales of salt	47304	t	-€ 1,655,640

Annex C.2.7 Stofzout cyclonen

Annex Table 19: Inputs and outputs of flow 9. Stofzout cyclonen

Current situation			
Inputs			
Name	**Quantity**	**Unit**	**Costs (€)**
Electricity (for pumping)	8.92	MWh	€ 651
Water, for dissolving	16940	t	€ 9,483
Outputs			
N/A			
Alternative Treatment			
Inputs			
N/A			
Outputs			
Name	**Quantity**	**Unit**	**Costs (€)**
Waste transport	1564000	tkm	€ 117,300
Waste treatment, landfill	7820	t	€ 782,000

Annex C.2.8 Veeg-, morszout, off spec

Annex Table 20: Inputs and outputs of flow 10. Veeg-, morszout, off spec

Current situation			
Inputs			
Name	**Quantity**	**Unit**	**Costs (€)**
Electricity (for pumping)	2.10	MWh	€ 153
Water, for dissolving	3986	t	€ 2,231
Outputs			
N/A			
Alternative Treatment			
Inputs			
N/A			
Outputs			
Name	**Quantity**	**Unit**	**Costs (€)**
Waste transport	368000	tkm	€ 27,600
Waste treatment, landfill	1840	t	€ 184,000

Annex C.2.9 Off spec broxo

Annex Table 21: Inputs and outputs of flow 11. Off spec broxo

Current situation			
Inputs			
Name	**Quantity**	**Unit**	**Costs (€)**
Electricity (for pumping)	0.34	MWh	€ 25
Water, for dissolving	650	t	€ 364
Outputs			
N/A			
Alternative Treatment			
Inputs			
N/A			
Outputs			
Name	**Quantity**	**Unit**	**Costs (€)**
Waste transport	60000	tkm	€ 4,500
Waste treatment, landfill	300	t	€ 30,000

Annex C.3 Inputs and outputs of alternative stabilisation

Alternative stabilisation is modelled separately, and allocated based on flow volume. The inputs and outputs for the alternative stabilisation are given in Annex Table 22.

Annex Table 22: Inputs and outputs of cavern stabilisation

Current situation				
Inputs				
N/A				
Outputs				
N/A				
Alternative Treatment				
Inputs				
	Name	**Quantity**	**Unit**	**Costs (€)**
All cases	Electricity (for pumping)	243.32	MWh	€ 17,762
	Brine	484905	m3	N/A
Sand as filler	Sand	218207	t	€ 2,182,071
	Sand transport	43641423	tkm	€ 3,273,107
Granulite as filler (sensitivity analysis)	Granulite	231603	t	€ 1,158,013
	Granulite transport, sea	259394918	tkm	Included in costs granulite
	Granulite transport, barge	46320521	tkm	
	Polyacrylamide	23160	kg	
	Dry salt	10244	t	N/A
Outputs				
N/A				

Annex D Life cycle datasets and database sources

Overview of all Ecoinvent datasets that were used.

Annex Table 23: List of ecoinvent 3.9.1 datasets used

Process	Dataset (all Ecoinvent 3.9.1)
Materials	
Water (tap)	Europe without Switzerland: market for tap water
Sand extraction for cavern stabilisation	RoW: sand quarry operation, extraction from river bed (proxy)
Granulite production for cavern stabilisation	RoW: limestone production, crushed, washed (proxy)
Acrylamide (for granulite cleaning)	GLO: polyacrylamide production
Waste treatment	
Treatment of sand-like material (for 'boorgruis')	CH: treatment of waste concrete gravel, recycling
Landfill of salt-containing solid residues	RoW: treatment of salt tailing from potash mine, residual material landfill
Transport	
Transport, truck (for waste)	RER: transport, freight, lorry 16-32 metric ton, EURO4
Transport, inland barge (for sand/granulite)	RER: transport, freight, inland waterways, barge
Transport, sea bulk carrier (for granulite)	GLO: transport, freight, sea, bulk carrier for dry goods
Electricity	
Wind NL	NL: electricity production, wind, >3MW turbine, onshore
Wind Norway	NO: electricity production, wind, >3MW turbine, onshore
Biomass (virgin wood)	NL: heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014
Municipal waste incineration	NL: electricity, from municipal waste incineration to generic market for electricity, medium voltage
Natural gas	NL: electricity production, natural gas, conventional power plant

For all electricity sources, transmission and subsequent losses are modelled. Electricity transmission is modelled based on the inputs & outputs of the process 'NL: market for electricity, high voltage' (ecoinvent 3.9.1), which includes transmission losses, transmission network infrastructure, and direct emissions to air (Annex Table 24).

Annex Table 24: transmission modelling for Hengelo electricity

	Quantity	Dataset (Ecoinvent 3.9.1)
Inputs		
Electricity high voltage	1.02 kWh	Different sources, as indicated in Annex Table 12
Transmission network	3.05249-06 m	GLO: transmission network, electricity, high voltage
Outputs		
Electricity	1 kWh	Electricity, high voltage
Nitrous oxide	5.00E-06 kg	Nitrous oxide (laughing gas) [Inorganic emissions to air]
Ozone	4.16E-06 kg	Ozone [Inorganic emissions to air]

The electricity models and salt datasets are both based on supplier specific LCA models, mostly Nobian's own internal models. The dataset for de-icing salt is used for giving an environmental credit for salt sales. Dry salt & brine are used in the preparation of the alternative cavern stabilisation filling materials. The full overview is shown in Annex Table 25.

Annex Table 25: List of Nobian specific datasets used

Process	Dataset (Nobian LCA Models)
Electricity	
Delfzijl own-generated	Electricity, from Delesto 1, DFZ 2021
Delfzijl own-generated	Electricity, from Delesto 2, DFZ 2021
Hengelo own-generated	Electricity, HEN 2021
Rotterdam own-generated	Electricity, from Delesto 1, DFZ 2021 (proxy)
Eneco BGR (supplier dataset)	Electricity, from Eneco BGR
Salt	
De-icing salt (credit for salt sales)	De-icing salt, DFZ 2021
Dry salt (for saturation granulite)	Dry salt, DFZ 2021
Brine (for mixing with sand & granulite)	Brine production, HEN 2021

Annex E Results Tables

Annex E.1 Life Cycle Impact Assessment Results

Life Cycle Impact Assessment results are presented in separate tables for both Scenarios, where a breakdown is given to the different contributions. Then the total impact of both scenarios is compared to the impact of the alternative scenario in the sensitivity analyses.

Annex Table 26: LCIA results for Scenario 1: current situation, including contribution analysis

	Pumps	Water	TOT
EF 3.1 Acidification [Mole of H+ eq.]	1.94E+02	3.63E+01	2.30E+02
EF 3.1 Climate Change - total [kg CO2 eq.]	6.08E+04	6.66E+03	6.75E+04
EF 3.1 Ecotoxicity, freshwater - total [CTUe]	8.45E+04	3.05E+04	1.15E+05
EF 3.1 Eutrophication, freshwater [kg P eq.]	2.91E+00	4.39E+00	7.30E+00
EF 3.1 Eutrophication, marine [kg N eq.]	5.85E+01	7.13E+00	6.56E+01
EF 3.1 Eutrophication, terrestrial [Mole of N eq.]	8.34E+02	6.78E+01	9.02E+02
EF 3.1 Human toxicity, cancer - total [CTUh]	2.54E-05	2.99E-05	5.53E-05
EF 3.1 Human toxicity, non-cancer - total [CTUh]	5.15E-04	3.89E-04	9.04E-04
EF 3.1 Ionising radiation, human health [kBq U235 eq.]	6.91E+02	2.52E+03	3.21E+03
EF 3.1 Land Use [Pt]	2.56E+06	2.65E+04	2.58E+06
EF 3.1 Ozone depletion [kg CFC-11 eq.]	6.92E-03	1.88E-04	7.11E-03
EF 3.1 Particulate matter [Disease incidences]	1.99E-03	3.44E-04	2.33E-03
EF 3.1 Photochemical ozone formation, human health [kg NMVOC eq.]	1.85E+02	2.48E+01	2.10E+02
EF 3.1 Resource use, fossils [MJ]	1.15E+06	1.35E+05	1.29E+06
EF 3.1 Resource use, mineral and metals [kg Sb eq.]	1.72E-01	3.48E-02	2.07E-01
EF 3.1 Water use [m³ world equiv.]	2.66E+03	9.12E+05	9.14E+05

Annex Table 27: LCIA results Scenario 1: current scenario, including contribution per flow

	01	02	03	04a	04b	07	09	10	11	TOT
EF 3.1 Acidification [Mole of H+ eq.]	1.90E-01	8.12E-02	1.16E+02	1.79E+01	3.83E+00	4.75E+01	3.46E+01	8.14E+00	1.33E+00	2.30E+02
EF 3.1 Climate Change - total [kg CO2 eq.]	5.98E+01	2.55E+01	3.65E+04	5.61E+03	1.20E+03	1.49E+04	7.16E+03	1.68E+03	2.75E+02	6.75E+04
EF 3.1 Ecotoxicity, freshwater - total [CTUe]	8.31E+01	3.54E+01	5.08E+04	7.79E+03	1.67E+03	2.07E+04	2.66E+04	6.26E+03	1.02E+03	1.15E+05
EF 3.1 Eutrophication, freshwater [kg P eq.]	2.86E-03	1.22E-03	1.75E+00	2.68E-01	5.74E-02	7.12E-01	3.54E+00	8.33E-01	1.36E-01	7.30E+00
EF 3.1 Eutrophication, marine [kg N eq.]	5.75E-02	2.45E-02	3.51E+01	5.39E+00	1.16E+00	1.43E+01	7.45E+00	1.75E+00	2.86E-01	6.56E+01
EF 3.1 Eutrophication, terrestrial [Mole of N eq.]	8.21E-01	3.50E-01	5.02E+02	7.69E+01	1.65E+01	2.05E+02	7.97E+01	1.88E+01	3.06E+00	9.02E+02
EF 3.1 Human toxicity, cancer - total [CTUh]	2.50E-08	1.06E-08	1.53E-05	2.34E-06	5.02E-07	6.22E-06	2.43E-05	5.72E-06	9.32E-07	5.53E-05
EF 3.1 Human toxicity, non-cancer - total [CTUh]	5.07E-07	2.16E-07	3.10E-04	4.75E-05	1.02E-05	1.26E-04	3.22E-04	7.57E-05	1.23E-05	9.04E-04
EF 3.1 Ionising radiation, human health [kBq U235 eq.]	6.80E-01	2.90E-01	4.16E+02	6.38E+01	1.37E+01	1.69E+02	2.00E+03	4.71E+02	7.68E+01	3.21E+03
EF 3.1 Land Use [Pt]	2.51E+03	1.07E+03	1.54E+06	2.36E+05	5.05E+04	6.26E+05	1.02E+05	2.40E+04	3.91E+03	2.58E+06
EF 3.1 Ozone depletion [kg CFC-11 eq.]	6.81E-06	2.90E-06	4.16E-03	6.38E-04	1.37E-04	1.70E-03	3.67E-04	8.63E-05	1.41E-05	7.11E-03
EF 3.1 Particulate matter [Disease incidences]	1.96E-06	8.34E-07	1.20E-03	1.83E-04	3.93E-05	4.88E-04	3.33E-04	7.84E-05	1.28E-05	2.33E-03
EF 3.1 Photochemical ozone formation, human health [kg NMVOC eq.]	1.82E-01	7.76E-02	1.11E+02	1.71E+01	3.66E+00	4.54E+01	2.54E+01	5.97E+00	9.73E-01	2.10E+02
EF 3.1 Resource use, fossils [MJ]	1.13E+03	4.84E+02	6.93E+05	1.06E+05	2.28E+04	2.83E+05	1.43E+05	3.36E+04	5.48E+03	1.29E+06
EF 3.1 Resource use, mineral and metals [kg Sb eq.]	1.70E-04	7.23E-05	1.04E-01	1.59E-02	3.41E-03	4.23E-02	3.28E-02	7.72E-03	1.26E-03	2.07E-01
EF 3.1 Water use [m^3 world equiv.]	2.62E+00	1.12E+00	1.60E+03	2.45E+02	5.26E+01	6.52E+02	7.16E+05	1.68E+05	2.75E+04	9.14E+05

Flow 01. Boorspoeling, flow 02. Boorgruis, flow 03. Slurry, flow 04a. Moederloog, flow 04b. Concentraatspui, flow 07. Zoutoplossing natwassers, zoutdroog/zeef, flow 09. Stofzout cyclonen, flow 10. Veeg-, morszout, offspec, flow 11. Off spec broxo

Annex Table 28: LCIA results Scenario 2: alternative treatment, including contribution analysis

	De-icing salt	Evaporation	Pumps	Stabilisation	Transport	Waste Treatment	TOT
EF 3.1 Acidification [Mole of H+ eq.]	-3.93E+01	4.40E+03	2.04E+01	3.06E+04	5.44E+04	2.30E+04	1.12E+05
EF 3.1 Climate Change - total [kg CO2 eq.]	-9.24E+03	1.38E+06	6.40E+03	3.57E+06	1.31E+07	3.34E+06	2.14E+07
EF 3.1 Ecotoxicity, freshwater - total [CTUe]	-5.35E+04	1.92E+06	8.90E+03	1.87E+07	9.12E+07	4.18E+07	1.54E+08
EF 3.1 Eutrophication, freshwater [kg P eq.]	-5.33E+00	6.60E+01	3.06E-01	2.63E+02	9.25E+02	3.72E+02	1.62E+03
EF 3.1 Eutrophication, marine [kg N eq.]	-1.05E+01	1.33E+03	6.16E+00	1.38E+04	2.08E+04	7.93E+03	4.39E+04
EF 3.1 Eutrophication, terrestrial [Mole of N eq.]	-7.21E+01	1.90E+04	8.79E+01	1.51E+05	2.21E+05	8.41E+04	4.76E+05
EF 3.1 Human toxicity, cancer - total [CTUh]	-1.15E-05	5.77E-04	2.67E-06	1.67E-03	6.30E-03	1.61E-03	1.01E-02
EF 3.1 Human toxicity, non-cancer - total [CTUh]	-2.88E-04	1.17E-02	5.43E-05	1.40E-02	1.18E-01	2.21E-02	1.65E-01
EF 3.1 Ionising radiation, human health [kBq U235 eq.]	-7.22E+02	1.57E+04	7.28E+01	9.48E+04	2.51E+05	6.26E+04	4.23E+05
EF 3.1 Land Use [Pt]	-8.93E+04	5.81E+07	2.69E+05	5.61E+08	1.12E+08	3.33E+08	1.06E+09
EF 3.1 Ozone depletion [kg CFC-11 eq.]	-5.48E-04	1.57E-01	7.29E-04	9.60E-02	2.88E-01	1.04E-01	6.45E-01
EF 3.1 Particulate matter [Disease incidences]	-2.37E-04	4.52E-02	2.10E-04	3.32E-01	8.76E-01	4.30E-01	1.68E+00
EF 3.1 Photochemical ozone formation, human health [kg NMVOC eq.]	-2.12E+01	4.21E+03	1.95E+01	4.29E+04	7.96E+04	3.20E+04	1.59E+05
EF 3.1 Resource use, fossils [MJ]	-1.43E+05	2.62E+07	1.21E+05	4.71E+07	1.89E+08	9.31E+07	3.56E+08
EF 3.1 Resource use, mineral and metals [kg Sb eq.]	-4.08E-01	3.92E+00	1.82E-02	4.34E+00	4.25E+01	5.56E+00	5.59E+01
EF 3.1 Water use [m³ world equiv.]	-4.80E+04	-1.85E+05	2.80E+02	2.41E+06	1.15E+06	4.54E+06	7.87E+06

Annex Table 29: LCIA results Scenario 2: alternative treatment, including contribution per flow

	01	02	03	04a	04b	07	09	10	11	TOT
EF 3.1 Acidification [Mole of H+ eq.]	1.01E+02	1.09E+02	7.76E+04	1.24E+04	8.52E+03	1.02E+04	2.77E+03	6.51E+02	1.06E+02	1.12E+05
EF 3.1 Climate Change - total [kg CO2 eq.]	1.97E+04	2.20E+04	1.47E+07	2.44E+06	1.91E+06	1.67E+06	4.89E+05	1.15E+05	1.87E+04	2.14E+07
EF 3.1 Ecotoxicity, freshwater - total [CTUe]	1.29E+05	1.49E+05	1.13E+08	1.67E+07	1.34E+07	5.78E+06	3.60E+06	8.47E+05	1.38E+05	1.54E+08
EF 3.1 Eutrophication, freshwater [kg P eq.]	1.44E+00	1.47E+00	1.15E+03	1.81E+02	1.41E+02	9.87E+01	3.79E+01	8.91E+00	1.45E+00	1.62E+03
EF 3.1 Eutrophication, marine [kg N eq.]	3.94E+01	4.41E+01	3.03E+04	4.76E+03	3.09E+03	4.25E+03	1.11E+03	2.61E+02	4.26E+01	4.39E+04
EF 3.1 Eutrophication, terrestrial [Mole of N eq.]	4.34E+02	4.73E+02	3.25E+05	5.21E+04	3.40E+04	4.90E+04	1.20E+04	2.81E+03	4.59E+02	4.76E+05
EF 3.1 Human toxicity, cancer - total [CTUh]	9.21E-06	1.02E-05	7.05E-03	1.15E-03	8.98E-04	7.37E-04	2.33E-04	5.48E-05	8.94E-06	1.01E-02
EF 3.1 Human toxicity, non-cancer - total [CTUh]	1.51E-04	1.75E-04	1.15E-01	1.91E-02	1.62E-02	9.85E-03	3.59E-03	8.45E-04	1.38E-04	1.65E-01
EF 3.1 Ionising radiation, human health [kBq U235 eq.]	3.78E+02	4.04E+02	2.97E+05	4.67E+04	3.40E+04	3.22E+04	1.02E+04	2.40E+03	3.92E+02	4.23E+05
EF 3.1 Land Use [Pt]	1.03E+06	3.93E+05	6.78E+08	1.16E+08	5.61E+07	1.75E+08	2.90E+07	6.83E+06	1.11E+06	1.06E+09
EF 3.1 Ozone depletion [kg CFC-11 eq.]	7.49E-04	4.77E-04	3.57E-01	8.62E-02	7.26E-02	1.12E-01	1.20E-02	2.82E-03	4.60E-04	6.45E-01
EF 3.1 Particulate matter [Disease incidences]	1.47E-03	3.86E-03	1.20E+00	1.84E-01	1.37E-01	1.10E-01	4.03E-02	9.49E-03	1.55E-03	1.68E+00
EF 3.1 Photochemical ozone formation, human health [kg NMVOC eq.]	1.40E+02	1.59E+02	1.11E+05	1.72E+04	1.18E+04	1.32E+04	3.95E+03	9.28E+02	1.51E+02	1.59E+05
EF 3.1 Resource use, fossils [MJ]	3.29E+05	3.13E+05	2.44E+08	4.09E+07	3.33E+07	2.65E+07	7.89E+06	1.86E+06	3.03E+05	3.56E+08
EF 3.1 Resource use, mineral and metals [kg Sb eq.]	5.11E-02	6.20E-02	3.93E+01	6.48E+00	5.54E+00	2.90E+00	1.22E+00	2.86E-01	4.67E-02	5.59E+01
EF 3.1 Water use [m³ world equiv.]	6.54E+03	2.71E+03	5.80E+06	8.27E+05	5.25E+05	4.38E+05	2.09E+05	4.91E+04	8.01E+03	7.87E+06

Flow 01. Boorspoeling, flow 02. Boorgruis, flow 03. Slurry, flow 04a. Moederloog, flow 04b. Concentraatspui, flow 07. Zoutoplossing natwassers, zoutdroog/zeef, flow 09. Stofzout cyclonen, flow 10. Veeg-, morszout, offspec, flow 11. Off spec broxo

Annex Table 30: Aggregated LCIA results of current situation and alternative treatment including sensitivity analyses

Impact categories		**Base case**	**Alternative treatment**	**Alternative (5% leaching)**	**Alternative (50km transport)**	**Alternative (granulite, economic)**	**Alternative (granulite, mass)**	**Alternative (boorgruis)**
Climate change	Climate Change (kg CO2 eq.)	6.75E+04	2.14E+07	2.14E+07	1.16E+07	2.11E+07	2.37E+07	2.14E+07
Ozone layer	Ozone depletion (kg CFC-11 eq.)	7.11E-03	6.45E-01	6.45E-01	4.29E-01	6.98E-01	7.35E-01	6.45E-01
Air quality & health	Human toxicity, cancer (CTUh)	5.53E-05	1.01E-02	1.01E-02	5.42E-03	1.04E-02	1.21E-02	1.01E-02
	Human toxicity, non-cancer (CTUh)	9.04E-04	1.65E-01	1.65E-01	7.70E-02	1.69E-01	1.81E-01	1.65E-01
	Ionising radiation, human health (kBq U235 eq.)	3.21E+03	4.23E+05	4.23E+05	2.35E+05	4.46E+05	4.74E+05	4.24E+05
	Particulate matter (Disease incidences)	2.33E-03	1.68E+00	1.68E+00	1.03E+00	1.44E+00	1.69E+00	1.68E+00
	Photochemical ozone formation, human health (kg NMVOC eq.)	2.10E+02	1.59E+05	1.59E+05	9.90E+04	1.47E+05	1.97E+05	1.59E+05
Effects on nature	Acidification (Mole of H+ eq.)	2.30E+02	1.12E+05	1.12E+05	7.16E+04	1.07E+05	1.69E+05	1.12E+05
	Ecotoxicity, freshwater (CTUe)	1.15E+05	1.54E+08	9.07E+08	8.52E+07	1.54E+08	1.75E+08	1.54E+08
	Eutrophication, freshwater (kg P eq.)	7.30E+00	1.62E+03	1.62E+03	9.28E+02	1.74E+03	1.90E+03	1.62E+03
	Eutrophication, marine (kg N eq.)	6.56E+01	4.39E+04	4.39E+04	2.83E+04	4.11E+04	5.72E+04	4.39E+04
	Eutrophication, terrestrial (Mole of N eq.)	9.02E+02	4.76E+05	4.76E+05	3.10E+05	4.41E+05	6.33E+05	4.76E+05
Resource use	Land Use (Pt.)	2.58E+06	1.06E+09	1.06E+09	9.80E+08	5.43E+08	5.71E+08	1.06E+09
	Resource use, fossils (MJ)	1.29E+06	3.56E+08	3.56E+08	2.14E+08	3.53E+08	3.85E+08	3.56E+08
	Resource use, mineral and metals (kg Sb eq.)	2.07E-01	5.59E+01	5.59E+01	2.40E+01	6.16E+01	6.55E+01	5.59E+01
	Water use (m^3 world equiv.)	9.14E+05	7.87E+06	7.87E+06	7.01E+06	1.08E+07	1.18E+07	7.87E+06

Annex E.2 PEF Results

The normalised & weighted results are presented in separate tables for both scenarios, where a breakdown is given to the different contributions. Then the total impact of both scenarios is compared to the impact of the alternative scenario in the sensitivity analyses. For background information, a table is given with the normalisation & weighting factors used.

Annex Table 31: PEF Score for Scenario 1: current situation, including contribution analysis

	Pumps	Water	TOT
Acidification	0.22	0.04	0.26
Climate Change - total	1.70	0.19	1.88
Ecotoxicity, freshwater - total	0.03	0.01	0.04
Eutrophication, freshwater	0.05	0.08	0.13
Eutrophication, marine	0.09	0.01	0.10
Eutrophication, terrestrial	0.18	0.01	0.19
Human toxicity, cancer - total	0.03	0.04	0.07
Human toxicity, non-cancer - total	0.07	0.06	0.13
Ionising radiation, human health	0.01	0.03	0.04
Land Use	0.25	0.00	0.25
Ozone depletion	0.01	0.00	0.01
Particulate matter	0.30	0.05	0.35
Photochemical ozone formation, human health	0.22	0.03	0.25
Resource use, fossils	1.48	0.17	1.65
Resource use, mineral and metals	0.20	0.04	0.25
Water use	0.02	6.76	6.78
Total PEF Score [pt.]	4.84	7.52	12.36

Annex Table 32: PEF Score for Scenario 1: current scenario, including contribution analysis by flow

	01	02	03	04a	04b	07	09	10	11	TOT
Acidification	0.00	0.00	0.13	0.02	0.00	0.05	0.04	0.01	0.00	0.26
Climate Change	0.00	0.00	1.02	0.16	0.03	0.42	0.20	0.05	0.01	1.88
Ecotoxicity, freshwater	0.00	0.00	0.02	0.00	0.00	0.01	0.01	0.00	0.00	0.04
Eutrophication, freshwater	0.00	0.00	0.03	0.00	0.00	0.01	0.06	0.01	0.00	0.13
Eutrophication, marine	0.00	0.00	0.05	0.01	0.00	0.02	0.01	0.00	0.00	0.10
Eutrophication, terrestrial	0.00	0.00	0.11	0.02	0.00	0.04	0.02	0.00	0.00	0.19
Human toxicity, cancer	0.00	0.00	0.02	0.00	0.00	0.01	0.03	0.01	0.00	0.07
Human toxicity, non-cancer	0.00	0.00	0.04	0.01	0.00	0.02	0.05	0.01	0.00	0.13
Ionising radiation, human health	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.01	0.00	0.04
Land Use	0.00	0.00	0.15	0.02	0.00	0.06	0.01	0.00	0.00	0.25
Ozone depletion	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Particulate matter	0.00	0.00	0.18	0.03	0.01	0.07	0.05	0.01	0.00	0.35
Photochemical ozone formation, human health	0.00	0.00	0.13	0.02	0.00	0.05	0.03	0.01	0.00	0.25
Resource use, fossils	0.00	0.00	0.89	0.14	0.03	0.36	0.18	0.04	0.01	1.65
Resource use, mineral and metals	0.00	0.00	0.12	0.02	0.00	0.05	0.04	0.01	0.00	0.25
Water use	0.00	0.00	0.01	0.00	0.00	0.00	5.31	1.25	0.20	6.78
Total PEF Score [pt.]	0.00	0.00	2.91	0.45	0.10	1.19	6.06	1.43	0.23	12.36

Flow 01. Boorspoeling, flow 02. Boorgruis, flow 03. Slurry, flow 04a. Moederloog, flow 04b. Concentraatspui, flow 07. Zoutoplossing natwassers, zoutdroog/zeef, flow 09. Stofzout cyclonen, flow 10. Veeg-, morszout, offspec, flow 11. Off spec broxo

Annex Table 33: PEF Score for Scenario 2: alternative treatment, including contribution analysis

	De-icing salt	Evaporation	Pumps	Stabilisation	Transport	Waste Treatment	TOT
Acidification	-0.04	4.91	0.02	34.14	60.67	25.69	125.39
Climate Change - total	-0.26	38.53	0.18	99.55	366.51	92.99	597.50
Ecotoxicity, freshwater - total	-0.02	0.65	0.00	6.33	30.88	14.15	52.00
Eutrophication, freshwater	-0.09	1.15	0.01	4.59	16.12	6.48	28.26
Eutrophication, marine	-0.02	2.01	0.01	20.94	31.49	12.01	66.44
Eutrophication, terrestrial	-0.02	3.98	0.02	31.74	46.48	17.66	99.87
Human toxicity, cancer - total	-0.01	0.71	0.00	2.06	7.78	1.98	12.53
Human toxicity, non-cancer - total	-0.04	1.67	0.01	2.00	16.84	3.16	23.64
Ionising radiation, human health	-0.01	0.19	0.00	1.12	2.98	0.74	5.03
Land Use	-0.01	5.63	0.03	54.38	10.81	32.27	103.10
Ozone depletion	0.00	0.19	0.00	0.12	0.35	0.13	0.78
Particulate matter	-0.04	6.80	0.03	49.98	131.87	64.69	253.34
Photochemical ozone formation, human health	-0.02	4.92	0.02	50.14	93.15	37.48	185.69
Resource use, fossils	-0.18	33.55	0.16	60.24	242.30	119.19	455.26
Resource use, mineral and metals	-0.48	4.65	0.02	5.14	50.39	6.60	66.33
Water use	-0.36	-1.37	0.00	17.89	8.51	33.69	58.37
Total PEF Score [pt.]	-1.60	108.17	0.51	440.38	1117.14	468.92	2133.52

Annex Table 34: PEF Score for Scenario 2: alternative treatment, including contribution analysis by flow

	01	02	03	04a	04b	07	09	10	11	TOT
Acidification	0.11	0.12	86.54	13.79	9.50	11.39	3.09	0.73	0.12	125.39
Climate Change	0.55	0.61	411.08	67.95	53.27	46.68	13.62	3.20	0.52	597.50
Ecotoxicity, freshwater	0.04	0.05	38.23	5.64	4.54	1.96	1.22	0.29	0.05	52.00
Eutrophication, freshwater	0.03	0.03	20.04	3.15	2.46	1.72	0.66	0.16	0.03	28.26
Eutrophication, marine	0.06	0.07	45.84	7.21	4.68	6.43	1.68	0.40	0.06	66.44
Eutrophication, terrestrial	0.09	0.10	68.12	10.94	7.13	10.29	2.51	0.59	0.10	99.87
Human toxicity, cancer	0.01	0.01	8.70	1.42	1.11	0.91	0.29	0.07	0.01	12.53
Human toxicity, non-cancer	0.02	0.03	16.48	2.73	2.32	1.41	0.51	0.12	0.02	23.64
Ionising radiation, human health	0.00	0.00	3.52	0.55	0.40	0.38	0.12	0.03	0.00	5.03
Land Use	0.10	0.04	65.70	11.27	5.44	16.97	2.81	0.66	0.11	103.10
Ozone depletion	0.00	0.00	0.43	0.10	0.09	0.14	0.01	0.00	0.00	0.78
Particulate matter	0.22	0.58	180.04	27.65	20.64	16.49	6.07	1.43	0.23	253.34
Photochemical ozone formation, human health	0.16	0.19	130.00	20.16	13.82	15.48	4.62	1.09	0.18	185.69
Resource use, fossils	0.42	0.40	312.58	52.38	42.63	33.97	10.10	2.38	0.39	455.26
Resource use, mineral and metals	0.06	0.07	46.65	7.69	6.58	3.44	1.44	0.34	0.06	66.33
Water use	0.05	0.02	43.05	6.14	3.89	3.25	1.55	0.36	0.06	58.37
Total PEF Score [pt.]	1.93	2.32	1477.02	238.77	178.51	170.90	50.31	11.84	1.93	2133.52

Flow 01. Boorspoeling, flow 02. Boorgruis, flow 03. Slurry, flow 04a. Moederloog, flow 04b. Concentraatspui, flow 07. Zoutoplossing natwassers, zoutdroog/zeef, flow 09. Stofzout cyclonen, flow 10. Veeg-, morszout, offspec, flow 11. Off spec broxo

Annex Table 35: Aggregated PEF Score of the current situation and alternative treatment including sensitivity analysis

Impact categories	Current situation	Alternative treatment	Alternative (5% leaching)	Alternative (50km transport)	Alternative (granulite, economic)	Alternative (granulite, mass)	Alternative (boorgruis)
Acidification	0.26	125.39	125.39	79.88	119.03	189.01	125.40
Climate Change - total	1.88	597.50	597.50	322.62	589.49	661.17	597.57
Ecotoxicity, freshwater - total	0.04	52.00	307.19	28.84	52.12	59.18	52.02
Eutrophication, freshwater	0.13	28.26	28.26	16.17	30.27	33.18	28.27
Eutrophication, marine	0.10	66.44	66.44	42.83	62.24	86.60	66.44
Eutrophication, terrestrial	0.19	99.87	99.87	65.01	92.64	132.86	99.87
Human toxicity, cancer - total	0.07	12.53	12.53	6.69	12.88	14.90	12.53
Human toxicity, non-cancer - total	0.13	23.64	23.64	11.01	24.20	25.86	23.64
Ionising radiation, human health	0.04	5.03	5.03	2.79	5.30	5.62	5.03
Land Use	0.25	103.10	103.10	94.99	52.64	55.32	103.14
Ozone depletion	0.01	0.78	0.78	0.52	0.84	0.89	0.78
Particulate matter	0.35	253.34	253.34	154.44	215.99	254.60	253.06
Photochemical ozone formation, human health	0.25	185.69	185.69	115.83	172.49	230.47	185.71
Resource use, fossils	1.65	455.26	455.26	273.53	452.19	492.99	455.39
Resource use, mineral and metals	0.25	66.33	66.33	28.53	73.07	77.69	66.33
Water use	6.78	58.37	58.37	51.99	80.50	87.33	58.42
Total PEF Score [pt.]	12.36	2133.52	2388.71	1295.66	2035.89	2407.68	2133.60

Annex Table 36: Normalisation (NF) and weighting (WF) factors provided for the PEF methodology (source: EF package)

Impact categories	Unit	NF	WF
Acidification	mol H+ eq./person	5.56E+01	6.20%
Climate change	kg CO_2 eq./person	7.55E+03	21.06%
Ecotoxicity, freshwater	CTUe/person	5.67E+04	1.92%
Eutrophication, freshwater	kg P eq./person	1.61E+00	2.80%
Eutrophication, marine	kg N eq./person	1.95E+01	2.96%
Eutrophication, terrestrial	mol N eq./person	1.77E+02	3.71%
Human toxicity, cancer	CTUh/person	1.73E-05	2.13%
Human toxicity, non-cancer	CTUh/person	1.29E-04	1.84%
Ionising radiation	kBq U-235 eq./person	4.22E+03	5.01%
Land use*	pt/person	8.19E+05	7.94%
Ozone depletion	kg CFC-11 eq./person	5.23E-02	6.31%
Particulate matter	disease incidences/person	5.95E-04	8.96%
Photochemical ozone formation	kg NMVOC eq./person	4.09E+01	4.78%
Resource depletion, fossils	MJ/person	6.50E+04	8.32%
Resource depletion, minerals and metals	kg Sb eq./person	6.36E-02	7.55%
Water use*	m^3 water eq of deprived water/person	1.15E+04	8.51%

*For the calculation of the NF of the impact categories "land use" and "water use", refer to Crenna et al (2019)

Source: Sala S, Cerutti AK, Pant R. (2018). Development of a weighting approach for Environmental Footprint. European Commission, Joint Research Centre, Publication Office of the European Union, Luxembourg. ISBN 978-92-79-68041-0.

Annex E.3 Total Cost of Ownership Results

The TCO results are presented in for both scenarios, where a breakdown is given to the different contributions. Then the total impact of both scenarios is compared to the impact of the alternative scenario in the sensitivity analyses.

Annex Table 37: Overview of total costs for Scenario 1: current situation and Scenario 2: alternative treatment, including sensitivity analyses

Scenario	Electricity, for pumping	Electricity, for evaporation	Transport	Waste treatment	Stabilisation material	Total (€)
Base	€ 20,533	-	-	€ 12,078	-	€ 32,610
Alternative	€ 19,925	€ 466,648	€ 8,541,503	€ 33,439,962	€ 2,182,071	€ 44,650,109
Alternative (50 km waste transport)[1]	€ 19,925	€ 466,648	€ 4,590,206	€ 33,439,962	€ 2,182,071	€ 40,698,812
Alternative (granulite)[2]	€ 19,925	€ 466,648	€ 5,268,396	€ 33,439,962	€ 1,175,775	€ 40,352,944
Alternative (boorgruis cleaning)[3]	€ 19,925	€ 466,648	€ 8,541,503	€ 33,516,156	€ 2,182,071	€ 44,726,302
Alternative (boorgruis landfill)[4]	€ 19,925	€ 466,648	€ 8,541,503	€ 33,466,999	€ 2,182,071	€ 44,677,145

1): Sensitivity analysis of the alternative treatment with 50 km transport to waste facilities.
2): Sensitivity analysis for granulite as alternative stabilisation material for caverns;
3): Sensitivity analysis for alternative treatment with higher costs for 'boorgruis' cleaning to recycling as sand;
4): Sensitivity analysis for alternative treatment with 'boorgruis' treated by landfilling instead of recycling as sand

Annex Table 38: TCO for both scenarios, including contribution analysis by flow

	01	02	03	04a	04b	07	09	10	11	TOT
Base	€ 20	€ 9	€ 12,346	€ 1,893	€ 406	€ 5,031	€ 10,133	€ 2,384	€ 389	€ 32,610
Alternative	€ 38,612	€ 31,787	€ 34,148,556	€ 5,008,398	€ 4,042,967	€ -2,900	€ 1,085,606	€ 255,437	€ 41,647	€ 44,650,109

Flow 01. Boorspoeling, flow 02. Boorgruis, flow 03. Slurry, flow 04a. Moederloog, flow 04b. Concentraatspui, flow 07. Zoutoplossing natwassers, zoutdroog/zeef, flow 09. Stofzout cyclonen, flow 10. Veeg-, morszout, offspec, flow 11. Off spec broxo