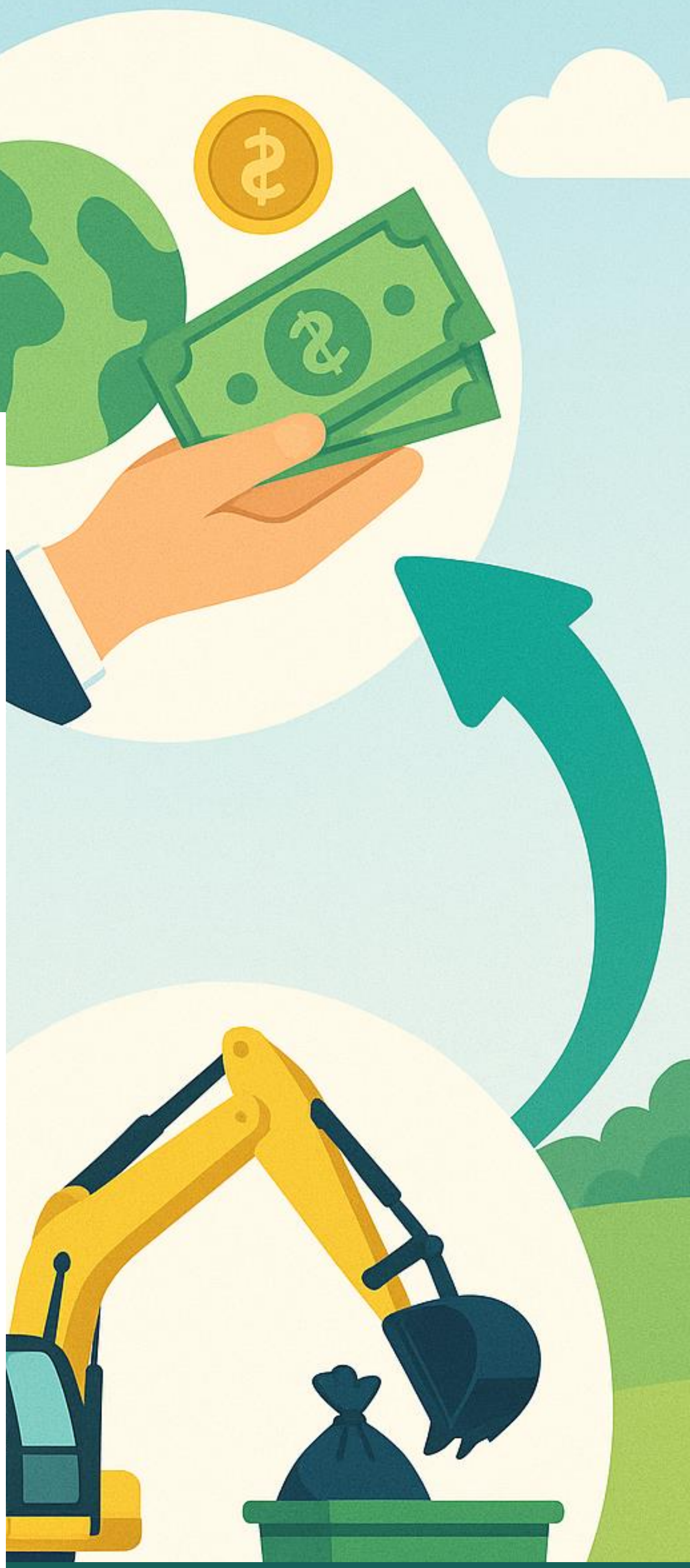

earthresQue

From Waste to Product: Assessing Circular and Linear Systems through LCA and CBA

May 2025

Senter for forskningsdrevet innovasjon

From Waste to Product: Assessing Circular and Linear Systems through LCA and CBA
Report no. 18
ISBN: 978-82-575-2999-4
RCN project 310042

Illustration front cover, header and end page: earthresQue
Publisher: NMBU – Norwegian University of Life Sciences

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Rescue of earth materials and wastes in the circular economy,
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Rapportbeskrivelse

Rapporttittel:	From Waste to Product: Assessing Circular and Linear Systems through LCA and CBA
earthresQue report no.:	18
ISBN:	978-82-575-2999-4
Dato:	2025-05-19
Rev.nr./ Rev.dato:	0
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Forskning

Privat sektor

Offentlig sektor

Summary

Landfilling is the most common waste management method for contaminated soil being excavated as part of infrastructure projects or construction sites in Norway. A more circular way of handling this type of waste is to recycle it with the aim of producing valuable construction products. In this study AF Decom's recycling facility, where they receive up to 150 000 tons of waste (contaminated soil) per year, has been used as a case to better understand circular systems. The plant produces secondary materials certified for concrete production, shotcrete, asphalt production, road base, and winter road grit. In 2024 and 2025, AF Decom published five environmental product declarations (EPD) for secondary/recycled materials.

By systematically assessing climate and land use impacts alongside socioeconomic costs, this study aimed to demonstrate how Life Cycle Assessment (LCA) and Cost-Benefit Analysis (CBA) are valuable decision-support tools for:

- Stakeholders managing contaminated soil to understand the necessity of a holistic perspective when comparing circular systems to linear alternatives to ensure a fair assessment; and
- Purchasers of construction materials with insight into how the definition and timing of the end-of-waste state significantly affect the environmental burdens assigned to recycled products.

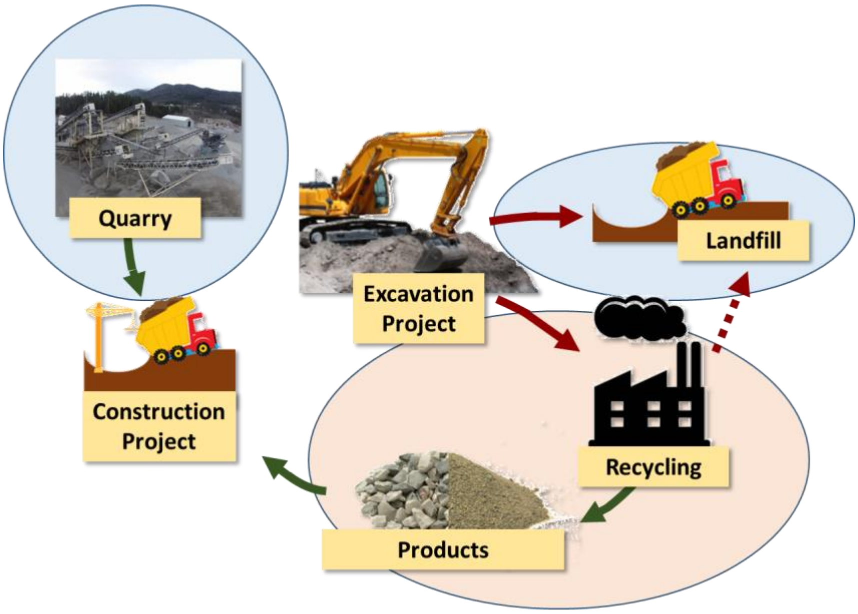
Life Cycle Assessment (LCA) methodology has been applied to compare circular and linear systems for treatment of contaminated soil. Different functional units and system boundaries were explored to assess the environmental performance of recycling, which can be considered both a waste treatment process and a production process and. Hence, recycling represents a multifunctional process. LCA with system expansion was used to assess the environmental impact of treating contaminated soil, while the production of secondary material from the same contaminated soil was assessed through an Environmental Product Declaration (EPD). The environmental impacts identified in the LCA was further used in a Cost-Benefit Analysis (CBA) where the broader socioeconomic impacts were assessed by monetizing climatic and land use effects for society.

The results from the waste management analysis of the contaminated soil, using Life Cycle Assessment (LCA) with system expansion, showed that the circular system leads to approximately 25% lower climate change impact and 60% reduced land use impact compared to the linear alternative. This highlights the importance of expanding the system boundaries to also account for the benefits of producing secondary products through the recycling process.

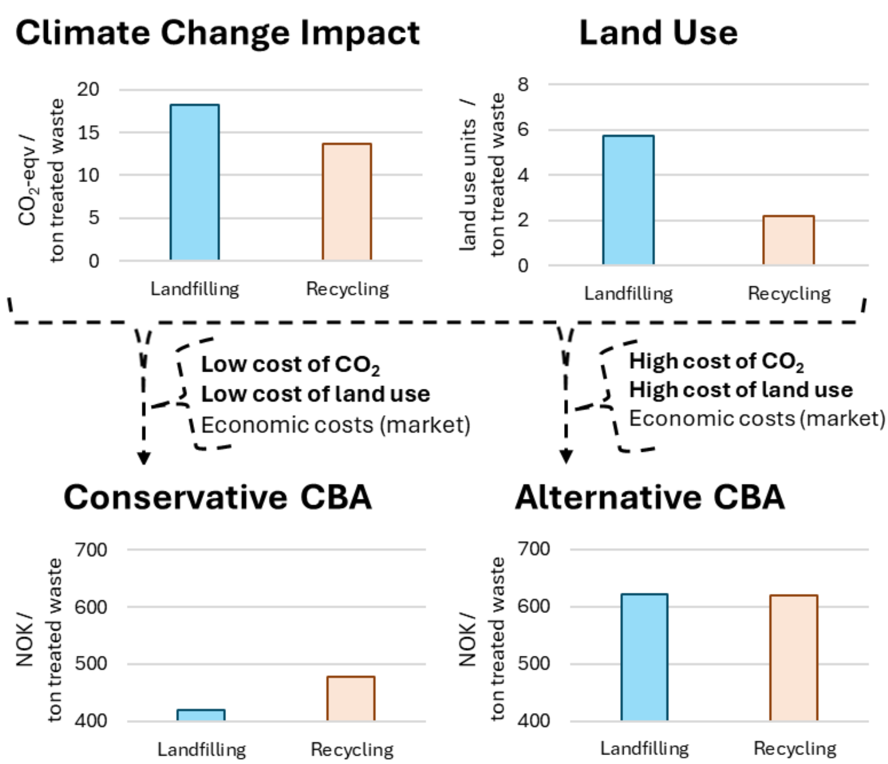
The Environmental Product Declaration (EPD) results further demonstrated the importance of the definition and timing of the end-of-waste state, as this determines how much of the recycling process' environmental impact should be allocated to the recycled product. Therefore, harmonizing the application of end-of-waste criteria is essential to ensure consistency and comparability in EPDs for recycled materials.

The cost-benefit analysis of the waste treatment systems shows that landfilling appears more favourable when conservative prices are used for climate and land use impacts. However, if the decision-makers choose to adopt recommended future valuations for carbon emissions and land

occupation, such as 11,730 NOK per ton CO_2 and 150 NOK/m² for land use, the trend shifts. Under these future pricing conditions, recycling becomes roughly equivalent to landfilling. This study does not fully account for the broader land use value, as it overlooks non-use values such as biodiversity loss. Overall, the CBA demonstrates how the inclusion of non-market values, alongside direct economic costs, can change the decision outcomes in favour of more circular systems.



Mass flows in linear (blue) and circular (red) systems for handling polluted soil. The linear system involves landfilling and virgin material use, while the circular system includes recycling with residuals sent to landfill.



The environmental impact for climate change (CO2-eqv.) and land use (m²a crop-eqv.) in the two systems were quantified by LCA. The outputs were further combined with cost estimates for climate, land use and market costs in a cost-benefit analysis (CBA)

Sammendrag

Deponering utgjør den vanligste metoden for håndtering av forurenset masse som graves ut i forbindelse med infrastruktur- og byggeprosjekter. En mer sirkulær tilnærming til håndtering av denne typen avfall er å resirkulere det med mål om å produsere sekundære byggevarer. I denne studien er AF Decoms gjenvinningsanlegg, som mottar nærmere 150 000 tonn forurenset jord per år, brukt som case for å få bedre innsikt i sirkulære systemer. Anlegget produserer sekundære materialer sertifisert for bruk i betongproduksjon, sprøytebetong, asfaltproduksjon, veifylling og strøgrus. I 2024 og 2025 publiserte AF Decom fem miljødeklarasjoner (EPD) for sekundære/resirkulerte materialer.

Studiens formål er, ved å systematisk å vurdere klima- og arealbrukseffekter sammen med samfunnsøkonomiske kostnader, å vise hvordan livsløpsanalyse (LCA) og kost-nytte-analyse (CBA) er verdifulle beslutningsverktøy for:

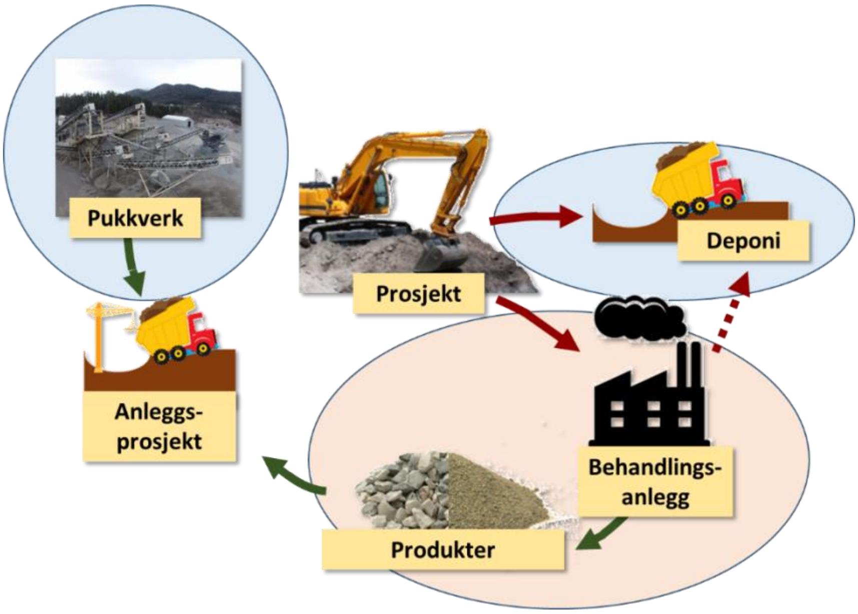
- Aktører som håndterer forurenset masse, for å forstå nødvendigheten av et helhetlig perspektiv når sirkulære systemer sammenlignes med lineære alternativer, og dermed å sikre en rettferdig og helhetlig vurdering; og
- Innkjøpere av byggematerialer, ved å gi innsikt i hvordan definisjon og tidspunktet for når avfallet ikke lenger regnes som avfall (end-of-waste) har stor betydning for miljøbelastningen som tilskrives resirkulerte produkter.

Livsløpsanalyse (LCA) er benyttet for å sammenligne sirkulære og lineære systemer for behandling av forurenset masse. Ulike funksjonelle enheter og systemgrenser ble benyttet for å vurdere miljøeffekten ved resirkulering, som både kan karakteriseres som en avfallsbehandlings- og en produksjonsprosess, og således representerer en multifunksjonell tjeneste. LCA med systemutvidelse ble brukt for å vurdere miljøpåvirkningen ved behandling av forurenset masse, mens produksjonen av sekundære materialer fra den samme massen ble vurdert ved bruk av miljødeklarasjoner (EPD). Miljøpåvirkningene som ble identifisert i livsløpsanalysen ble videre brukt inn i en kost-nytte-analyse (CBA), der de samfunnsøkonomiske konsekvensene ble vurdert ved å sette en kroneverdi på klima- og arealbrukseffekter.

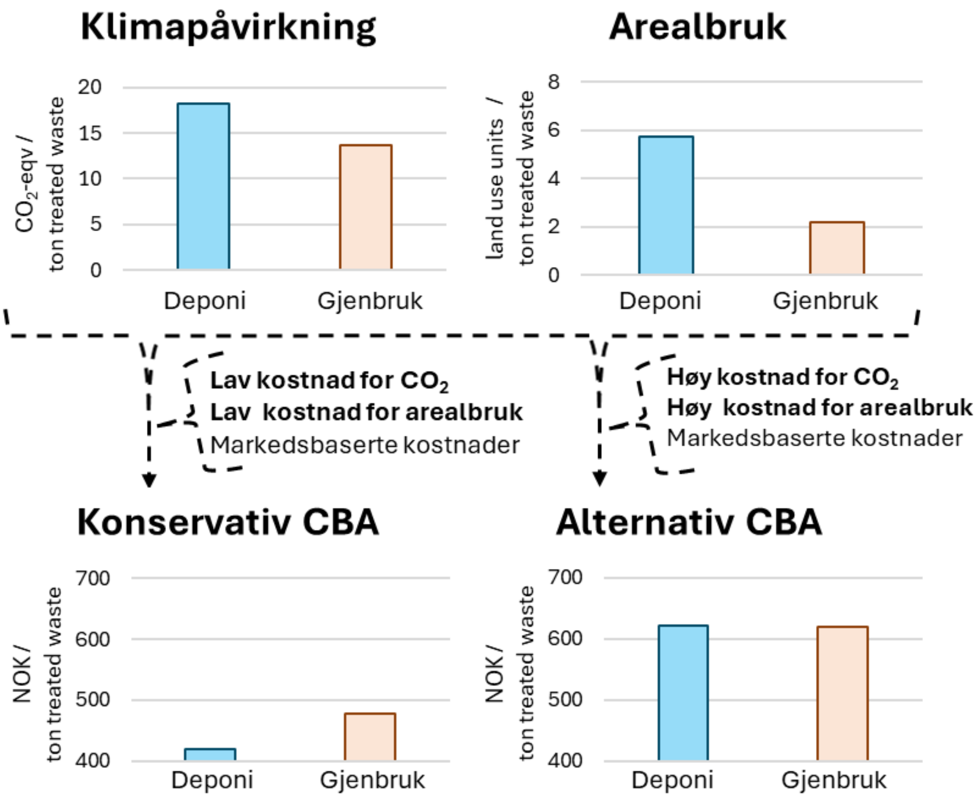
Resultatene fra analysen av avfallshåndtering av den forurensede massen som ble gjennomført med bruk av LCA med systemutvidelse, viser at det sirkulære systemet medfører omtrent 25 % lavere klimapåvirkning og 60 % lavere arealbrukseffekt sammenlignet med det lineære alternativet. Her kommer det frem hvor viktig det er å utvide systemet slik at det også tas hensyn til nytten ved at resirkuleringsprosessen produserer sekundære produkter til samfunnet. EPD-resultatene viser hvor avgjørende det er å definere når avfall ikke lenger skal defineres som avfall (end-of-waste) fordi dette bestemmer hvor stor del av resirkuleringsprosessen som skal tilskrives det resirkulerte produktet. Det er derfor er det viktig å harmonisere bruken av end-of-waste-kriterier for å sikre konsistens og sammenlignbarhet i EPDer for resirkulerte materialer.

Kost-nytte-analysen av avfallshåndteringssystemene viser at deponering fremstår som mer fordelaktig når konservative kostnader benyttes for klimagassutslipp og arealbrukspåvirkninger. Dersom beslutningstakere derimot velger å bruke anbefalte fremtidige verdier, som 11 730 NOK per tonn CO_2 og 150 NOK/m² for arealbruk, vil bildet endres og resirkulering blir omtrent like gunstig som deponering. Studien tar imidlertid ikke fullt ut høyde for bredere arealverdier, da den utelater ikke-bruksverdier som tap av biologisk mangfold. Totalt sett viser CBA-en hvordan

inkludering av ikke-markedsverdier, sammen med direkte økonomiske kostnader, kan endre beslutningsgrunnlaget i favør av mer sirkulære løsninger.



Massestrømmer i lineære (blå) og sirkulære (røde) systemer for håndtering av forurenset jord. Det lineære systemet innebærer deponering og bruk av jomfruelige materialer, mens det sirkulære systemet inkluderer resirkulering, med noe restavfall sendt til deponi.



Klimapåvirkning (CO_2-ekv.) og arealbruk (m^2a avlingsekv.) i de to systemene ble kvantifisert med livsløpsanalyse (LCA). Resultatene ble deretter kombinert med konservative og alternative kostnadsestimater for klima, arealbruk og markedsbaserte kostnader i en kost-nytte-analyse (CBA).

Content

1 Introduction

This work has been supported by the earthresQue centre for research driven innovation, Rescue of Earth Materials and Wastes in the Circular Economy, partly funded by the Research Council of Norway, project number 310042 /F40.

Landfilling is the most common waste management method for contaminated soil being excavated as part of infrastructure projects or construction sites in Norway. A more circular way of handling this type of waste is to recycle it with the aim of producing valuable construction products. In this study AF Decom's recycling facility, where they receive up to 150 000 tons of waste (contaminated soil) per year, has been used as a case to better understand circular systems.

The plant produces end materials certified for concrete production, achieving the EN12620 certification. The output products have also been certified for shotcrete while the aggregates are used in asphalt production (conforming to EN13043) and road base (conforming to EN13242. The recycling plant has also received certification to use their 2/8mm as winter road grit in 3 municipalities in Norway (https://www.cdegroup.com/about/case-studies/af-decom-norway). In 2024 and 2025, AF Decom published five environmental product declarations (EPD) for secondary/recycled materials produced at Nes Miljøpark:

- Vasket 0/4 mm (AF Decom, 2025)
- Blandet 0/8 mm (AF Decom, 2024a)
- Vasket, blandet 0/63 mm (AF Decom, 2024d)
- Vasket 6/16 mm (AF Decom, 2024b)
- Vasket 16/63 mm (AF Decom, 2024c)

Life Cycle Assessment (LCA) methodology has been applied to compare circular and linear systems for treatment of contaminated soil. Different functional units and system boundaries were explored to assess the environmental performance of recycling, which can be considered both a waste treatment process and a production process and. Hence, recycling represents a multifunctional process. The majority of the data for the LCA study is taken from Nørsterud (2022) and the above mentioned EPDs.

The environmental impacts identified in the LCA was further used in a Cost-Benefit Analysis (CBA) where the broader socioeconomic impacts were assessed by monetizing climatic and land use effects for society.

1.1 Aim of the study

Despite growing interest in circular solutions within the construction sector, considerable uncertainty remains regarding the overall benefits of recycling contaminated soil compared to landfilling. This uncertainty applies not only to the treatment of polluted masses, but also to the production and application of recycled construction materials.

By systematically assessing climate and land use impacts alongside socioeconomic costs, this study aimed to demonstrate how Life Cycle Assessment (LCA) and Cost-Benefit Analysis (CBA) are valuable decision-support tools for:

- Stakeholders managing contaminated soil to understand the necessity of a holistic perspective when comparing circular systems to linear alternatives in order to ensure a fair assessment; and
- Purchasers of construction materials with insight into how the definition and timing of the end-of-waste state significantly affect the environmental burdens assigned to recycled products.

2 Methods and systems

As described in chapter **Error! Reference source not found.**, the study applies LCA and CBA to compare linear and circular systems for contaminated soil being excavated as part of infrastructure projects or construction sites. The overall approach of these two methods is described in chapters 2.1 and 2.2 below. In addition, a brief overview of the major characteristics of each of the methods is presented in Table 1.

Table 1 Major characteristics of LCA and CBA

LCA (Life Cycle Assessment)	CBA (Cost-benefit analysis)
Focuses on environmental **flows** (e.g., emissions, land use, energy)	Focuses on **monetised impacts** (costs and benefits to society)
Scientific, **environmentally detailed**	**Economically comprehensive**, includes market and non-market values
Strong for evaluating **environmental performance**	Strong for evaluating **economic efficiency and trade-offs**
Often used for **comparative assessments** of products or systems, decision-support at different levels	Often used to support **investment, policy or regulation decisions**
Does **not assign monetary value** to impacts	Converts externalities (e.g. CO_2-emissions, land use) into **economic terms**

2.1 Life Cycle Assessment (LCA)

A Life Cycle Assessment (LCA) covers the whole life cycle of a product or service and is often associated with the term «cradle-to-cradle». By applying the LCA method, the potential environmental impacts along the lifecycle of a product or a service can be analysed and assessed. LCA represents a structured, comprehensive and internationally standardised (ISO, 2006b, 2006c) method for quantifying environmental and health impacts, resources consumed and resource depletion that are associated with any goods or services ("products"). It is applicable to products, processes, services and organisations, in order to document their environmental performance, to identify potentials for environmental improvements, to compare alternative options as well as to substantiate eco-labelling criteria. In accordance with the International Reference Life Cycle Data System (ILCD) Handbook (European Commission, 2010), Life Cycle Thinking and LCA create a scientific basis for supporting modern environmental policies and business decision support related to sustainable consumption and production.

A life cycle assessment is based on three fundamental principles:

- One considers the entire technical system required to produce, use and dispose the product (system analysis), and not just the product itself.
- One considers the entire material and energy flow through the value chain of the product, and not just an isolated process or activity.
- One considers several relevant environmental impact categories for the entire system, and not just one single environmental indicator (e.g. emissions of solvents or dust).

Furthermore, an LCA consists of four steps: The first step is to define the goal and scope, which create the basis for the system boundaries and the following steps of the assessment. The second step involves data collection for the system and establishing the life cycle inventory. The collected data is then categorised and characterised in the third step, according to the potential impact in different environmental impact categories. Interpretation of the results and the overall assessment represents the fourth and final step of an LCA.

2.1.1 Life Cycle Impact Assessment (LCIA) methods

In the impact assessment step of a LCA, all the collected consumption and emission data is assessed in terms of potential environmental impacts. There are several existing methods for life cycle impact assessments that quantify potential impacts within certain environmental categories. The impact categories range from Climate Change, Acidification, Ozone Depletion, Radiation, Human and Environmental Toxicity to usage of energy, scarce resources, water and land areas. A full scale LCA should cover a broad range of categories in order to avoid problem shifting (solving one problem while causing another), but it is common to select a few that can be considered most important for the system under study. This study has analysed the environmental impact categories climate change and land use.

Climate change

The impact category climate change has been assessed applying the life cycle impact assessment (LCIA) method ReCiPe midpoint (H) version 2016 (Huijbregts et al., 2017)

Land use

The land use LCIA category in ReCiPe 2016 Midpoint method addresses the agriculture land occupation potential (LOP), and includes the complete cycle of land transformation, occupation and relaxation, based on estimations of biodiversity damage potential (BDP). Land use is expressed by the unit m2*year crop equivalents and refers to the relative species loss caused by a specific land use (Huijbregts et al., 2017). The change of land cover leads to loss of habitat (and thus potential loss of species), and land-use intensification leads to soil disturbance. The characterisation factors for land transformation and occupation were developed on the basis of relative changes in species richness as estimated by de Baan, Alkemade, and Koellner (2013) and (Elshout, van Zelm, Karuppiah, Laurenzi, & Huijbregts, 2014). The effects of land relaxation are based on recovery times from Curran, Hellweg, and Beck (2014).
Conceptually, this approach assumes that a natural situation would be present had no land use occurred. Therefore, the species richness of the current, anthropogenic land use is compared with the natural reference, not accounting for any other anthropogenic land uses that might have been in place before the current land use. It follows that the impact of land transformation from one anthropogenic land use to another is not covered. Land use occupation is measured as area time (m2a), and

transformation is measured as area from and to (e.g. m2 from coniferous forest to sand extraction area).

2.2 Cost-benefit analysis (CBA)

Cost-benefit analysis (CBA) is a systematic method used to evaluate the anticipated or actual benefits and costs of a project, decision, process, or policy (Boardman, Greenberg, Vining, & Weimer, 2011). It involves a detailed comparison of the direct and indirect costs and benefits associated with different policies, decisions, or systems. Direct costs and benefits typically refer to the economic impacts on the individual or entity directly involved in or impacted by the activities evaluated in the CBA. For example, this might include transportation costs incurred by a firm when moving polluted soils to a landfill or washing facility. Indirect costs, on the other hand, encompass unintended effects on society, such as environmental, health, and land-use impacts.

In comparing alternative projects, CBA involves assessing the discounted costs and benefits over a specified timeframe, ensuring that future values are adjusted to reflect their present worth. The decision criteria often involve selecting the option with the highest net present value (NPV), where the benefits outweigh the costs. Market prices are used to value these costs and benefits when available. For goods and services without market prices, non-market valuation methods are used. The valuation approaches for market, and non-market goods are often guided by the Total Economic Value (TEV) framework, which carefully considers both use and non-use values to capture the full economic significance of the goods and services in question (Pascual et al., 2015; Tinch et al., 2019).

The cost-benefit analysis (CBA) in this study aims to highlight the societal impacts resulting from the decisions made by the owner of contaminated soil when choosing between landfilling and recycling 1 ton of polluted soil. In addition to assessing the direct financial costs borne by the owner, the analysis incorporates broader external impacts by monetizing indirect costs related to climate change and land occupation. These environmental impacts are derived from the underlying life cycle assessment (LCA), which supplies the data used to assign monetary values to non-market effects within the CBA framework.

2.3 Systems to be modelled

In this study we explore the implications of different functional units and system boundaries for the multi-functional system *recycling of contaminated soil from an excavation project*. The multi-functionality occurs as the system can be considered both a waste treatment service and a producer of recycled products. This is illustrated in Figure 1.

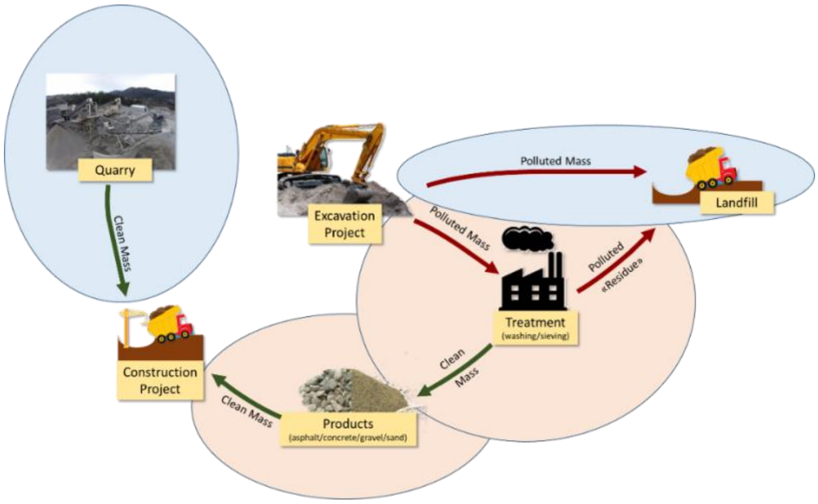


Figure 1 Treatment of excavated contaminated soil either in landfill or in a recycling plant which also produces recycled/secondary products to be used in new construction projects.

Figure 1 illustrates the multi-functionality of the recycling plant by the light red circles demonstrating the polluted mass being turned into clean mass in new products by a circular system. The light blue circles demonstrate the linear system where the polluted mass is landfilled which requires virgin masses to be extracted from quarries.

Both functions, treatment of polluted masses and production of material, can be compared to other alternatives and create the basis for decision support by different actors and stakeholders. This is illustrated in Figure 2.

Figure 2 Different actors/stakeholders along the circular value chain wanting decision-support for making the right choices.

The different questions asked by actors 1 and 2 in Figure 2 above, require different functions to be analysed and hence different system boundaries. In order to answer the question asked by the owner of the contaminated soil, an LCA of waste treatment of the contaminated soil can be performed. The purchaser's question, on the other hand, needs a product-oriented LCA, which present the environmental footprint at a product level, to support the decision. The different LCAs and associated system boundaries and comparisons are described in chapters 2.3.1and 2.3.2.

2.3.1 LCA and CBA of waste treatment

To support the owner of the contaminated soil in deciding which treatment method to be chosen, an LCA of waste treatment is recommended. Two or more relevant treatment solutions can then be analysed and compared, as illustrated in Figure 3.

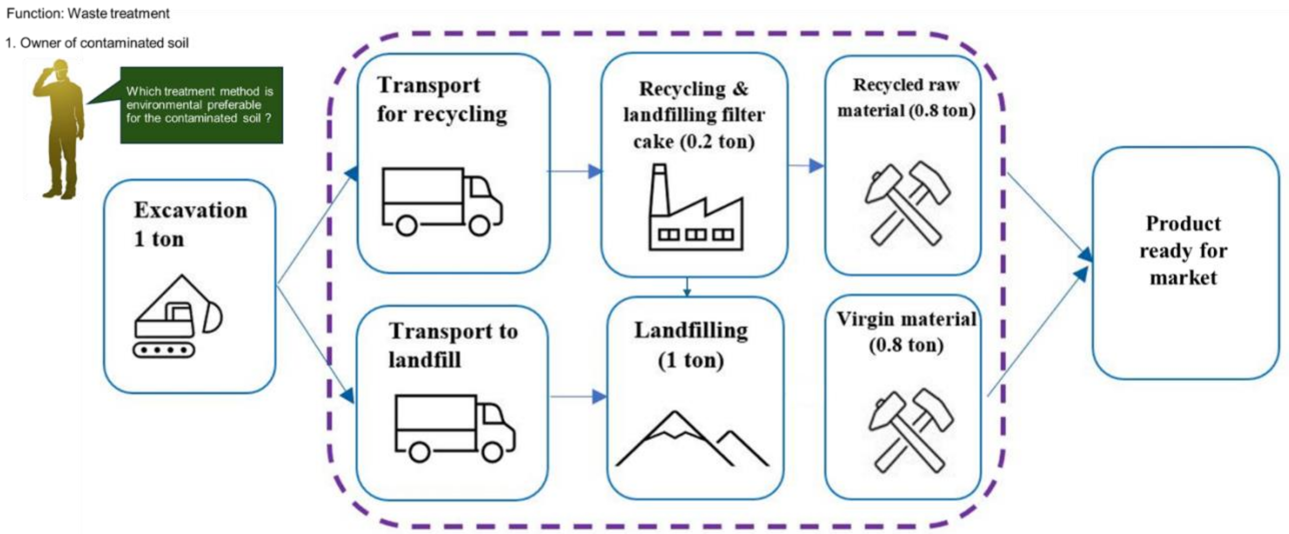


Figure 3 LCA of waste treatment with system expansion.

The two waste treatment methods recycling and landfilling with associated system boundaries are presented in Figure 3. Both systems start with transport to the respective locations followed by the waste treatment itself (recycling and landfill, respectively). The recycling systems end with the recycled material which is ready to be transported to the market (not included). The landfill system is expanded by virgin production of the same amount and quality as the recycled material as this system by itself does not produce any material. In order to fulfil the same functions to the society, the landfill system is expanded to include this extra function.

The functional unit for the analysis can be defined as: transport and waste treatment of 1 ton polluted excavated material, as well as supply of the same quality and amount of material to a market.

2.3.2 Product-oriented LCA

To support the purchaser of material in deciding which treatment method to choose, a product-oriented LCA of the material is recommended. This can be compared with LCAs representing corresponding material/products. However, in a product-oriented LCA, the multi-functionality of the recycling plant has to be allocated between the system generating the waste and the system utilising the recycled material. This is illustrated in Figure 4.

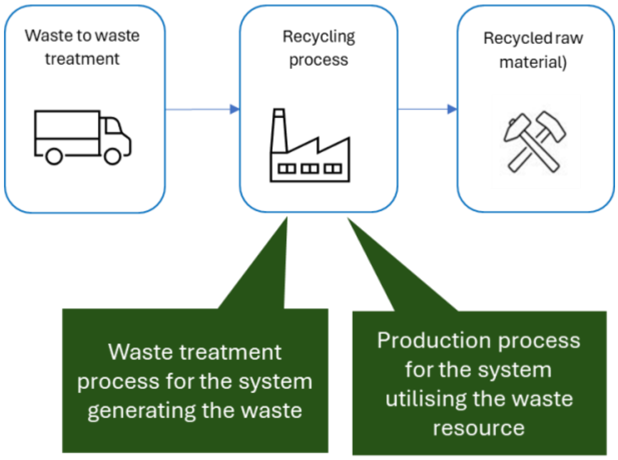


Figure 4 Allocation of a recycling process due to its multi-functionality.

As shown in Figure 4, recycling of material from one system to another means that allocation is needed because the same material belongs to two different systems. The choice of method for modelling material recycling can have a decisive impact on the environmental performance of products being analysed (Ekvall, Björklund, Sandin, & Jelse, 2020; Raadal, Saxegård, & Modahl, 2023). According to Ekvall et al. (2020), there are currently 12 different recycling modelling approaches in LCA for allocating the burdens and benefits of recycling between different stages of product cascade systems. These various product level approaches can generally be categorised according to one of the three principal approaches:

1. cut-off (also known as recycled content);
2. 50:50 approach methods; and
3. system expansion by substitution (also referred to as avoided burden, system reduction, cut-off plus credit).

The discussion concerning the choice of approach to apply has been ongoing since the early 90's but no consensus has yet been reached (Ekvall et al., 2020). The Circular -Footprint Formula (CFF) was, however, developed (Zampori & Pant, 2019) as part of the development of the EC environmental footprint (EF) method. The CFF formula is derived from the 50:50 approach, although it allocates shared end-of-life processes based on market dynamics between the previous and subsequent product, and includes material quality indexing (Allacker, Mathieux, Pennington, & Pant, 2017). According to Saxegård, Wikström, and Williams (2024), CFF is a harmonisation of existing product level methods.

An Environmental Product Declaration (EPD) is a product oriented LCA type III environmental declaration that is compliant with ISO 14025 (ISO, 2006a) and considers the full Life Cycle Assessment of goods and services. It can be used for all types of goods and services and are third-party verified which gives the information credibility and therefore is suitable for procurement. EPDs that are based on the same product category rules (PCR) are comparable as the PCR set the rules for the life cycle assessment that the EPD must meet, such as allocation rules, data quality requirements and system boundaries (EPD International, n.d.). EPD-Norge is the program operator for the Norwegian EPD programme and promotes cooperation and harmonisation with other environmental declaration programmes.

The European standard for EPDs of construction products EN 15804 *Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products* (CEN, 2019) divides the life cycle of a construction product into Modules A-C and require the results to be separately reported for each module. A cradle-to-grave EPD includes all three modules. The resulting system can be described as a cut-off approach, where the recycling activities are divided between the product being recycled and the product where the recycled material is used. The boundary between the life cycles is defined as the point where the recyclable material becomes a marketable product – the point of end-of-waste. A fourth module, Module D, includes benefits and loads that any net outflow of secondary material and energy causes in subsequent life cycles. This is the reason behind the name of this recycling modelling approach: Cut-off plus credit. The life cycle of modules for which the results shall be reported are typically illustrated in Figure 5.

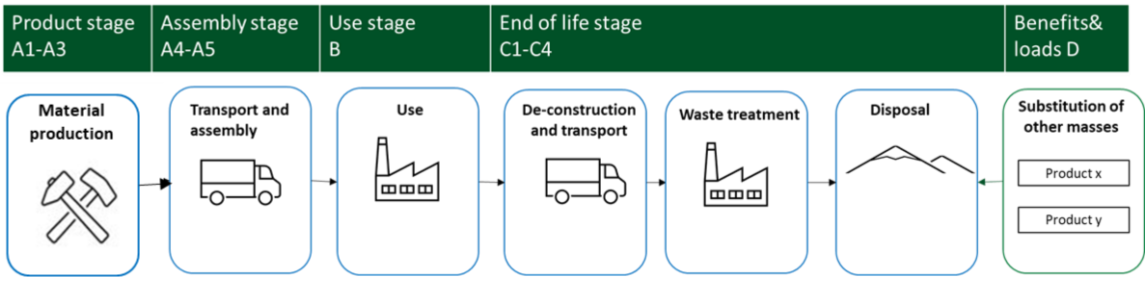


Figure 5 The life cycle stages and corresponding modules in an EPD according to EN 15804 (CEN, 2019).

The EPD system has been chosen as the methodological choice for product-oriented LCA in this study. In accordance with the General Programme Instructions for the international EPD System (EPD International, 2021), allocation of waste and hence use of recycled material shall follow the polluter pays principle and its interpretation in EN 15804 (CEN, 2019): "Processes of waste processing shall be assigned to the product system that generates the waste until the end-of-waste state is reached." Moreover, the end-of-waste state is reached when all the following criteria for the end-of-waste state are fulfilled (adapted from EN 15804):

- the recovered material, component or product is commonly used for specific purposes
- a market or demand, identified, e.g. by a positive economic value, exists for such a recovered material, component or product;
- the recovered material, component or product fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products; and
- the use of the recovered material, product or construction element will not lead to overall adverse environmental or human health impacts.

This means that the point to which the contaminated soil reaches its end-of-waste state is decisive for where the burdens from the recycling plant should be allocated in the EPD. This is illustrated in Figure 6.

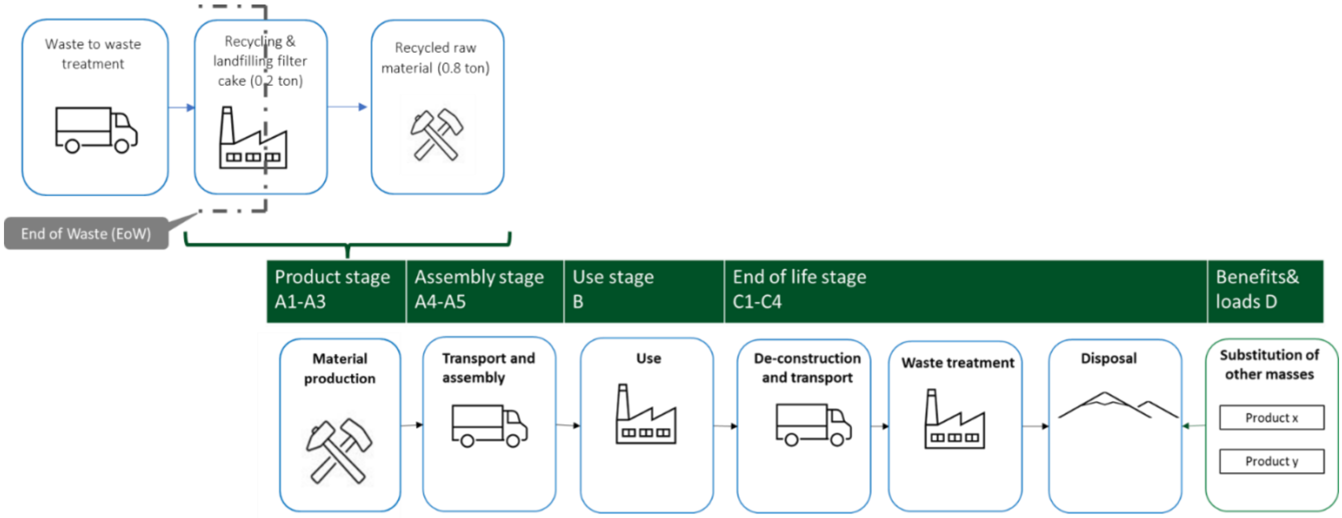


Figure 6 Allocation of recycling burdens dependent of when end-of-waste state is reached.

If end-of-waste state is reached before the recycling plant, then the burdens from the recycling plant are allocated to the recycled product. If end-of-waste state, on the other hand, is reached after the recycling plant means that the same burdens should be allocated to the waste. Hence, the recycled product has no burdens from the recycling process.

The end-of-waste criteria are also implemented in the Norwegian Pollution Act, chapter 5, §27 (Forurensningsloven, 1981).

3 Data and assumptions

3.1 Life Cycle Assessment (LCA)

The data applied for waste treatment of contaminated soil either in the recycling plant or at the landfill and related transports have been taken from Nørsterud (2022). The transport distances to landfill and recycling plant are 59.5 km and 54.5 km, respectively. Some updates have been made in this report with regard to the production of virgin material from quarries: Nørsterud (2022) based the environmental impact from the production of virgin material (0/8mm and 8/16 mm) using the average of four chosen EPDs. In this report, the virgin material production data is based on the minimum dataset value for climate change impact (fossil) for "knusetrinn 2" (includes crushing steps 0, 1 and 2) compiled from 30 Norwegian EPDs for crushed stone (Petrovic & Raadal, 2024). This value is 1.65 kg CO_2-eq/tonne product, while the number used in Nørsterud (2022) was 3.08 kg CO_2-eq/tonne product (average of four EPDs).

Data for land use for the recycling plant has been based on personal communication and from employees at AF Decom, while land use data related to landfill and quarries are taken from operating permits as well as historical aerial photographs (Nørsterud, 2022).

3.2 Cost-benefit Analysis (CBA)

3.2.1 Direct costs

The direct costs of handling 1 tonne of polluted soil through either landfilling (linear system) or recycling (circular system) are expressed in Norwegian kroner (NOK). For the linear system, the costs include transport to landfill, landfilling of the polluted soil, and the purchase of virgin materials equivalent in type and quantity to those recovered in the circular system. For the circular system, the costs cover transport to the recycling facility, washing and treatment of the soil, and the income from the sale of recycled products such as steel. Since the study follows the treatment of 1 tonne of polluted soil, it also includes the revenues from recycled steel and the cost of landfilling residual materials (e.g. filter cake) that cannot be sold as products in the circular system.

All relevant quantities and direct cost and benefit components are presented in Table 2. Quantity data are sourced from the annual report for Nes Miljøpark (Johansen, 2023), while cost inputs are provided by various stakeholders in the value chain (AF Decom, NOAH, Lindum, market prices for gravel, etc.). Although specific input costs such as fuel and energy were not itemized in the CBA, they are indirectly accounted for through the use of market prices, which reflect the service providers' costs for delivering the treatment services.

Table 2 Quantities and costs in the linear and circular systems, respectively, used in the CBA.

Landfilling	**Quantity(ton)**	**NOK/ton**
Transportation to landfill	1	100
Landfilling operation	1	200
Virgin products Fine fraction (0/2) (not relevant product for virgin material, not applicable as aggregate for market)	0.271	0
Gravel 2/8	0.103	225
Drain gravel 8/16	0.103	235
Kult 16+	0.284	135
Recycling	**Quantity(ton)**	**NOK/ton**
Transport of 1-ton of contaminated soil to recycling	1	100
Treatment in recycling plant	1	200
Recycled products Fine matter 0,063/2 (27%)	0.271	80
Gravel 2/8 (10%)	0.103	225
Drain gravel 8/16 (10%)	0.103	235
Kult 16+ (28%)	0.284	135
Steel to recycling (income)	0.0017	-2000
Landfilling remains: Filter cake (24%)	0.24	200
Transport of filter cake to landfill (deposited on site)	0	0

3.2.2 Indirect costs

For indirect costs/benefits, the analysis considers climate change impacts and land occupation for both the linear and circular systems. The input and results from the LCA by Nørsterud (2022) have been used as the basis for climate change (kg CO2-equivalent) and land occupation (m2) impacts. The quantities and costs are given in Table 3.

Table 3 Quantities and prices for indirect costs/benefits.

	Quantity (from LCA)	Prices (low)	Prices (high)
Climate change			
Landfilling	18.2 (kg CO2-eq/ton)	NOK1920/ton	NOK11730/ton
Recycling	13.6 (kg CO2-eq/ton)	NOK1920/ton	NOK11730/ton
Land occupation			
Landfilling	0.15 (m2/ton)	0.1 NOK/m2	150NOK/m2
Recycling	0.05(m2/ton)	0.1 NOK/m2	150NOK/m2

Climate change

Data on carbon prices in Europe were used to convert CO2-equivalent emissions into monetary values. Recommended CO_2 prices for cost-benefit analysis in Europe have been used, as outlined by Wangsness and Rosendahl (2022). The report suggests applying a carbon cost of 166 euros per ton emitted CO2 in 2025, rising to 1014 euros per ton by 2050 (Wangsness & Rosendahl, 2022). This study has used 166 euros per ton CO_2 in the primary scenario (low CO_2 price) and 1014 euros per ton (high CO_2 price) as an alternative scenario.

Land use

For land use, the opportunity costs of land were used to convert land occupation units (m^2) associated with handling 1 tonne of polluted soil in both the circular and linear systems to monetary values. It is recommended to use only the producer surplus[1] (Boardman et al., 2011) from resource use, implying that only the net return is regarded as a benefit and not the entire value obtained from land use. The producer surplus is typically assumed to be equal to the production profits after subtracting wage costs and costs of other inputs. This study has considered the opportunity cost of land for (i) agriculture (wheat production in Norway) and (ii) housing (rental market) as described below.

<u>Wheat production</u>

The average wheat yield per square metre in Norway is about 0.5 kg (Seehusen & Uhlen, 2019). When assuming wheat price per tonne of 3300 NOK/ton and assuming an average of 5 per cent income-weighted Earnings Before Interest, Taxes, Depreciation and Amortization (EBITDA)-margin (obtained from the Brønnøysund Register of Company Accounts[2], the net return from using 1 square metre of land for wheat production is approximately 0.1 NOK.

<u>Housing</u>

Assuming land use in housing (Average annual rents per sqm 3000) and the same average return of 5 per cent income-weighted EBITDA margin (The Brønnøysund Register of Company Accounts) as in the previous example (wheat production) occupation of 1 sqm of land in a year would yield approximately 150 NOK/m^2. For housing, EBITDA is primarily derived from rental income.

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[1] Producer surplus (PS) is a measure of the economic benefits businesses receive when selling their goods and services in the market.

[2] A related study has followed the same approach (Iversen, Grimsrud, Lindhjem, & Navrud, 2024)

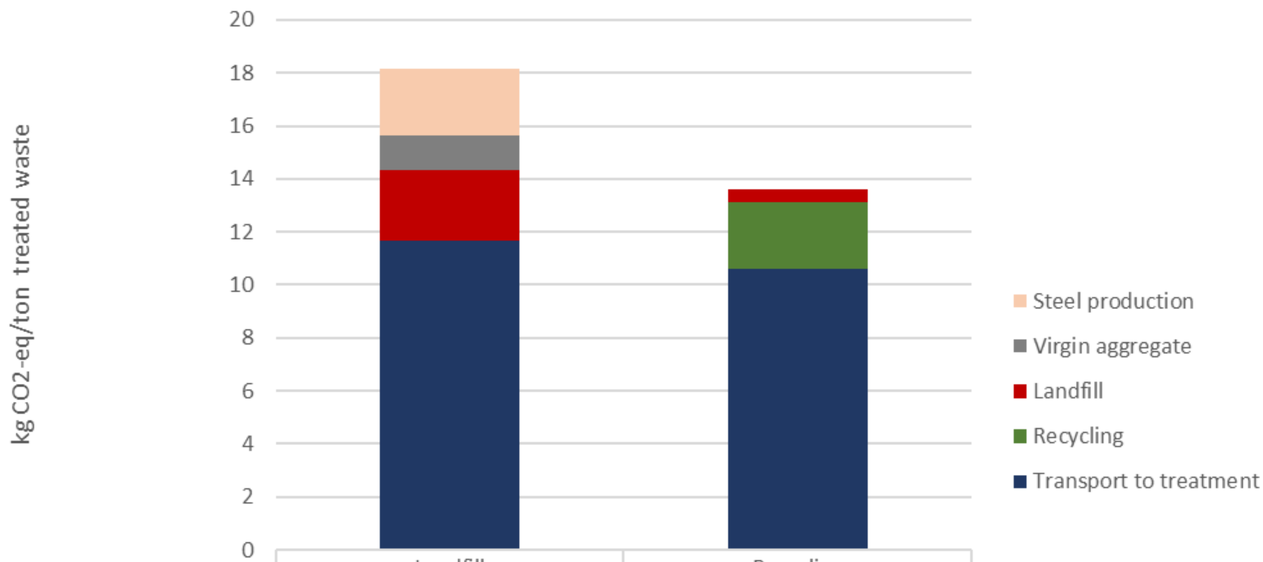
It is, however, important to note that the analysis to reflect the opportunity costs of land occupation in this analysis is simplified to provide useful estimates for understanding potential trade-offs when handling polluted masses using linear or circular systems. However, although valuable in that sense, the analysis may not fully account for land use value and overlooks non-use values like biodiversity loss, limiting its ability to fully reflect the environmental impacts associated with land occupation.

4 Results

4.1 LCA and CBA of waste treatment

4.1.1 Climate change

Figure 7 presents the climate change impact for the systems Landfill and Recycling as presented in Figure 3. The results are shown per life cycle activity and as total (net results). The Landfill system includes the additional activity production of virgin material in order to fulfil the functional unit (both treat waste and produce new material) while the recycling systems fulfil this activity itself due to its multifunctionality.



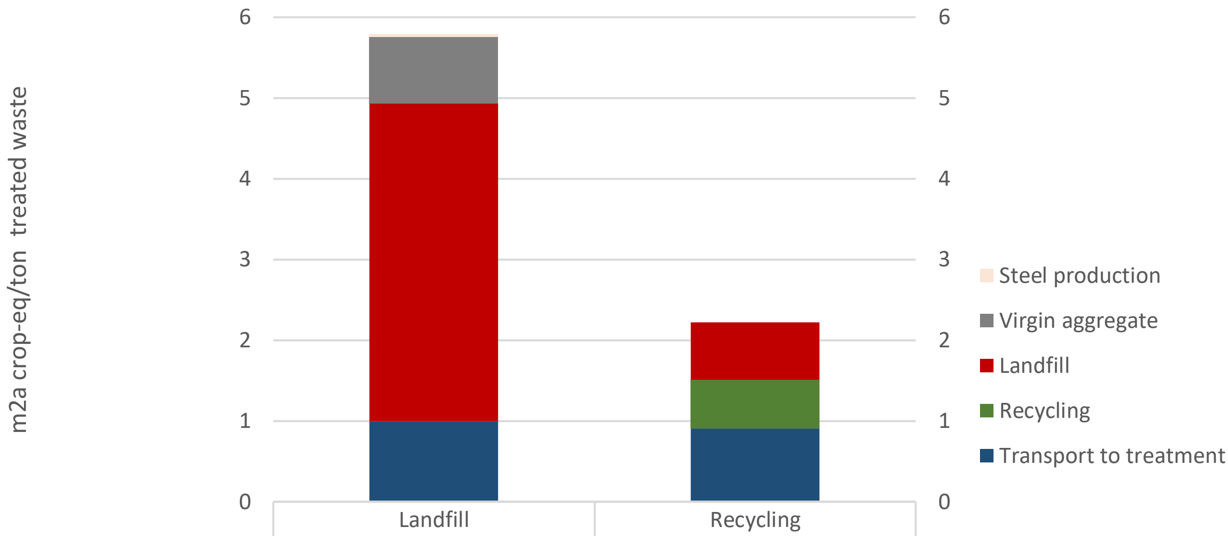
	Landfill	Recycling
Steel production	2.5	
Virgin aggregate	1.3	0.0
Landfill	2.6	0.5
Recycling	0.0	2.5
Transport to treatment	11.7	10.6

Figure 7 Climate change impact related to landfill and recycling of contaminated soil, LCA with system expansion.

The figure shows that the recycling alternative performs better for climate change compared to the landfill alternative with a result of 13.6 kg CO_2-eq/ton treated waste, which is 25% lower than the impact from the landfill alternative (18.2 kg CO_2-eq/ton treated waste). As the figure shows, the recycling and landfill activities cause almost the same impact. The extra benefit from the multi-functionality of the recycling system means that the landfill system needs to add the production of virgin steel and aggregate.

4.1.2 Land use

Figure 8 presents the land use impact shown as m^2a crop-eq for the landfill and recycling systems. The results are shown per life cycle activity and as total (net results). The landfill system includes the additional activity production of virgin material in order to fulfil the functional unit (both treat waste and produce new material) while the recycling systems fulfils this activity itself due to its multifunctionality.



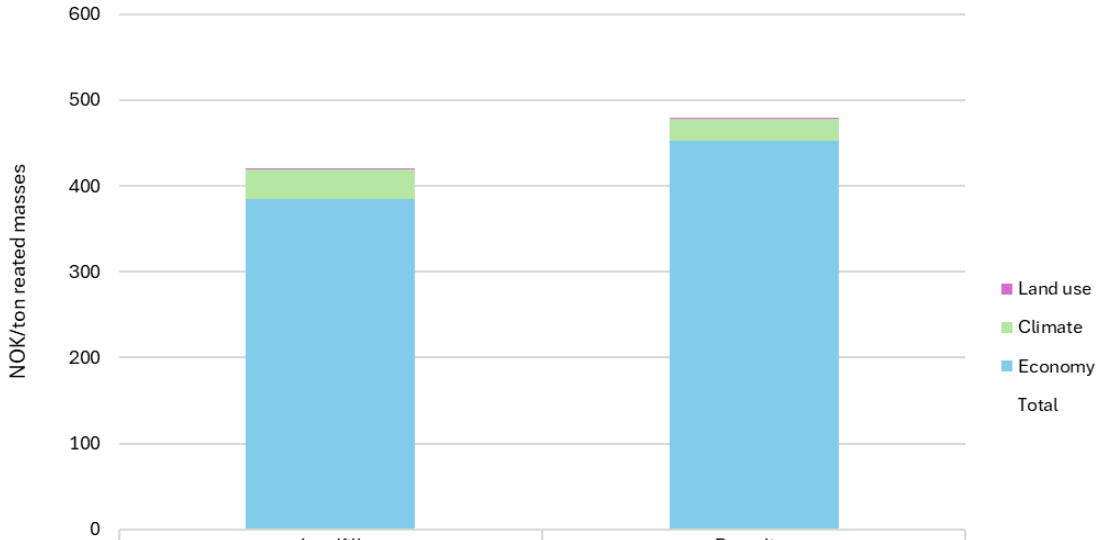
	Landfill	Recycling
Steel production	0.03	
Virgin aggregate	0.8	
Landfill	3.9	0.7
Recycling	0.0	0.6
Transport to treatment	1.0	0.9

Figure 8 Land use related to landfill and recycling of contaminated soil, LCA with system expansion.

As seen from the figure, the recycling system results in approximately 60% less land use impact compared to the landfill system due to less need for land use for the landfill and steel production activities.

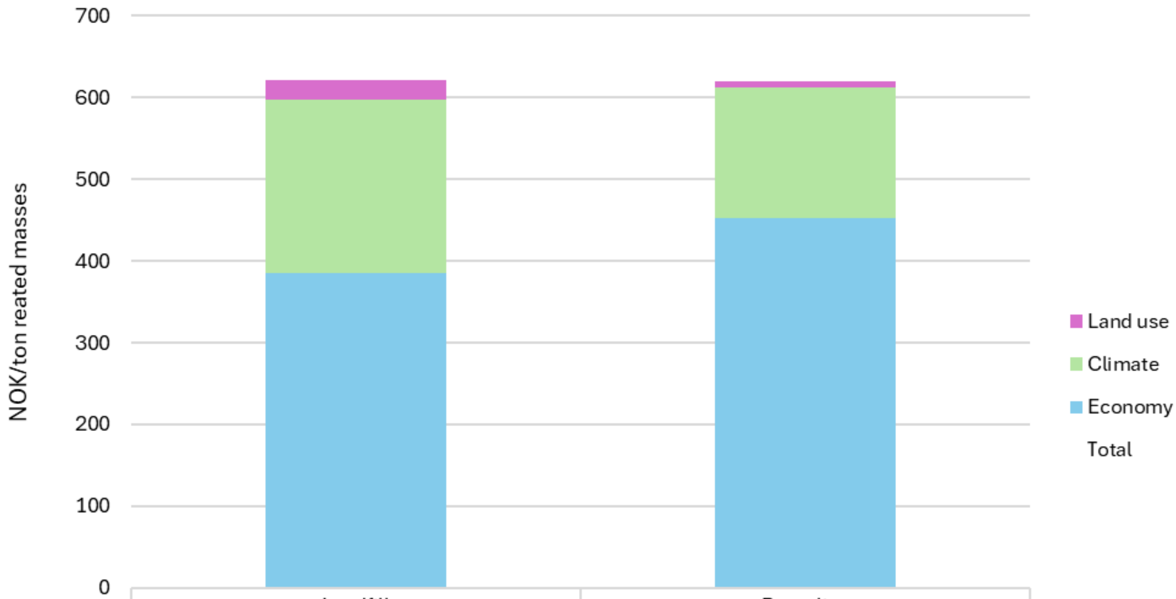
4.1.3 Cost-benefit analysis (CBA)

Figure 9 presents the cost breakdown in NOK/ton treated waste by either landfilling or recycling, comparing direct economic costs, cost for climate effects (CO2-equivalent emissions), the opportunity costs of land occupation, and total costs. While Figure 9 shows the picture when using a relatively more conservative price for CO_2-emissions (NOK 1920/ton) and a relatively lower opportunity costs for the land uses for wheat production (0.1 NOK/sqm), Figure 10 compares the same picture but now valuing the externalities as follows: the future recommended CO_2 price (NOK 11 730/ton) and the opportunity costs of land use as residential (150 NOK/sqm).



	Landfill	Recycling
Land use	0,02	0,01
Climate	35	26
Economy	385	452
Total	420	478

Figure 9 Comparing direct and indirect costs of handling 1 ton of polluted soil using the linear landfilling and circular recycling systems assuming conservative price for CO_2-emissions (NOK 1920/ton) and a low opportunity cost for the land use.



	Landfill	Recycling
Land use	23	8
Climate	213	160
Economy	385	452
Total	621	620

Figure 10 Comparing direct and indirect costs of handling 1 ton of polluted soil using the linear landfilling and circular recycling systems assuming future recommended CO_2 price (NOK 11 730/ton) and a high opportunity cost for the land use.

The cost of landfilling is lower than recycling when a conservative CO_2 price and low opportunity cost for land use are assumed. The higher cost of the recycling alternative is due to the additional requirement of landfilling the filter cake residue, which cannot be transformed into a usable product. Importantly, this is a societal cost, not one directly experienced by the owner of the polluted soil. In fact, the financial costs to the owner are assumed to be approximately the same whether choosing landfilling or recycling.

Although the climate and land use impacts are greater for landfilling than for recycling, these externalities are not sufficient, under conservative pricing assumptions, to outweigh the economic cost difference between the two systems. However, under an alternative scenario with higher CO_2 and land use prices, the picture changes significantly. The total cost of landfilling increases sharply, becoming approximately equal to that of the recycling system due to the higher valuation of environmental impacts.

This shift suggests that circular waste management systems are likely to become more cost-effective under:

1. Future-oriented pricing of externalities, such as elevated CO_2 prices from waste handling
2. The inclusion of additional indirect cost categories in decision analysis—such as biodiversity loss and human health impacts—as demonstrated through land use in this study.

4.2 Product-oriented LCA (EPD)

4.2.1 Climate change

Figure 11 presents the climate change impacts of producing virgin and recycled crushed stone/gravel, covering modules A1-A3, depending on when the end-of-waste state is reached. In the EPDs for crushed stone/gravel, the crushing stages typically refer to the different stages in the production process where the material is broken down into smaller fractions. The crushing stages are related to the type of gravel/crushed stone being produced as the number of crushing stages affects both the physical properties of the final product (e.g., size and quality) and its environmental impact (e.g., energy consumption, emissions). The data applied in Figure 10 for production of virgin crushed stone is based on an analysis of 30 EPDs for crushed stone products from the Norwegian market (Petrovic & Raadal, 2024). The number in the figure represents the lowest climate change impact per ton crushed stone produced, when all the steps 0, 1, and 2 are included. The data for the recycled product when assuming endo-of-waste stage is reach after the recycling plant (right part of Figure 11) represents an average of AF Decom's published EPDs (AF Decom, 2024a, 2024b, 2024c, 2024d, 2025).

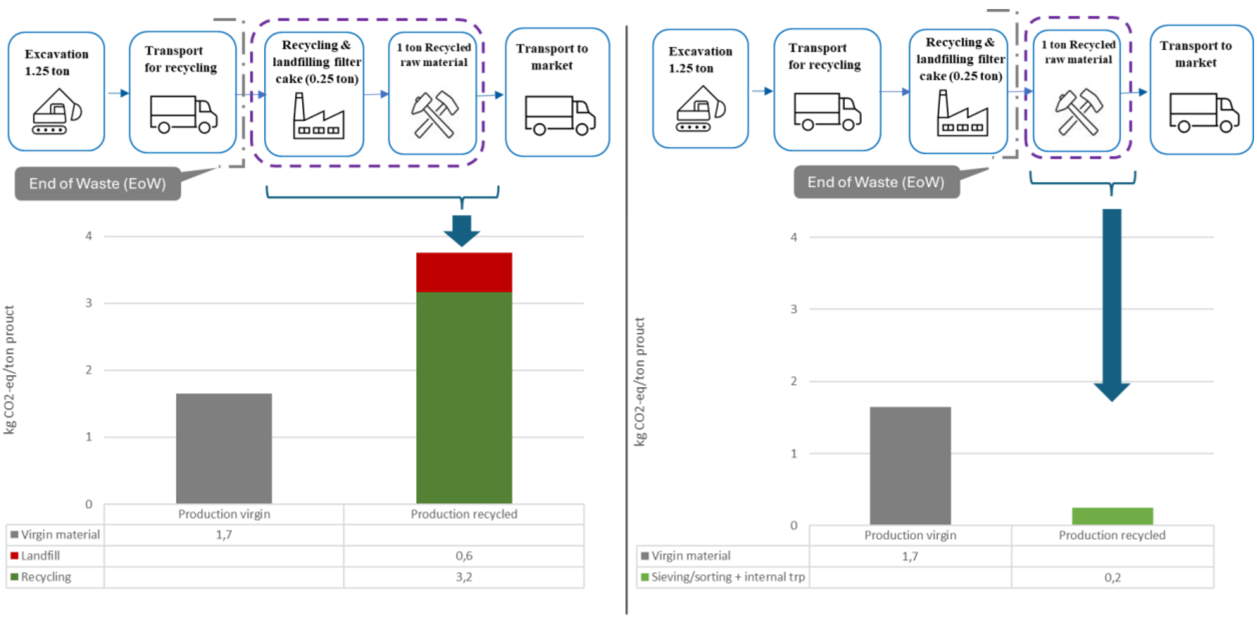


Figure 11 Climate change for production of virgin and recycled crushed stone/gravel, dependent on the occurrence of end-of-waste state. Product-oriented LCA, presented as modules A1-A3 in an EPD.

Figure 11 clearly demonstrates that the timing of reaching the end-of-waste state significantly influences the ranking between the production of virgin and recycled crushed stone/gravel in terms of climate change impact. If the end-of-waste stage is assumed to be reached before the contaminated soil enters the recycling plant (left part of Figure 11), then the burdens from the recycling plant are allocated to the recycled product. If end-of-waste state, on the other hand, is reached when the products leave the recycling plant (right part of Figure 11), means that the same burdens should be allocated to the contaminated soil and the recycled product only has burdens from sieving/sorting of the products and related internal transport.

As described in chapter 2.3.2and in accordance with EN 15804 (CEN, 2019), the end-of-waste state is reached when all the following criteria for the end-of-waste state are fulfilled:

1. the recovered material, component or product is commonly used for specific purposes
2. a market or demand, identified e.g. by a positive economic value, exists for such a recovered material, component or product;
3. the recovered material, component or product fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products; and
4. the use of the recovered material, product or construction element will not lead to overall adverse environmental or human health impacts.

Based on the above-mentioned criteria, it is not likely that the end-of-waste state is reached when the contaminated soil enters the recycling plant. Hence, it seems reasonable that the recycled gravel/aggregates have reach the end-of-waste criteria and thereby have become new products. This can be exemplified by the use in various applications, such as filling material in trenches, aggregates in sprayed concrete and grit sand. There is hence a demand for the products as they are used for specific purposes. Some of the recycled products are certified in accordance with NS-EN 13043:2002+NA:2008 (Aggregates for bituminous mixtures and surface treatments for roads, airfields and other trafficked areas), NS-EN 13242:2002+A1:2007+NA:2009 (Aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction) and NS-EN

12620:2002+A1:2008+NA:2016 (Aggregates for concrete). The responsibility for proving that end-of-waste state is reached lays, however, on the waste owner.

Since the end-of-waste state is likely to be reached when the contaminated soil leaves the recycling plant, the environmental burdens from the recycling plant should be allocated to the contaminated soil. Hence, the system boundaries shown in the right part of Figure 11 should be applied when assessing the environmental burden of producing the recycled material.

4.2.2 Land use

Figure 12 presents land use impacts, shown as m^2a crop-eq, of producing virgin and recycled crushed stone/gravel, covering modules A1-A3, depending on when the end-of-waste state is reached.

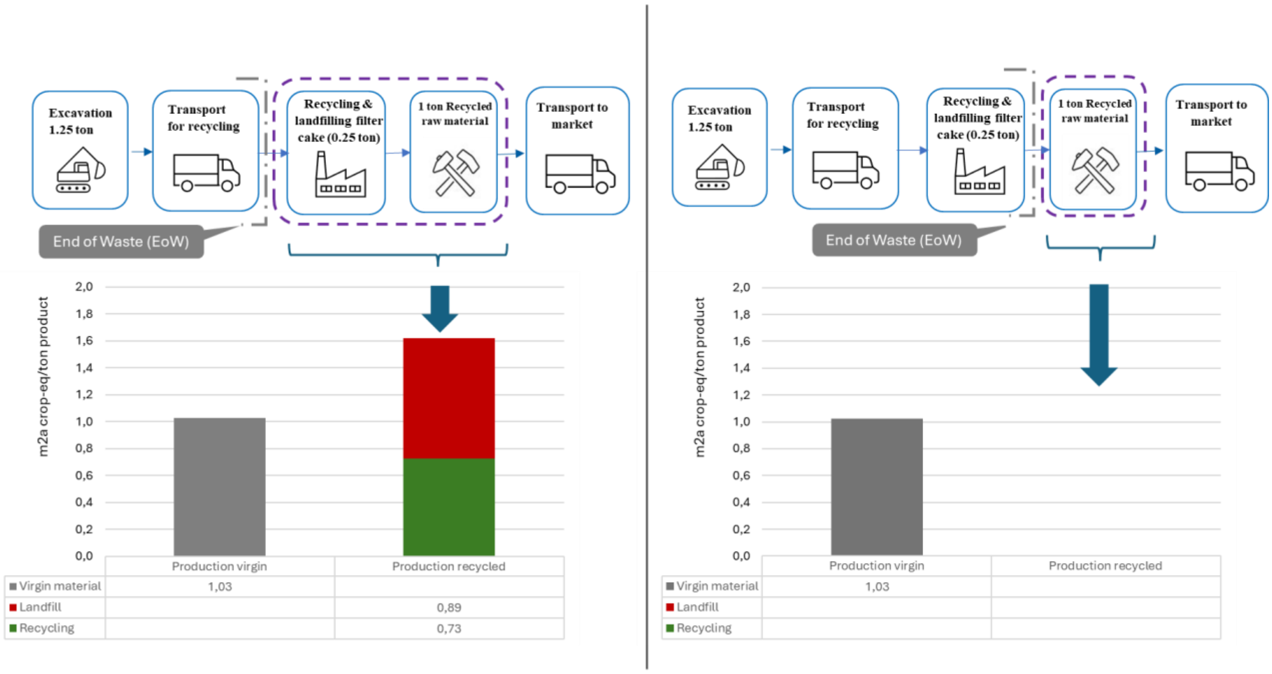


Figure 12 Land use for production of virgin and recycled gravel, dependent on the occurrence of end-of-waste state. Product-oriented LCA.

Also, for land use it is demonstrated that the timing of reaching the end-of-waste state significantly influences the environmental ranking between the production of virgin and recycled crushed stone/gravel. If the end-of-waste stage is assumed to be reached before the contaminated soil enters the recycling plant (left part of Figure 11), then the land use related to the recycling plant are allocated to the recycled product. If the end-of-waste state is reached when the products leave the recycling plant (right part of Figure 11), means that the same land use should be allocated to the contaminated soil. As the above mentioned EPDs do not present data for land use in the same format as the results given by Nørsterud (2022), the recycled product is assumed approximately free of land use burdens from the recycling process.

Based on the same arguments as presented for climate change in chapter 4.2.1, the system boundaries shown in the right part of Figure 12 should be applied when assessing the environmental burden of producing the recycled material.

5 Conclusions

This study demonstrates that Life Cycle Assessment (LCA) and Cost-Benefit Analysis (CBA) are valuable decision-support tools for various stakeholders when evaluating linear versus circular waste management strategies for treatment of contaminated soil. Different functional units and system boundaries were explored to assess the environmental performance of recycling, which can be considered both a waste treatment process and a production process and. Hence, recycling represents a multifunctional process. LCA with system expansion was used to assess the environmental impact of treating contaminated soil, while the production of secondary material from the same contaminated soil was assessed through an Environmental Product Declaration (EPD). The environmental impacts identified in the LCA was further used in a Cost-Benefit Analysis (CBA) where the broader socioeconomic impacts were assessed by monetizing climatic and land use effects for society.

The results from the waste management analysis of the contaminated soil, using Life Cycle Assessment (LCA) with system expansion, showed that the circular system leads to approximately 25% lower climate change impact and 60% reduced land use impact compared to the linear alternative. This highlights the importance of expanding the system boundaries to also account for the benefits of producing secondary products through the recycling process.

The Environmental Product Declaration (EPD) results further demonstrated the importance of the definition and timing of the end-of-waste state, as this determines how much of the recycling process' environmental impact should be allocated to the recycled product. Therefore, harmonizing the application of end-of-waste criteria is essential to ensure consistency and comparability in EPDs for recycled materials.

The cost-benefit analysis of the waste treatment systems shows that landfilling appears more favourable when conservative prices are used for climate and land use impacts. However, if the decision-makers choose to adopt recommended future valuations for carbon emissions and land occupation, such as 11,730 NOK per ton CO_2 and 150 NOK/m^2 for land use, the trend shifts. Under these future pricing conditions, recycling becomes roughly equivalent to landfilling. This study does not fully account for the broader land use value, as it overlooks non-use values such as biodiversity loss. Overall, the CBA demonstrates how the inclusion of non-market values, alongside direct economic costs, can change the decision outcomes in favour of more circular systems.

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Forskning

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