NEW-MINE

EU TRAINING NETWORK FOR RESOURCE RECOVERY THROUGH ENHANCED LANDFILL MINING

European Training Network for Resource Recovery Through Enhanced Landfill Mining (NEW-MINE)

D4.1 Final report on WP multi-criteria assessment

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Confidential

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1. Introduction and objectives

Through the work of 15 ESRs, NEW-MINE has involved the development of innovative technologies and concepts for Enhanced Landfill Mining (ELFM), i.e. "*the integrated valorisation of landfilled waste streams as materials and energy, using innovative transformation and upcycling technologies and respecting the most stringent social and ecological criteria".* The three ESRs belonging to WP4 have been working on sustainability assessments of these emerging technologies and concepts, by addressing their environmental, economic and societal impacts.

Through the development and application of systems analysis methods and approaches, the overall objective of WP 4 has been to facilitate systematic and trustworthy assessments of economic, environmental and societal impacts of ELFM. Given the early phase of development of this concept and related technologies, a key objective has been to develop learning-oriented assessment approaches that contribute in-depth knowledge on the factors and conditions that influence the impacts and various consequences of such projects. These methods have been applied in specific ELFM cases as well as in a wide range of different landfill management and landfill mining scenarios and settings that could be encountered within European boarders. Beyond guiding future ELFM research towards essential knowledge gaps and sustainability challenges, such assessments on critical performance drivers and trade-offs facilitate the selection and development of sustainable projects and clarify the role of policy and market interventions.

2. Methods

A cornerstone of ELFM is that this concept should not only be economically justified but also clearly motivated from an environmental and societal point of view. However, the fact that such projects can involve multiple objectives, be executed in many different ways and places and thereby result in largely different outcomes, adds complexity to their implementation and sustainability consequences. Dependent on the selection of landfills for mining, choices of project set-ups and technologies and implications of surrounding policy and market conditions, the implementation of ELFM could thus generate a range of both positive and negative economic, environmental and societal impacts. Assessing the sustainability of ELFM is further challenged by its emerging character, where lack of real-life projects and records of accomplishment create large uncertainties that need to be accounted for.

Addressing these challenges of variability in site, project and system conditions and various types of uncertainties in sustainability assessments of ELFM have constituted a common focus for the three ESRs of WP 4, **Figure 1**. *ESR 13* has focused on environmental impacts and developed and adopted integrated life cycle assessment (LCA) approaches to address variability and uncertainties in different ELFM scenarios and landfill reference cases, with special emphasis on including spatial and temporal information. In particular, the research of ESR 13 has involved (i) LCA and scenario analysis to address influencing factors in the environmental impact assessment of landfills, (ii) LCA + quantitative risk assessment (QRA) to integrate spatial and temporal variation in the LCA of landfills and (iii) multiple scenario modelling for integrated economic and environmental assessment of emerging ELFM technologies (i.e. plasma gasification), and waste valorization routes, to facilitate process development. The latter was done in collaboration with ESR 14.

ESR 14 has worked on business economics and developed a generic economic assessment model to account for a wide range of ELFM scenario possibilities. The model covers variation of multiple factors and conditions occurring on the site, project and system levels. In addition, it enables more fine-grained assessments of what factors and factor combinations that build up the economy using variance-based sensitivity analysis. The flexibility of the model has enabled several studies such as (i) assessment of critical factors for the economic performance of traditional LFM in Europe, (ii) exploration of business strategies for improved profitability of traditional LFM and (iii) integrated economic and environmental assessment of multiple LFM & ELFM scenarios together with ESR 13.

ESR 15 has focused on societal aspects of ELFM implementation and evaluation. This research has employed an anticipatory approach and involved interviews with different stakeholders related to a planned ELFM project in Belgium. These interviews resulted in (i) an overview of various uncertainties and stakeholder needs that must be considered to facilitate implementation of ELFM and (ii) five stakeholder archetypes that could help decision- and policy-makers to better understand the different parties and trade-offs that are involved in the implementation process. In addition, a system dynamics approach has been used to conceptualize the cause-effect relationships of various societal impacts of ELFM. The results of this research will in the next step be used to quantify a selected set of societal impacts through discrete choice experiments and to develop societal assessment factors to be integrated in the economic and environmental models of ESR 13 and 14.

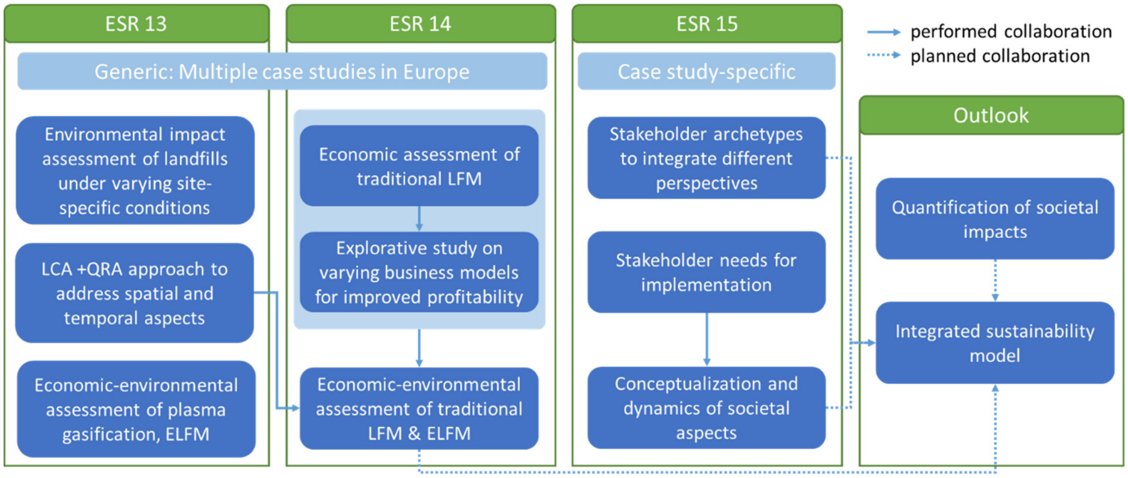


Figure 1. Schematic illustration of WP 4 including the main activities and collaborations of ESRs 13-15.

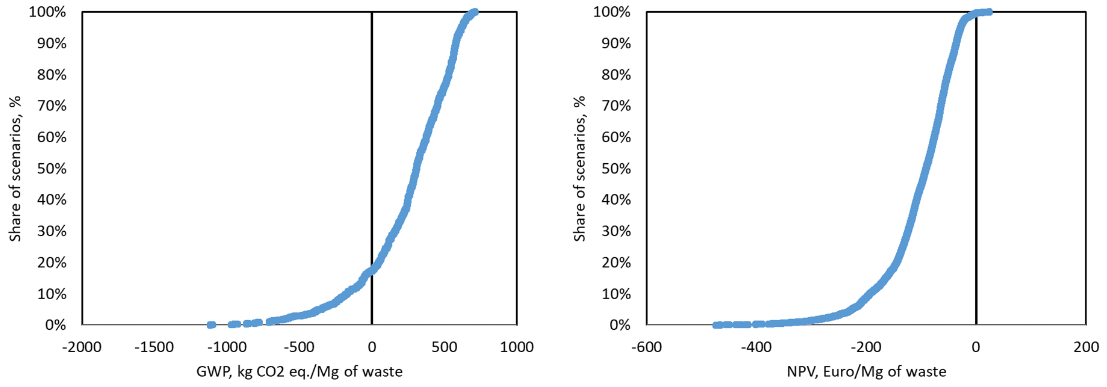
3. Results

Throughout the course of the NEW-MINE project, the three ESRs have developed and applied systems analysis methods and approaches in different studies of relevance for their individual PhD tracks. Here, follows an overview of some of their main findings with special emphasis on displaying the overall sustainability potential and challenges for ELFM. For further details about the specific results of the individual ESRs of WP 4, see their final RTDE reports.

3.1 Economic and environmental impacts of ELFM scenarios

In the end of the NEW-MINE project, the systems analysis methods developed by ESR 13 and 14 were combined to perform an integrated economic and environmental assessment of ELFM. This study involved a large number of ELFM scenarios covering a wide range of different landfill settings, technical project set-ups and surrounding policy and market conditions that can be encountered in Europe. In contrast to previous assessments of traditional LFM, these scenarios included advanced technologies for WtE (e.g. pyrolysis and plasma gasification) and upcycling and valorization of generated WtE residues to geopolymers.

The results from the study show that the realization of ELFM projects is indeed challenging, both from an environmental and economic perspective, **Figure 2**. In terms of climate impact, the scenario result ranges from a net savings of 1115 to a net burden of 711 kg CO_2 eq. per Mg of excavated waste. However, only about 20% of the scenarios show net CO_2 eq. savings compared to conventional landfill management options. When it comes to economic performance, the result for the ELFM scenarios ranges from a net deficit of 473 to a net profit of 24 Euro per Mg of excavated waste. Just 5% of the scenarios are profitable.



(a) (b)

Figure 2. Cumulative distribution of the 531,441 ELFM scenario results in terms of (a) environmental performance (climate impact in kg CO_2 eq.) and (b) economic performance (in NPV) per Mg of excavated waste.

3.2 Critical factors for economic and environmental performance of ELFM

There are several important factors occurring on the site, project and system levels that can explain the variations in the environmental and economic outcome of the different ELFM scenarios, **Table 1**.

Table 1. Variance-based sensitivity indices displaying the relative importance of factor variation with respect to the overall ELFM scenario results in terms of environmental performance (climate impact in kg CO_2 eq.) and economic performance (in NPV).

		Environmental performance	Economic performance
F1	Waste composition	**0.2887**	**0.1628**
F2	Reference case	0.0007	**0.2529**
F3	Excavation & sorting	**0.4880**	**0.1389**
F4	WtE treatment	0.0324	0.0833
F5	Residue treatment	**0.3155**	0.0603
F6	Land value	0.0000	0.0556
F7	Substitution factors	0.0291	0.0994
F8	Background energy	**0.0806**	0.0000
F9	Materials and energy market	0.0000	0.0182
F10	Waste treatment and disposal	0.0000	**0.3001**
F11	Transport distance	0.0000	0.0000
F12	Financial accounting	0.0000	0.0000

For the climate impact, the variation in waste composition is of high importance because it determines the amounts of potentially recoverable resources (e.g. metals and energy carriers) as well as residues in need of re-deposition (e.g. fines). Also the occurrence of anaerobically degradable organic materials is of relevance because it is directly related to the landfill gas potential of the deposit and thus the climate emissions of the reference case that can be avoided by ELFM. However, the two most critical factors for the variation in climate impact of the scenarios relate to the project level in terms of technology choices for excavation and sorting and treatment of residues. The different advancement levels of the sorting process in the scenarios dictates the material composition, quality and fate of different separated waste fractions, thereby influencing the share of the exhumed waste that will be sent for disposal or further valorization. Treatment of residues refers to a wide variation from the option of re-landfilling to further processing to construction aggregates or upcycling to geopolymers. It is notable that the different alternatives for WtE treatment is of low importance for the variation in climate impact of the ELFM scenarios and this is due to that the best available technologies were selected for all of them, resulting in relatively small performance variations. For plasma gasification, electricity production is the only considered syngas valorization option.

In contrast to the climate impact, the most important factors for the economic performance of the ELFM scenarios relate to system conditions. The reference case is largely influenced by regional policies and involves the incumbent landfill management option if the deposit is not mined. In the scenarios, the reference case varies from do nothing (i.e. aftercare is not required), over moderate costs in terms of landfill cover and gas and leachate treatment to intense requirements involving active stabilization and aftercare or even remediation. Waste treatment and disposal refers to the management of generated bulk waste materials (e.g. fines), which need to be re-landfilled with corresponding wide regional variations in disposal costs and gate fees.

3.3 Strategies for developing environmentally and economically beneficial ELFM projects

The granular understanding of what factors build up the environmental and economic performance of the ELFM scenarios can serve as guidance to, for instance, facilitate selection of suitable landfill compositions for mining and development of tailored technical project set-ups.

In terms of climate impact, net CO_2 eq. savings is expected in ELFM scenarios involving landfills rich in recoverable materials and energy carriers, employing advanced sorting technologies and upcycling of WtE residues to geopolymers replacing climate impact-intensive cement production, **Figure 3**. This is especially so if the project in question is realized in a region with a fossil-based energy system, thereby improving the climate impacts from WtE of the separated residue-derived fuel.

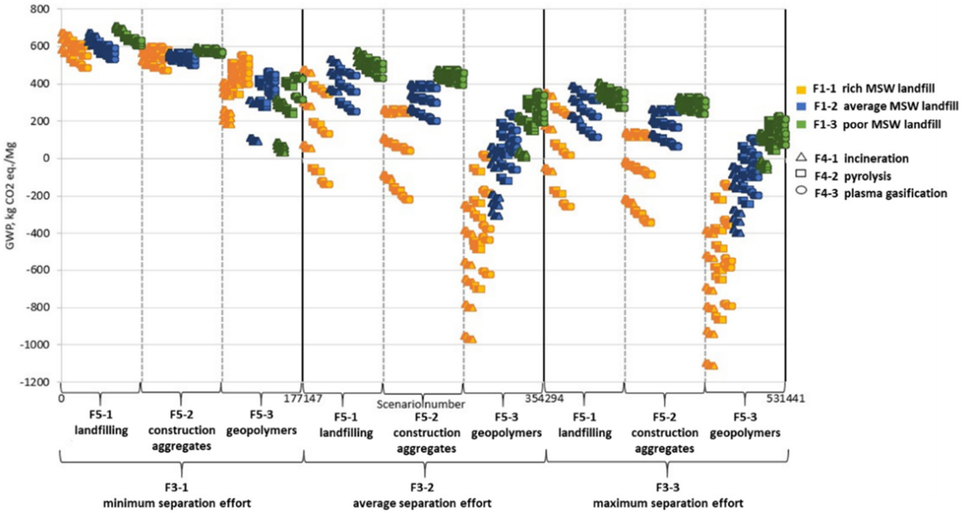


Figure 3. Graphical analysis of the climate impact of the ELFM scenarios grouped in terms of the factors that can be influenced by LFM practitioners.

When it comes to economics, such a straightforward blueprint for improved performance of the ELFM scenarios just through the selection of landfill compositions and technology choices is more difficult to provide. Although the NPV slightly increases in the scenarios involving rich landfills, the potential for avoided landfill aftercare costs or reclaiming valuable urban land are significantly more important factors to consider in this respect. Furthermore, the scenarios involving more advanced sorting technologies generally display decreased NPVs meaning that such investments do not pay off in terms of significantly higher revenues for materials and energy or reduced disposal costs for residues. For

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instance, the NPV is more or less indifferent for the varying alternatives for treatment and upcycling of WtE residues. However, the economic consequences of such technology choices are largely influenced by regionally contingent policy and market conditions, dictating the marketability and price-settings for recovered resources and waste treatment and disposal costs for residues. Given that such system conditions vary considerably between regions, so could the economic implications of technology choices.

3.3 Societal aspects of ELFM

In order to facilitate implementation of societally motivated ELFM projects, there is a need to go beyond quantitative economic and environmental assessments and address different stakeholder needs and broader social and socio-economic impacts. Here, the research by ESR 15 has provided important knowledge contributions.

In a semi-structured interview study with industrial, academic, institutional and residential actors involved in a planned ELFM project in Remo, Belgium, different uncertainties were analyzed and put in relation to different stakeholder needs. When implementing such a project, the results show that ELFM practitioners need to consider four major stakeholder needs: (i) the need for investment support for industrial actors, (ii) the need for environmental benefits through ELFM, (iii) the protection of neighboring communities against potential disamenities and (iv) the need for societal benefits for the neighboring communities. The need for investment support focus on the often-perceived lack of profitability and could be met by implementing different subsidy schemes and tax exemptions. As the majority of European landfills are in public ownership, public-private partnerships (PPP) could also be a potential measure to reduce such costs and investment risks for industrial actors. However, it should be noted that institutional and governmental actors should prevent industrial cherry-picking and set clear incentives to maximize environmental gains from such projects. To protect community members from disamenities, various mitigation and safety measures to reduce local impacts and disturbances from excavation, processing and transportation of waste could be implemented. Furthermore, the acceptance for LFM projects could also be further facilitated by realizing societal benefits for neighboring communities and the public in terms of e.g. creation of recreational land, provision of employment opportunities or financial compensation. On a more general level, the lack of clear and specific regulations for ELFM contribute to many of the current uncertainties related to such projects. While there are no regulations in place that directly hinder implementation, there are also no regulations that foster ELFM. Developing such a regulatory framework could reduce many of the societal and regulatory uncertainties, thereby contributing with an increased public acceptance and decreased investment risks for ELFM practitioners.

Another important contribution of ESR 15 involved the use of system dynamics methods to conceptualize different societal impacts of ELFM, **Figure 4**. This overview of the main societal impacts of an ELFM project show that most of the local and regional benefits of ELFM projects are manifested through the potential after-use of the landfill while most of the burdens are caused by ELFM operations. The leverage points to influence societal benefits in terms of environmental gains are mainly managed by industrial actors in terms of landfill site selection and various technological choices. Furthermore, potential intra-dimensional trade-offs have to be considered. For example, through the creation of a recreational area on the excavated landfill, residential house prices could increase benefiting house owner, while rents would also increase, creating a disadvantage for tenants. Another example of such trade-offs is that the disparity between short- and mid-term risks and potential burdens and the long-term benefits could create conflicts between different age groups within the neighboring communities.

To tackle these society-wide challenges for ELFM implementation, ELFM regulation should be embedded in a broader, systemic context and a more general circular economy strategy. More differentiated taxation models could help mitigate some equity-related issues of ELFM projects, but

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more research is needed to quantify societal impacts and to integrate the societal dimension of ELFM with existing environmental and economic assessments.

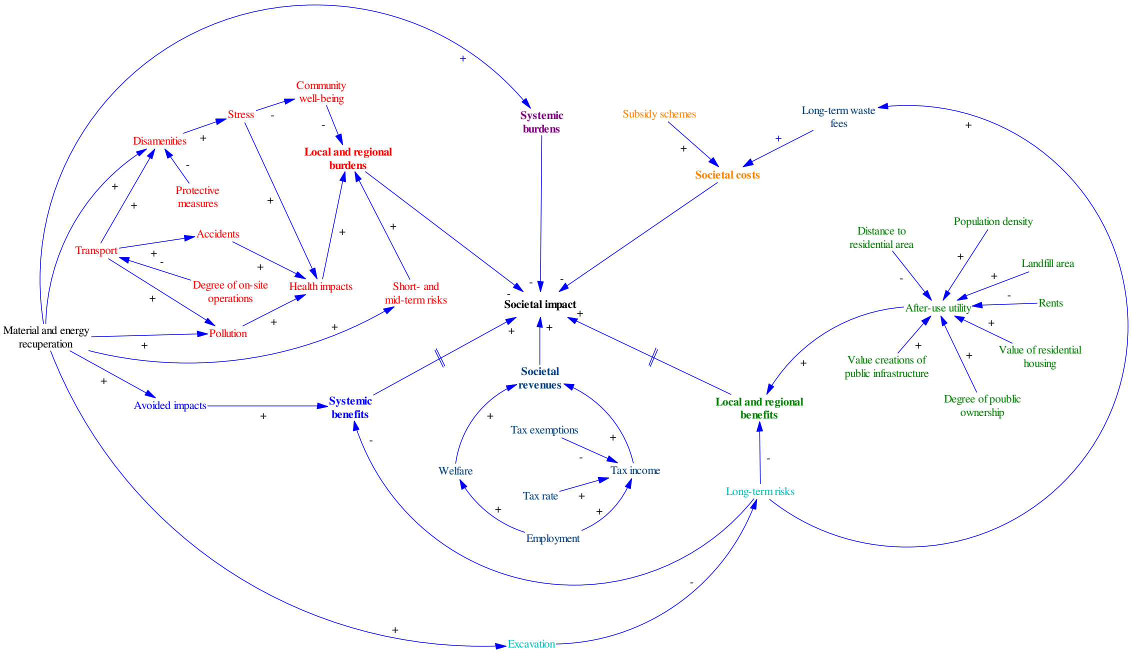

Figure 4. The composition of the societal impact of an LFM project. Societal benefits and revenues are displayed in blue and green, while societal burdens and costs are displayed in red, orange, and purple.

4. Conclusions and lessons learnt

The research of WP 4 clearly demonstrates the current sustainability challenges of implementing ELFM. However, through the development and application of systems analysis methods and approaches, the ESRs have also contributed with important knowledge that can serve as guidance for continued ELFM research and facilitate future development of sustainable projects. Many of their conducted studies have circulated around the question of under what conditions and settings ELFM could be economically, environmentally and societally justified. In this respect, their collective findings clearly stress the importance of a strategic selection of landfills for mining and pinpoint several site-specific factors and local settings that could facilitate implementation and improve the overall performance of future projects. Such knowledge offers an important contribution to previous research where most of the studied landfills seem to have been more or less randomly picked.

As the work of ESR 15 clearly highlights, industrial actors are the stakeholders that mainly can influence the environmental consequences of ELFM through different technological choices. When it comes to such technical project set ups, however, the results from ESR 13 and 14 highlight potential trade-offs between climate and economic performance. When it comes to the climate impact, the employment of advanced sorting technologies, efficient WtE processes and upcycling of WtE residues to high value-added products is generally beneficial. From an economic perspective, however, such investments seldom pay off in terms of material and energy sales but can still sometimes be motivated because they reduce the amounts of residues in need of disposal. In order to decide upon which technical set-up that is preferable financially, different options must be considered in the light of the waste composition in question and surrounding policy and market conditions that determine the marketability and price-settings for recovered resources as well as the treatment and disposal costs of generated residues. In addition, resource recovery alone cannot motivate ELFM projects economically, but such revenues typically need to be combined with other tangible values such as

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avoided landfill aftercare costs and reclamation of land. Here, also the research of ESR 15 highlights the potential importance of enabling a societally motivated after-use of the mined area for facilitating public acceptance and project implementation.

One of the key challenges for implementation of ELFM is the difficulty to develop such projects cost-efficiently. Although this challenge partly could be addressed by a more strategic selection of landfills and development of tailored project set-ups, a more wide-spread implementation of ELFM presumably also relies on policy interventions. In this respect, there are plenty of available options for reducing the capital costs and investment risks of industrial actors (e.g. investment support and PPP), increase marketability and revenues for recovered resources (e.g. recycling quotas and green energy) and reduce disposal costs for residues (e.g. landfill tax exemption). However, given that the environmental and societal consequences of ELFM can vary widely from case to case, such policy interventions need to be accompanied by specific guidelines and obligations regarding when, where and how projects should be realized. Here, the joint work of the ESRs of WP4 provides important contributions in terms of the systemic understanding of how different site, project and system conditions influence the economic, environmental and societal impacts of ELFM. However, before policy interventions really can come into question, the ELFM knowledge area needs to mature further by taking the current knowledge levels of such process and value chains beyond laboratory and small-scale trials to full-scale operations in which the technical feasibility and economic, environmental and societal consequences are demonstrated in practice.