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EVALUATING AND CLASSIFYING LANDFILL MINING IN ANALOGY TO NATURAL DEPOSITS

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SUMMARY: The aim of this study is to apply the United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 (UNFC-2009) to a landfill-mining project to identify the landfilled materials as potential anthropogenic 'reserves' or 'resources', and to reveal critical factors for the classification of the project. Based on data from a landfill-mining project in Belgium, the focus of the evaluation was set on technological options and the project's socioeconomic viability. Four scenarios have been investigated, representing different alternatives for the combustible waste fraction's thermal treatment (on-site vs. off-site incineration) and for specific stakeholder interests (public vs. private). The Net Present Values were found to be negative for all four scenarios, ranging between -197 million € in the best and -284 million € in the worst case. Based on required future changes in metal prices, sorting and incineration cost to make the project economically viable, the scenarios resulted in different final resource classifications under UNFC-2009.

1. INTRODUCTION

Although landfill mining has attracted increased scientific interest in the recent past, research has primarily focused on the characterization of landfilled wastes so far. Economic aspects are - if at all - often touched upon rather superficially. In-depth economic evaluations of landfill mining are scarce, and the few existing studies are based on diverse assumptions and methods, making comparisons difficult. As materials recovered from old landfills compete with and complement the supply of geogenic (primary) resources on the market, it appears obvious to evaluate and classify such anthropogenic materials in line with concepts existing for primary mineral resources.

Therefore, the goal of this study is to apply the three-dimensional primary resource classification framework UNFC-2009 to a landfill-mining project to identify the landfilled materials as potential anthropogenic anthropogenic 'reserves' (current economic extraction by a defined project and sale confirmed) or 'resources' (reasonable prospects for economic extraction by a defined project and sale in the foreseeable future) or none of both, and to reveal critical factors for the classification of the project. The focus of the evaluation based on data from a landfill-mining project in Belgium was set on technological / project set-up options and economic viability as well as on the effects of system boundary choices.

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The main contribution of this study to the literature on landfill mining evaluation is that the economic analysis considers specific stakeholder interests, namely the perspective of a private investor in contrast to the broader view of a public entity, taking also non-monetary effects into account. Further, two different alternatives for the combustible waste fraction's thermal treatment (on-site vs. off-site incineration) are investigated. To decide whether the deposit can be labeled as 'currently economically viable for extraction' or whether there are at least 'reasonable prospects for future economic extraction', the concept of "cut-off values" is transferred to anthropogenic resources as a key instrument. The study should provide a transparent base for future evaluations of further types of anthropogenic resources as well as their integration into UNFC-2009.

2. CONCEPTUAL FRAMEWORK

The globally recognized United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 (UNFC-2009) offers a consistent classification system for various kinds of primary resources and related extractive activities. To identify that part of the total resource potential, which is known to be economically feasible for extraction under present conditions (reserves), basically three crucial points need to be considered (cf. Figure 2).

1) Knowledge on composition, size and quality of the extractable[1] resource stock (G-axis)
2) Project and technical feasibility: Under what technical conditions can materials be extracted and valorized? (F-axis)
3) Socioeconomic viability (E-axis)

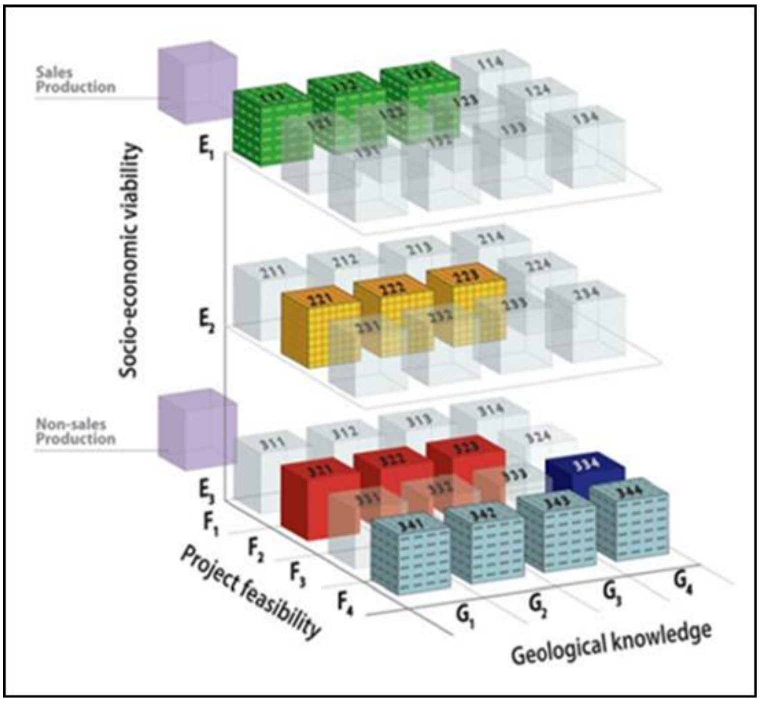

Figure 1. United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 (UNFC-2009). Legend: 1st digit (E) –"Socioeconomic viability"; 2nd digit (F) –"Field project status & technical feasibility"; 3rd digit (G) – "Knowledge on resource stock". Reproduced courtesy of the United Nations Economic Commission for Europe.

[1] However, UNFC-2009 offers also categories for in-situ quantities, where extraction methods do not yet exist.

3. OBECTIVES

The overall objective of this study is to apply the primary resource classification framework UNFC-2009 to a landfill-mining project in order to identify the landfill as an anthropogenic resource or a reserve. In a first step the technical feasibility of extracting and using the landfill's resource potential as secondary raw materials is examined. Subsequently, the socioeconomic viability of mining the identified extractable raw materials is explored for four scenarios, representing different alternatives for the combustible waste fraction's thermal treatment and for specific stakeholder interests. Based on these results the scenarios are classified under UNFC-2009.

4. MATERIALS AND METHODS

4.1 Background on the landfill-mining case study

The Enhanced Landfill Mining (ELFM) project is located at the Remo Milieubeheer landfill site in Houthalen-Helchteren, Belgium. The landfill received over 16 metric tons of waste from the 1970s onwards and covers today an area of 1.3 square kilometers. It contains an equal share of municipal (MSW) and industrial (IW) solid waste and is engineered in compliance with Flemish legislation and the EU Landfill Directive. The landfilled waste is planned to be entirely excavated over a period of 20 years, with operations starting in 2017. In this study some assumptions were made that slightly diverge from the ELFM consortium's plans. Ferrous and non-ferrous metals, amounting to 3% of the total content[2], as well as the stone fraction will be sold after extraction, while paper, plastics, wood and textiles will be entirely turned into Refused Derived Fuel (RDF) and energetically recovered for electricity generation in a fluidized bed incinerator (the ELFM project uses plasma technology). At the end of excavation activities the regained land will be sold as industrial area, while ELFM restores nature without any land sales.

4.2 Operative procedure for evaluating a landfill-mining project under UNFC-2009

To facilitate the UN framework's applicability for the classification of anthropogenic resources, an initial operative evaluation procedure has been developed for a case study on landfill mining . To classify a primary resource deposit before starting actual mining activities, the stages "prospection", "exploration" and "evaluation" have to be run through. In **Errore. L'origine riferimento non è stata trovata.** those three steps are linked to the goals of a landfill-mining project and then mapped to the corresponding UNFC-2009 axis, serving as a basis for the final classification. As the specific landfill was selected already beforehand the prospection stage was skipped in this work (cf. Table 1).

[2] 30 % Copper, 70 % Aluminum

Table 1. Operative procedure for evaluating a landfill-mining project under UNFC-2009 based on Winterstetter et al. (2015). MFA = Material Flow Analysis, DCF = Discounted Cash Flow Analysis.

Evaluation steps	Goal	Localization in UNFC-2009	Methods for decision foundation	Preliminary classification indicators
Prospection	First estimates on resource potential: Selection of a project	-	Macro scale MFA: Analysis & evaluation of landfill statistics & literature data on waste composition	General characteristics of site & landfill, e.g. type of landfill
Exploration	Gain knowledge on composition of the deposit & share of extractable & potentially usable materials	G-Axis	Detailed investigation of the landfill: Data from waste disposal log book & waste sampling & analysis Micro scale MFA with specific recovery efficiencies	Certainty of knowledge on the landfill´s extractable material content
	Identify different options for technologies & project set-ups	F-Axis	Technology assessment, policy framework analysis, stakeholder analysis	Maturity of technology, institutional structures & permissions
Evaluation	Socioeconomic viability of recovery, including direct financial effects & non-monetary modifying factors	E-Axis	DCF analysis & cut-off values for key parameters	Net Present Values (NPV) a) NPV > 0: Reserve b) NPV < 0: Resource or not?
Classification	Combination of all criteria & classification under UNFC-2009			

4.2.1 Exploration

Within the ELFM project extensive sampling activities and characterization studies of the waste samples have been performed to increase the knowledge about the landfill body's quantitative and qualitative composition. In addition, consistency checks have been completed based on the available log book data on the waste deposition at the site. Based on these information relevant material and energy flows are quantified in a Material Flow Analysis, by comparing the landfill's total resource potential to the extractable and potentially usable share of materials.

4.2.2 Evaluation of 4 scenarios

In the actual evaluation step, the socioeconomic viability of mining the identified extractable raw materials is explored, based on a Discounted Cash Flow (DCF) analysis. This method is also widely used for the evaluation for mining projects of primary resources.

At first, only direct costs and revenues, representing a private investor's micro perspective are included, while in a second step, non-monetary modifying factors that might significantly impact the project's economic viability are evaluated in a public entity's macro view. Specifically, greenhouse gas (GHG) emissions of the landfill-mining project are compared to a "Do-Nothing" scenario. Additionally, the impact of extended landfill aftercare obligations is investigated, and a conservative discount rate is assumed. Uncertainties originating from model input parameters of the economic analysis, such as recovered material quantities, costs and prices, are considered in an uncertainty and sensitivity analysis by performing Monte Carlo simulations.

Four scenarios are investigated (Figure 2), representing different alternatives for the combustible waste fraction's thermal treatment (on-site vs. off-site incineration) and for specific stakeholder interests (public vs. private perspective).

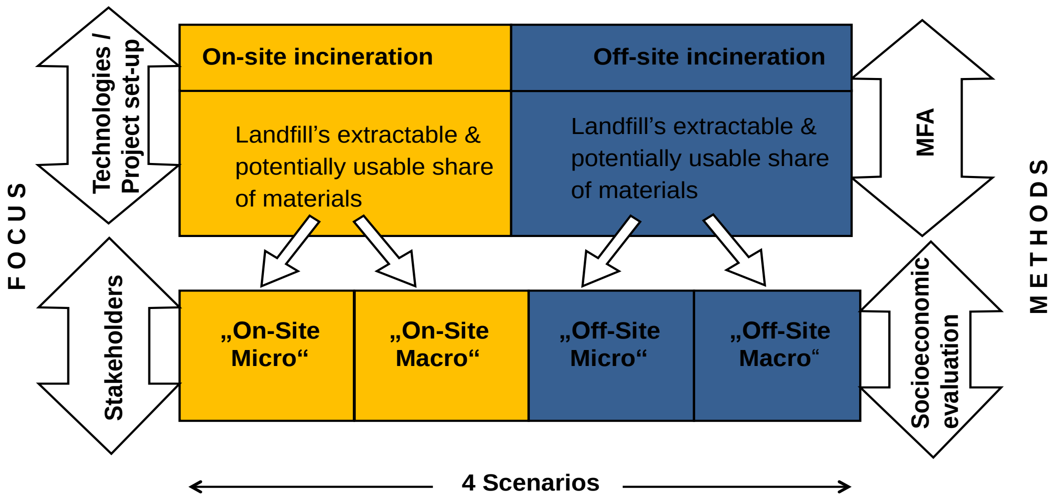

Figure 2. Investigated scenarios focusing on technological options and stakeholder interests.

The Net Present Values (NPV), computed by subtracting the investment cost from the sum of the discounted cash flows over a certain period of time, can be seen as the expected profit of the investment. In a first step only costs and revenues on the micro-economic level (i.e. excluding externalities), from a private investor's perspective. The macro perspective can highlight relevant factors that need to be included (i.e. monetized) in the economic assessment to create (additional) economic incentives for landfill mining. In the study at hand potential greenhouse gas emission savings of a landfill-mining project compared to a "Do-Nothing" scenario are monetized via a hypothetical CO_2 tax, to show exemplarily how non-monetary externalities can be included in the evaluation. In addition, a lower discount rate is applied and longer aftercare obligations in the "Do-Nothing" scenario are assumed, meaning that the avoided emissions and the avoided aftercare costs are higher due to landfill mining and can thus be considered as revenues. The sensitivity of the evaluation results with respect to input parameter variation is analyzed to identify the main drivers of economic performance.

4.2.3 Classification

A positive NPV implies that a project is economically viable. Consequently, the deposit to be evaluated can be classified as a reserve.

Feasibility studies in the mining sector often provide the "cut-off grade", which is defined as the level of mineral content that is used to discriminate between ore and waste within a given ore body, i.e. the level below which extraction is not economically viable. If the NPV turns out to be negative, ruling out the deposit to be a reserve, the calculated cut-off values for key parameters serves as a basis for assessing whether the deposit can be labeled a 'resource' or not. By comparing the cut-off values to the respective actual prices and costs, it becomes clear how these parameters need to change to turn the NPV at least into "0" and so to reach the break-even point. Based on historical and prospected future price / cost developments, the calculated factor for a neutral NPV can be judged realistic or not to reach in the foreseeable future. Thus, cut-off values give a hint about whether there are reasonable prospects for economic extraction or not, and serve therefore as decisive indicator for the following resource classification under UNFC-2009.

5. RESULTS AND DISCUSSION

The NPVs for the four landfill-mining scenarios are calculated based on a range of estimates regarding potentially recoverable and salable quantities (Table 2).

Table 2. Potentially recoverable & salable quantities (Total amount of annually excavated waste: 807 000 t wet matter)

	G1 Low estimate	G2 Medium estimate	G3 High estimate
Regained salable land (m2/a)	490,000	520,000	550,000
On-Site incineration: Electricity (MWh/a)	190,000	230,000	280,000
Off-Site incineration: RDF sold to external incinerator (t/a)	130,000	170,000	210,000
Stones / minerals (t/a)	50,000	85,000	120,000
Nonferrous metals (t/a)	1,200	2,400	3,600
Fine metals (t/a)	6,800	9,200	11,700
Metals from RDF preparation (t/a)	2,200	4,600	7,000
Ferrous metals (t/a)	7,000	14,000	22,000
Amount of materials to be re-landfilled (fines, sorting residues, incineration ash t/a)	560,000	480,000	400,000

The Net Present Values were found to be negative for all four scenarios, implying that none of the project's variations is currently economically viable, and therefore can certainly not be classified as reserves (Table 3).

Table 3. Average NPVs in €/t of total excavated waste based on Winterstetter et al. (2015) and Winterstetter and Laner (2014). Cash flows are discounted over 20 years with average discount rates of 3 % (macro) or 12 % (micro).

Scenario	On-Site Macro	On-Site Micro	Off-Site Macro	Off-Site Micro
Total discounted cost (€)	-680,000,000	-410,000,000	-563,000,000	-296,000,000
Total NPV (€)	-246,000,000	-233,000,000	-284,000,000	-197,000,000
NPV in € /t	-15.3	- 14.5	-17.6	-12.3

Cut-off values are therefore calculated for important economic performance parameters, to determine if and under which conditions the landfill can be labeled as resource. The scenarios are classified under UNFC-2009 based on required future price increases or cost decreases of parameters related to the thermal treatment of the combustible waste fraction as well as to the sales of recovered metals. To make the projects economically viable, i.e. to break even, we decided to analyze in a first step the effect of either increasing non-ferrous metal prices or of decreasing gate fees in the off-site incineration scenarios and higher feed-in tariffs for electricity in the on-site incineration scenarios (Table 4).

In the scenario "Off-Site Micro" the prices for non-ferrous metals would have to increase 10-fold. Alternatively, instead of paying gate fees to incinerate RDF off-site, which were assumed in average with 65 € / t RDF, the landfill miner should be paid 90 € / t RDF, to break even. In the scenario "Off-Site Macro" the landfill miner should receive 47 € / t RDF, or instead the prices for metals would have to increase 7.5-fold.

In the scenario "On-Site Macro" non-ferrous metal prices need to be 6.6 times higher than current prices and feed-in tariffs for electricity would have to increase by factor 2.6 from 45 €/ MWh to 116 €/ MWh. In the scenario "On-Site Micro" non-ferrous metal prices have to increase 11.6-fold, and the feed-in tariffs for electricity would have to increase by factor 4.6 from currently 45 €/ MWh to 207 €/ MWh.

These results might seem counterintuitive at first, as for the macro scenarios the factors to reach the cut-off values are lower, even though they have more negative NPVs (cf. Table 3 and Table 4). This is due to the lower discount rate (3 % in the macro scenarios compared to 12 % in the micro scenarios) resulting in a more balanced distribution of revenues over time. The GHG emission saving potential turned out to be negative, representing, however, only one amongst several other existing non-monetary effects of landfill mining to be potentially included in the macro evaluation.

Table 4. Factors to reach cut-off values for different <u>single</u> parameters. *Average price for the period 2010 – 2014 in Belgium.

Necessary changes in <u>single</u> parameters to break even: / Scenarios	Non-ferrous metal prices (Current: 1220 €/t*)	Feed-in tariffs electricity (Current: 45 €/MWh*)	Gate fees off-site incineration (Current: 65 €/t RDF*)
On-Site Macro	x 6.6	x 2.6	-
On-Site Micro	x 11.6	x 4	-
Off-Site Macro	x 7.5	-	Receive 47 € /t
Off-Site Micro	x 10	-	Receive 90 € /t

For all four scenarios it appears highly unrealistic to classify the landfilled materials as resources with "reasonable prospects for future economic extraction". However, focusing on only one parameter to distinguish between the UNFC-2009 categories "potentially commercial" vs. "non-commercial" does not reach far enough, as the evaluation depends on a number of factors. Therefore the cut-off values should be calculated under consideration of potential future changes of a set of main modifying factors. Nispel et al. (2012), for instance, assume that in the next 20 years ferrous and non-ferrous metal prices will double and operators of incineration plants will pay, due to overcapacities, at least 10 € per ton RDF made from the landfill's combustible materials. Additionally, they forecast operating costs of sorting plants to decrease by 20 % due to the use of more energy efficient technologies. Moreover, for the macro scenarios we assumed avoided aftercare costs for 30 years instead of 50 years after closure (for the micro scenarios 0 instead of 20 years), as the landfill-mining project will be postponed by 20 years into the future and aftercare costs have to be paid in the meantime.

Given all these hypothetical positive assumptions, the off-site scenarios of the landfill mining project would yield NPVs of in average -1.3 million € for the scenario "Off-site Micro" and 40 million € for the scenario "Off-Site Macro".

Regarding the on-site incineration scenarios, with 20 % lower sorting costs, doubling metal prices and feed-in tariffs for electricity assumingly to double by 2035 the scenario "On-Site Micro" would yield a negative NPV of -54 million € and the scenario "On-Site Macro" would result in a positive NPV of 88 million €.

In fact, keeping doubling metal prices and 20 % lower sorting costs, in scenario "On-Site Macro" it would be enough for feed-in tariffs to increase by factor 1.4 from currently 45 €/ MWh to 64 €/ MWh, while scenario "On-Site Micro" requires feed-in tariffs of 121 €/ MWh (factor 2.7) to reach at least the break-even point. In scenario "Off-Site Macro" a landfill miner could still pay 5.7 € / t for the disposal of RDF, while in scenario "Off-Site Micro" a payment of 11 € / t of RDF to the landfill miner would suffice to break even.

Table 5. Several assumed future changes in parameters related to metal sales, sorting costs and thermal treatment and the expected NPVs. *Average price for the period 2010 – 2014 in Belgium.

Assumed future parallel changes in: / Scenarios	Secondary metal prices (Current: Non-ferrous: 1220 €/t, Ferrous: 190 €/t*)	Feed-in tariffs electricity (Current: 45 €/MWh*)	Gate fees incineration (Current: Pay 65 €/t RDF*)	Sorting costs (Current: in average 22 €/t)	Expected NPV (mio €)	Cut-off values for gate fees / feed-in tariffs to break even (with assumptions for sorting cost -20% & metal prices x2 staying the same)
On-Site Macro	x 2	x 2	-	- 20 %	88	Feed-in 64 € / MWh (x 1.4)
Off-Site Macro	x 2	-	Receive 10 € /t	- 20 %	40	Pay 5.7 € /t RDF
Off-Site Micro	x 2	-	Receive 10 € /t	- 20 %	-1.3	Receive 11 € /t RDF
On-Site Micro	x 2	x 2	-	- 20 %	-54	Feed-in 121 € / MWh (x2.7)

The micro-perspective scenarios are classified as uneconomic (E3), due to the unlikely increases in prices and revenues needed to reach the cut-off values, with both individually changing parameters (cf. Table 4) and still with several parallel changing parameters (cf. Table 4). Especially the required positive payment for RDF disposal is in the authors' view rather questionable.

While the macro-perspective scenarios do not achieve positive NPVs under current economic conditions either (cf. Table 3), for them reaching cut-off values seems, however, more realistic. Therefore they are classified as "potentially economic" (=E2) (cf. Figure 3).

The F-axis (second digit) expresses "field project status and technical feasibility". Even though only well-known technologies are applied in the scenarios and the institutional structure is already established, i.e. the current landfill owner is seriously planning the project with committed partners, the project is still in the feasibility stage with mainly design and planning activities and operations on a pilot scale. The legal framework for landfill mining has not been developed so far. Therefore, all scenarios are classified as potentially feasible (F2).

In terms of "knowledge on the landfill´s extractable material content", all scenarios are graded with „G1", as the quantities contained in the landfill can be estimated with a high level of confidence deduced from both the sample excavations and the landfill's logbook data. Also the applied technologies for material extraction and recovery can be estimated with sufficient detail for assessing the landfill's extractable raw material potential.

In line with the Petroleum Resources Management System (PRMS) specifications for petroleum under UNFC-2009 the G-classes can also be used to express an uncertainty range, i.e. low, medium and high estimates, of potentially recoverable and salable quantities of materials and energy (cf. Table 2).

Combining those three criteria, the macro-perspective scenarios are categorized as E2F2G1 ("resources") and the micro-perspective scenarios are evaluated as not even potentially economic

(E3F2G1) (Figure 3).

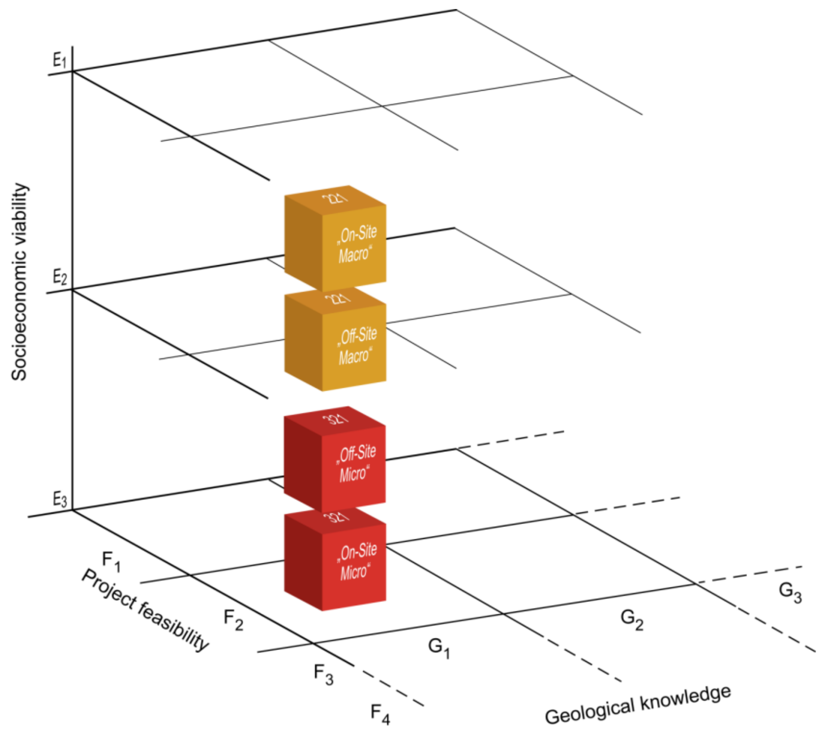

Figure 3. The applicability of UNFC-2009 is illustrated by classifying the 4 scenarios of the original landfill-mining project. Legend: 1st digit –"Socioeconomic viability"; 2nd digit –"Field project status and technical feasibility"; 3rd digit – "Knowledge on composition".

6. CONCLUSIONS AND OUTLOOK

In this study, the natural resource classification framework UNFC-2009 was applied to a landfill-mining project in Belgium to identify the landfilled materials as potential anthropogenic resources or reserves, and to reveal critical factors for the resource classification of the project.

The applicability of UNFC-2009 to landfill mining has been proven successfully. In order to obtain a comprehensive overview of existing and potentially extractable anthropogenic resource inventories and to allow the full integration into UNFC-2009, we are currently working on the definition of suitable, quantifiable criteria to provide a methodological framework for the evaluation and classification of anthropogenic stock and flow materials. The heterogeneous nature of anthropogenic resources requires thorough research and understanding of the system variables and influencing factors of mining specific materials from different sources. This will also facilitate decision-making for political and private business stakeholders.

Based on very positive expectations towards future treatment costs and potential revenues from material valorization, the present landfill-mining project appears to be economically feasible. Therefore, the macro-perspective scenarios are classified as resources, while the micro-perspective scenarios are considered as not even remotely economic. Consequently, a private investor is probably going to put money into landfill mining only if external effects of landfill mining are monetized via subsidies, tax reductions, or the like.

In this context the systematic integration of non-monetary effects will be of high priority, as for most anthropogenic materials extraction is not (yet) economically viable under current conditions. Social and environmental externalities (e.g. eliminating sources of pollution) tend to generate additional benefits and should therefore be monetized and included in the evaluation. Combining aspects of waste and resource management is hereby a key challenge.

All in all, the integration of anthropogenic materials under UNFC-2009 will improve the estimates of global total resources inventories and their extractable fractions by considering various boundary conditions, allowing for fair comparisons between naturally occurring and anthropogenic resource deposits.

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