REPAiR

REsource Management in Peri-urban AReas: Going Beyond Urban Metabolism

D4.7 Sustainability assessment for the management of key waste streams in Ghent, Naples, Hamburg, Lodz and Pecs: *Status Quo* versus alternative strategies

Authors: Davide Tonini (JRC), Sue Ellen Taelman (UGent), Alessandro Arlati (HCU), Silvia Iodice (Unina), Chiara Mazzarella (Unina), David Sanjuan Delmas (UGent), Csaba Vér (Biokom), Ágnes Óvári (RKI), Andrea Suvák (RKI), Andreas Obersteg (HCU), Magdalena Rybaczewska-Błażejowska (IGiPZ PAN), Damian Mazurek (IGiPZ PAN), Marcin Mazur (IGiPZ PAN), Cecília Mezei (RKI)

Contributors: Maria Cerreta (Unina), María Ignacia Rodríguez Escobar (UGent), Daniele Dalla Vecchia (UGent), Jo Dewulf (UGent). Tamás Szabó (RKI), Viktor Varjú (RKI), Andrea Lopes (HCU), Tatina Moschini (HCU), Andrea Spirito (HCU), Sara Salerno (HCU), Tom Claeys (IVAGO), Gustavo Arciniegas (Geo-col), Michał Konopski (IGiPZ PAN)

Grant Agreement No.:	688920
Programme call:	H2020-WASTE-2015-two-stage
Type of action:	RIA – Research & Innovation Action
Project Start Date:	01-09-2016
Duration:	48 months
Deliverable Lead Beneficiary:	JRC
Dissemination Level:	PU
Contact of responsible author:	davide.tonini@ec.europa.eu

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No 688920.

Dissemination level: PU = Public

Change control

n°	DATE	AUTHOR	ORGANI SATION	DESCRIPTION / COMMENTS
1.0	21/01/2020	Sue Ellen Taelman	UGent	Template
1.1	19/02/2020	Sue Ellen Taelman	UGent	Input case Ghent - overall introduction
1.2	25/03/2020	Davide Tonini; Sue Ellen Taelman	JRC; UGent	Naples food waste case; Status Quo Ghent case, detailed description
1.3	26/03/2020	Davide Tonini	JRC	Formatting according to template REPAiR
1.4	03/06/2020	Sue Ellen Taelman	UGent	Strategy description
1.5	18/06/2020	Csaba Vér, Ágnes Óvári	Biokom, RKI	Pécs description case study
1.6	24/06/2020	Silvia Iodice	Unina	Naples case study Key waste stream: construction and demolition waste
1.7	25/06/2020	Silvia Iodice	Unina	Results for Naples case study: Construction and Demolition Waste (Annex B)
1.8	25/06/2020	Alessandro Arlati	HCU	Description of the case study Hamburg and first two scenarios
1.9	26/06/2020	Sue Ellen Taelman	UGent	Strategy results + feedback Pécs case
2.0	26/06/2020	Alessandro Arlati	HCU	Description of S3, S4 and S5
2.1	29/06/2020	Alessandro Arlati	HCU	Midpoint and Endpoint results for Hamburg case
2.2	30/06/2020	Davide Tonini	JRC	General comments and rephrasing
2.3	30/06/2020	Silvia Iodice	Unina	Midpoint and Endpoint results for Naples case study: Construction and Demolition Waste
2.4	30/06/2020	Alessandro Arlati	HCU	Insertion of figures, tables and flow

				diagrams in the Hamburg case
2.5	30/06/2020	Damian Mazurek	IGiPZ PAN	Status quo description, insertion of figures, tables for Łódź case study
2.6	01/07/2020	Damian Mazurek, Magdalena Rybaczewska-Błażejowska	IGiPZ PAN	Status quo description, insertion of diagrams for Łódź case study
2.7	01/07/2020	Davide Tonini	JRC	Introduction, harmonisation wording used, individual feedbacks
2.8	01/07/2020	Andreas Obersteg	HCU	Review of the Hamburg text
2.9	01/07/2020	Alessandro Arlati	HCU	Correction according to feedbacks and insert tables in Annex Hamburg
3.1	02/07/2020	Silvia Iodice, Sue Ellen Taelman	Unina, UGent	Total annual impact (selected indicators) Net annual impact change relative to the Status Quo (selected indicators)
3.2	02/07/2020	Damian Mazurek, Magdalena Rybaczewska-Błażejowska	IGiPZ PAN	Description updates, Diagrams updates, Results description for Łódź case study
3.3	02/07/2020	Davide Tonini	JRC	Publishable Summary, Section 4 (Discussion), harmonisation wording used, individual feedbacks
3.4	03/07/2020	Davide Tonini, Sue Ellen Taelman	JRC, UGent	Reorganisation of Annexes, individual feedbacks
3.5	08/07/2020	Gustavo Arciniegas	Geo-Col	General feedback and comments, and full review.
3.6	08/07/2020	Damian Mazurek	IGiPZ PAN	Diagrams update for Łódź case study
3.7	09/07/2020	Damian Mazurek, Michał Konopski	IGiPZ PAN	Midpoint results description update for Łódź case study,

				American/British English verification
3.8	15/07/2020	Alessandro Arlati	HCU	Fix changes according to comments
3.9	20/07/2020	Silvia Iodice	Unina	Fix changes according to comments
4.0	20/07/2020	Csaba Vér	BIOKOM	Update in Pécs case results and Annex F
4.1	21/07/2020	Silvia Iodice	Unina	Diagrams update for Naples case study
4.2	22/07/2020	Silvia Iodice	Unina	Re-reading and final adjustments
4.3	22/07/2020	Davide Tonini	JRC	Review, consolidation of all comments, and final adjustments
4.4	22/07/2020	Damian Mazurek	IGiPZ PAN	Diagrams update for Łódź case study, descriptions re-reading
4.5	23/07/2020	Damian Mazurek	IGiPZ PAN	Diagrams update for Łódź case study
4.6	23/07/2020	Davide Tonini	JRC	New Figures, Consolidation and final adjustments
4.7	24/02/2021	Davide Tonini	JRC	Revision based on the review by the evaluators – feedback and input
4.8	08/03/2021	Sue Ellen Taelman	UGent	Revision based on the review by the evaluators – feedback and input

Acronyms and Abbreviations

AD	Anaerobic Digestion
AD&C	Anaerobic Digestion and Composting
AoP	Area-of-Protection
BKW	Biogas- und Kompostwerk Anlage Bützberg
BSF	Black Soldier Fly
CAPEX	Capital Expenditures
CDW	Construction and Demolition Waste
CNG	Compressed Natural Gas
CDW	Construction and Demolition Waste
CHP	Combined Heat and Power
CLO	Compost-Like Organic
DM	Dry Matter
EIS	Eco-innovative Solution
End-of-Pipe	Any waste management system that processes waste before disposing it
FA	Focus Area
FU	Functional Unit
FW	Food Waste
HDPE	High Density Polyethylene
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory

MBT	Mechanical-Biological treatment plant
MSW	Municipal Solid Waste
MVB	Müllverbrennungsanlage Borsigstraße
NA	Natural Aggregates
NPK	Nitrogen, Phosphorous, Potassium
NSC	Non-Separately Collected
OELEX	End-of-Life Expenditures
OPEX	Operational Expenditures
OW	Organic Waste
PULL	Peri-Urban Living Lab
RA	Recycled Aggregates
SC	Separately Collected
SME	Small and Medium Enterprises
SQ	Status Quo
SRH	Stadtreinigung Hamburg
VFG	Vegetables, Fruit and Garden
ZRE	Zentrum für Ressourcen und Energie (Centre for resources and energy)

Table of Contents

Publishable Summary

This deliverable assesses the sustainability of both the *Status Quo* and a set of strategies for the management of organic waste in the selected Focus Areas in the cities of Ghent, Naples, Hamburg, Łódź, and Pecs and for the management of construction and demolition waste in the Focus Area of Naples. This is done by applying the sustainability framework developed in the context of the REPAiR project where solutions or strategies (i.e. combination of solutions) can be quantitatively compared to their corresponding *Status Quo*, here identified as the best proxy of the current-day management of the waste. The framework encompasses 27 indicators that cover 25 impact categories, which are classified in five Areas-of-Protection (AoP) namely: human health, ecosystem health, natural resource, prosperity, and human well-being. Striving to thoroughly describe the studied areas, primary data have been collected with respect to waste generation and composition flows, collection schemes and treatment operations in the *Status Quo* alongside literature data or best-available estimates to describe the eco-innovative solutions/strategies proposed by the stakeholders.

Our findings suggest that solutions aiming to prevent wastages or to maintain organic waste within the food/feed supply chain appear the most favourable, e.g. production of animal feed through black soldier flies investigated for the Focus Area of Ghent. This is in line with the results obtained for the pilot case of Amsterdam Metropolitan Area described elsewhere in the REPAiR project outputs. Focusing on the lower level of the waste hierarchy, mostly considered in the cases of Naples, Hamburg, and Lodz, increasing the levels of anaerobic digestion coupled with post-composting appears to be the preferred solution owing to the increased energy recovery relative to the other strategies, e.g. direct centralised or domestic composting, and to the recovery of nutrients and carbon in the form of compost. Strategies only aiming at increasing the level of direct centralised and home composting (i.e. only aerobic treatment without energy recovery) are clearly less preferable, except for the incurred costs (Area-of-Protection Prosperity) that are often the lowest among the alternative solutions, although in many cases they are still higher than the *Status Quo*. This was also observed in the pilot case on the Amsterdam Metropolitan Area (Deliverable D4.8). For the specific case of construction and demolition waste, we observe that substantial potential for improvement exists as often the quality of the recyclates is low or the full potential of the recyclable material in the buildings is not captured at the demolition stage. On top, while savings per tonne of construction and demolition waste may appear low, the total annual savings are instead substantial as construction and demolition waste represents the largest portion of waste generated in Europe.

For future projects, we suggest to apply the sustainability assessment framework (cfr. Taelman et al. 2020) to the envisaged strategies at an early stage of the project, even with preliminary data, as this provides meaningful results in order to phase out non-sustainable strategies and carry on and/or further develop only those that present a clear advantage compared to the *Status Quo*. In this report, we also provide a broader discussion on the limitations of our sustainability assessment framework. Upon consideration of the scientific feedbacks received throughout the project (including publications, conferences, etc.), we believe that life cycle thinking based methods remain essential for assessment of circular economy strategies but should be enhanced, e.g. with future scenario analyses and participatory process to better define scenarios, assumptions and surrounding conditions and

the introduction of dedicated circularity indicators could be helpful to better grasp the circularity potential of scenarios. In addition, as data gaps may prevent making sound conclusions, one of the main challenges of this study it to collect sufficient qualitative data both for the *Status Quo* and the alternative solutions. Last, while we had strong arguments not to enter this field within the REPAiR project, methodological developments in relation to specific indicators (e.g. for the Area-of-Protection "Natural Resources") seem desirable to capture the importance of biotic resources.

1. Introduction

Striving towards a more circular economy, European cities face important challenges in managing their waste. While many treatment and valorisation options exist, their impacts on the environmental, social, and economic dimensions are often not fully understood. However, a science-based knowledge of the consequences associated with these management options is key to support sound decisions. In the endeavour to advance the scientific knowledge in the field and to inform decision-makers and local authorities with science-based evidence, we assess the sustainability of the management of key waste streams in Ghent, Naples, Hamburg, Łódź, and Pecs. For all cities, we focus on the management of organic/food waste (compared to food waste, organic waste also includes some additional organic fractions, e.g. garden waste), as this was indicated as the most relevant stream by stakeholders in previous project deliverables. In addition, for the specific case of Naples, we also illustrate the case of construction and demolition waste, as this was pinpointed as equally important in that context. Applying the framework for sustainability assessment presented in Taelman *et al.* (2020), we quantify the impacts of different strategies for waste management on 27 midpoint impact indicators (e.g. Global Warming, Private Space Consumption, Operational Expenditures) that are classified into 5 areas-of-protection (human health, ecosystem health, natural resources, human well-being, prosperity). In order to synthesize and communicate results in a manner that is understandable by a broad audience, we further aggregate the midpoint results via multi-criteria decision analysis to derive a ranking of the strategies assessed per each of the five areas-of-protection. Maintaining a separation between the individual areas-of-protection allows positioning the assessment on the so-called "robust sustainability ground", as compensation across pillars (e.g. by summing economic and environmental results) is avoided. However, the drawback is that we obtain five rankings instead of a single one, thus making communication less straightforward. This deliverable is a follow up of Deliverable D4.8 that focuses on the pilot case of the Amsterdam Metropolitan Area (Tonini *et al*., 2020). Many of the datasets and assumptions taken in that context are applied to the case studies addressed herein. The aims are as follows:

- Assessing the sustainability of selected strategies against that of the *Status Quo*, for each case study.
- Drawing overall learnings and limitations/perspectives in relation to the assessment approach and related findings.

This deliverable is composed of the following sections:

- Section 2: Description of the five Focus Areas, the key flows under study, the scenarios, modelling approach, assumptions and inventory.

- Section 3: Results of the sustainability assessments for the five Focus Areas.
- Section 4: Overall summary of the results, limitations and perspectives.

2. Materials and Methods: the five Focus Areas

We perform a sustainability assessment for the management of key waste streams in the following Focus Areas (FAs): Ghent, Naples, Hamburg, Lodz, and Pecs. In total, we investigate six case studies as follows: food/organic waste (FW) management for the FAs of Ghent, Naples, Hamburg, Lodz, and Pecs and construction and demolition waste management (CDW) for the FA of Naples. The assessment is performed following the sustainability framework developed in Deliverable D4.4 and D4.5 (see also Taelman *et al.*, 2020) encompassing five areas of protection (AoPs) with a total of 27 indicators for 25 impact categories, either environmental, social or economic oriented (Annex A). For additional details, the reader is referred to Taelman *et al.* (2020). The assessment applies a consequential approach (Weidema *et al.*, 2009) striving to include the consequences of applying changes to the current waste management system. In the context of this deliverable, we call *Status Quo* the reference management scheme of the selected waste stream. This is typically identified with the last available year for the regional waste statistics at the time when the study was initiated and varies across the case studies (e.g. 2015-to-2018). For the sake of simplicity, we call "strategy" any management scheme that is alternative to the *Status Quo* and quantitatively compared against that. Most of the strategies consist of spatially-explicit implementations of more than one eco-innovative solution (e.g. increased separate collection and biological treatment, etc.). The strategies assessed in this Deliverable should therefore be seen as illustrative examples of "possible strategies" and may not fully reflect the combination of eco-innovative solutions (i.e. strategies) presented elsewhere in the REPAiR project outputs. The strategies investigated are based on the solutions proposed by local stakeholders via the PULLs. The temporal scope of the analysis is 2020-2030. This particularly affects the assumptions regarding the energy system in place (i.e. mix of fuels displaced through waste-to-energy technologies).

2.1. Ghent

2.1.1. General

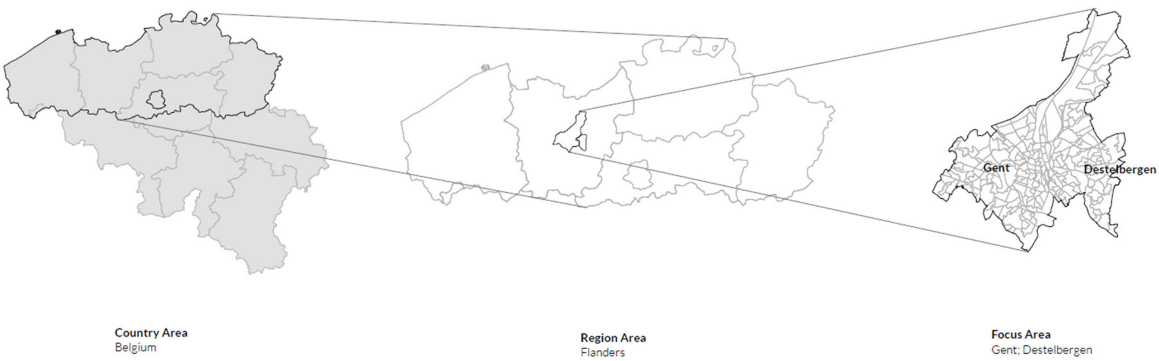


Figure 1, Ghent case study, from country to Focus Area.

The area **Ghent-Destelbergen** is identified as a FA within the REPAiR Project (Figure 1). Gent and Destelbergen are neighbouring municipalities in East-Flanders, a province in the Flemish region of Belgium. The two municipalities are each legally responsible for the implementation of their municipal waste policy. Both municipalities delegate their authority for the collection and treatment of waste to the inter-municipal organisation IVAGO.

The LCA-related indicators of the sustainability analysis were implemented with *Simapro software* v9.0 and the life cycle ecoinvent v3.5 database and Agri-footprint were used to model the background system. Data inventory for the Status Quo consists mainly of primary site-specific data, provided by local actors. All indicators of the framework of Taelman et al. (2020) were applied.

2.1.2. Key waste stream: Vegetables, Fruit and Garden Waste (VFG)

In line with the EU target of recycling 65% of municipal waste by 2030 and a binding target to reduce landfill to a maximum of 10% of municipal waste by 2030, the PULL workshops in Ghent (cfr. WP5) focused on bio- and residual waste from households. Since biowaste still represents a considerable amount of the residual waste from households, increasing the separate collection of biowaste from household (and more specific vegetable, fruit and garden waste: VFG) contributes to the policy objective of the Implementation Plan to further reduce the amount of residual household waste. This is also in line with the *Ketenroadmap Voedselverlies '15-'20* (Roadmap food waste '15-'20)[1], which aims to reduce food waste by 15%.

The Functional Unit (FU) considered in this study is 1 t of VFG waste as generated by households and small-and-medium-enterprises (SMEs) in the FA per year. Any (co-)product generated alongside the management of the waste is credited to the system by expanding it to account for the substitution of conventional market products.

Status Quo

Description

The VFG waste management in 2016 in the FA is described herein. IVAGO organises Ghent in zones, which differ in the way that non-separately collected-VFG (*further referred to NSC-VFG*), i.e. mixed household waste that contains the fraction of VFG and separately collected VFG (*abbr. to SC-VFG*) are collected. In the Z-zone or 'zakken–zone' (English: 'bags–zone') customers can dispose of their residual waste (containing NSC-VFG) in yellow High Density Polyethylene (HDPE) garbage bags, which they can buy on a roll. IVAGO collects regularly (that is, weekly) these bags in the street (curbside or door-to-door collection). The households in the Z-zone can request a HDPE bin to dispose of their VFG in (separate collection) on a voluntary basis. Conversely, in the C- zone or 'container-zone' ('bins-zone') customers are obliged to buy a green (for VFG) and a grey (for residual) waste bin. They pay a fixed price per type of bin that gets emptied. VFG bins are cheaper than mixed household waste bins (same volume and carrying capacity). The same system as in the C-zone is applied in Destelbergen, however, collection of the residual waste is done by a company called 'Lammertyn', while the VFG (in green bins) is collected by IVAGO. Ghent also has buildings with more than 10 housing units. Residents of such housings have to dispose of all their residual waste in yellow bags, and have to throw these bags in big black containers. If a resident wishes, he/she can also offer his VFG separately in small green bins. Overall, in the FA, a door-to-door collection system is applied.

[1] The 'Ketenroadmap voedselverlies 2015-2020' is an action plan to prevent food waste in Flanders by 2020. It was signed on 31 March 2014 by the Flemish government and partners from the value chain: Boerenbond, FEVIA Vlaanderen, Comeos Vlaanderen, Horeca Vlaanderen en OIVO.

In 2016, 9,469 t of VFG were collected separately in the FA, i.e. approximately 75 kg per household per year. After collection, all SC-VFG is first stored in the north of Ghent at a storage facility of SUEZ, a French environmental services company. The VFG is dropped off by waste collection trucks and brought to a concrete, open air storage area where it is mixed. Afterwards, trucks take all the VFG to IVVO in Yper (+/- 95km), where the VFG is anaerobically digested and composted. NSC-VFG is directly, after collection, transported to the incineration plant at IVAGO. Still a substantial amount of VFG ended up in the mixed household waste (6,250 t or 40% of total VFG generated), i.e. about 50 kg of NSC-VFG per household in 2016. About 2 weeks per year, the NSC-VFG is brought to SUEZ for temporary storage due to yearly maintenance of the incineration plant.

Table 1 Collection of SC-VFG and NSC-VFG in the FA, per zone, expressed in kg per year (2016).

Collection type	Zone FA	kg/yr	Contribution
SC-VFG	C Zone	6,25E+06	
SC-VFG	Z Zone	2,00E+06	
SC-VFG	Apartments	9,19E+04	
SC-VFG	Destelbergen	1,12E+06	
Total SC-VFG		***9,47E+06***	**60%**
NSC-VFG	C Zone	1,46E+06	
NSC-VFG	Z Zone	3,47E+06	
NSC-VFG	Apartments	1,05E+06	
NSC-VFG	Destelbergen	2,67E+05	
Total NSC-VFG		***6,25E+06***	**40%**
	TOTAL VFG	**1,57E+07**	**100%**

System boundaries

Collection processes, transport (hauling), incineration of NSC-VFG, anaerobic digestion and composting of SC-VFG were the processes included in the foreground system while both the further treatment of some recovered resources from the treatment processes (e.g. wastewater treatment) and subsequent disposal/treatment of residues (e.g. landfilling of heavy fractions) were included in the background system. The fate of these resources is known, but no detailed information on recycling or manufacturing processes was available, so average data from databases was used. The waste incinerator contains 10 stages: waste bunker, furnace, separation of ferrous metals from bottom ashes, boiler, turbine, semi-wet washing, sleeve filters, wet washing, DeNOx and a stack. The SC-VFG fraction undergoes 12 sub-processes: mixing/fragmentation/sieving, pulping, sand removal, anaerobic digestion, incineration of biogas in a combined heat-and-power (CHP) unit, drum screens, hygienisation, ripening, sieving, storage, wastewater treatment, and air cleaning, available at the IVVO site. Details about the material and energy streams taken into account are available on request. In Figure 2, simplified versions of both the foreground and background systems are shown.

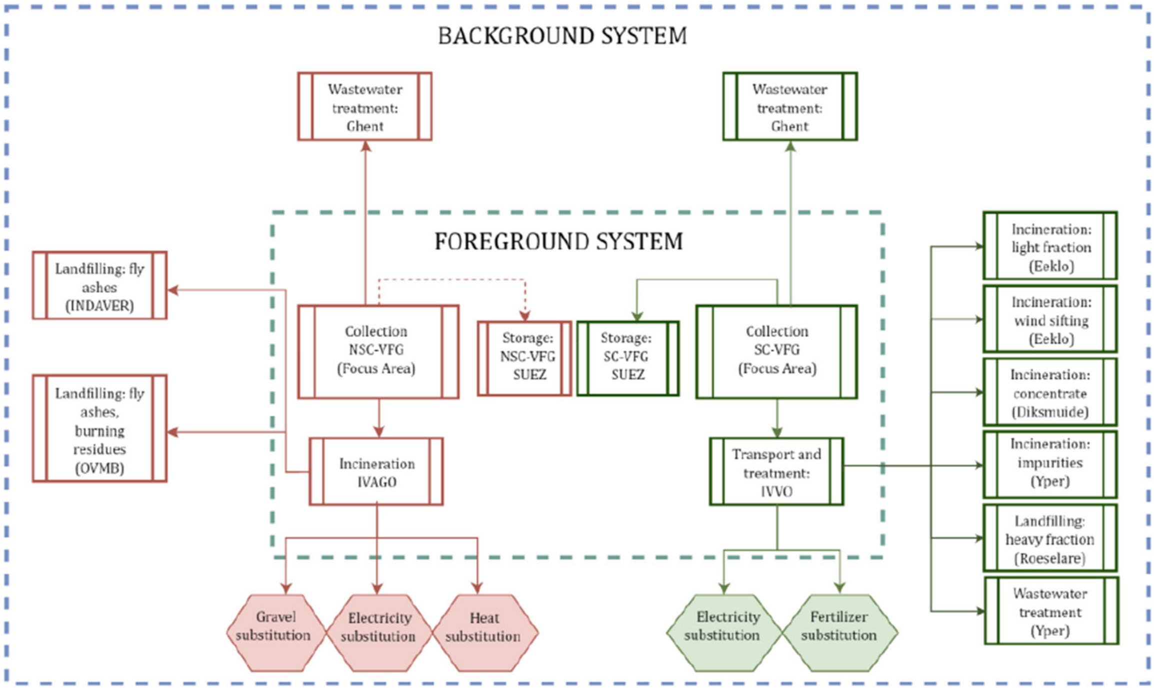


Figure 2, Processes in the foreground and background system collecting and treating VFG, its residues and avoided products. SC-VFG-related processes and flows are green coloured while the NSC-VFG-related ones are red. Arrows only serve to indicate the flow of SC/NSC-VFG and residues.

The environmental impacts of co-products generated alongside the management of the VFG waste are credited to the system by means of substitution to include the impacts of the corresponding (conventional) market products, similar to the approach of Tonini *et al.* (2020). By incinerating NSC-VFG, waste energy (electricity and heat) is recovered in its end-of-life phase. This energy production avoids energy production by other technologies that e.g. use fossil resources such as coal, oil, etc. It was assumed that production of electricity from the Belgian production mix and heat from a 100 MW natural gas fuelled CHP unit are avoided by heat and electricity production (Ecoinvent Centre, 2019). Next, it was assumed that bottom ashes avoid the excavation of gravel, which is normally used in the natural aggregates that serve as a base layer to strengthen roads, as published by Allegrini *et al.* (2015). SC-VFG treatment produces compost. Because it was unknown for which purposes the compost is applied (e.g. as substitution for peat), the substitution has been performed based on Tonini *et al.*, (2020), assuming an average EU mix for the substitution of NPK mineral fertilisers. This mix includes 24.5% urea, 27% ammonium nitrate, 33% calcium ammonium nitrate and 15.5% urea-ammonium nitrate, diammonium phosphate and potassium chloride.

Data inventory

Overall, care was taken to include all relevant foreground processes and use site-specific data as much as possible (obtained from local actors) or adapt (similar) processes from LCA databases/literature with location-specific data. The composition of mixed household waste in Ghent was analysed based on a sampling done in the FA, performed by the Organic Waste Systems (OWS) company. The ultimate composition of VFG was based on a literature study (Komilis *et al*. 2012).

For the collection, most primary data for the LCI was provided by IVAGO. The cleaning company GOM provided an estimation on soap/water usage for truck cleaning. Electricity usage for the life cycle of a HDPE bin was taken from a study by Brogaard & Christensen (2016). The average volume of a HDPE bag and the estimation on the amount of NSC-VFG in the Z zone were based on a report by OVAM (OVAM, 2014). For the incineration, most primary data was provided by IVAGO. Google Maps was used to estimate the surface of industrial land area occupied. Primary data for the anaerobic digestion and composting process was provided by IVVO. Emissions of the CHP unit were estimated based on a study by Benato *et al.* (2017). Emissions of the air cleaning were based on studies by Andersen *et al.* (2010), Pagans *et al.* (2006), Van der Heyden *et al.* (2015) and Nemecek & Kägi (2007). The transport distance from SUEZ to IVVO, and total occupied industrial land area were based on Google maps. More details regarding material and energy usage during collection, incineration or AD/composting are available in Scheirlinckx (2018).

To complete the economic assessment, apart from primary data of IVAGO, available data from the pilot case of the Amsterdam Metropolitan Area (Deliverable D4.8; Tonini *et al.*, 2020) was used for some specific fields such as labour, insurance and maintenance. When this data was used, the incineration plant was a proxy with the inventory of the incinerator AEB and the AD/composting plant was a proxy with the (average) inventory of Meerlanden, Middenmeer and Indaver (see Tonini *et al.*, 2020; Appendix C).

For the social assessment, employment rates, accidents, collection fees and area occupied by treatment plants were based on primary data of IVAGO and/or IVVO. Similar to the Amsterdam Metropolitan Area (AMA) approach, stakeholder involvement was considered zero for the *Status Quo*. The standardized coefficient as calculated within the AMA case study was used to calculate landscape disamenities, and additionally the households per distance range were provided by the City of Ghent. The City of Ghent also provided input in the living space (floor area) of households in the Ghent area. The reader is referred to the original publications and related supporting information material for additional details regarding the foreground system (Rodriguez Escobar, 2020). Ecoinvent 3.5 (consequential version) and Agri-footprint were used as the background databases.

MAIN STRATEGY: Improved VFG collection system and production of Black Soldier Flies

This strategy combines four single solutions, as listed below:

EIS 1: CNG fuelled collection trucks

This EIS investigates the effect of another type of vehicles to collect the waste in the entire FA. CNG fuelled trucks, as opposed to diesel fuelled ones in the reference scenario, are now considered.

EIS 2: Mandatory separation of VFG in whole FA

This EIS considers the enlargement of the zone where having VFG bins is mandatory to the entire focus area, including now the Z-zone and apartments as well. As observed by a sampling performed on residual household waste in Ghent by the OWS company, the fraction VFG waste within the residual waste corresponds to 19.3% (mass-based) in the dense Z-zone and apartments and decreased to 14% once separate collection becomes mandatory, which indicates that the mandatory separation process has proven to increase the capture rates of SC-VFG. However, this data is provided based on a sampling done only a few weeks after the transition towards mandatory separation. This probably means that more VFG could be captured separately than the sampling reveals. Therefore, it was assumed that 50% of the NSC-VFG in the Z-zone and the apartments is now separated. Table 2 provides the SC-VFG and NSC-VFG amounts for this EIS.

Table 2, Collection of SC and NSC VFG in the FA, per zone, expressed in kg per year (EIS mandatory separation of VFG).

Collection type	Zone FA	kg/yr	Contribution
SC-VFG	C Zone	6,25E+06	
SC-VFG	Z Zone	3,74E+06	
SC-VFG	Apartments	6,18E+05	
SC-VFG	Destelbergen	1,12E+06	
Total SC-VFG		***1,17E+07***	**75%**
NSC-VFG	C Zone	1,46E+06	
NSC-VFG	Z Zone	1,74E+06	
NSC -VFG	Apartments	5,26E+05	
NSC -VFG	Destelbergen	2,67E+05	
Total NSC-VFG		***3,99E+06***	**25%**
	TOTAL VFG	**1,57E+07**	**100%**

Another assumption made concerns the fuel consumption for collection. Since every household in the FA will now have a bin for the separation of the VFG, the collection will have a different impact in terms of the fuel (diesel) needed for the trucks. In particular, according to the findings reported in Scheirlinckx (2018), when the collection trucks have more frequent stops for collecting the waste (which is the result of mandatory separation), the fuel consumption is less per kg VFG collected (the routing will remain the same).

EIS 3: Increased frequency (weekly) of VFG collection

The collection schedule is changed to a weekly collection of the VFG waste for the Z-zone and apartments (instead of each 2 weeks). The C-zone and Destelbergen were not included in the collection scheme change of the solution, mainly because after personal communication with IVAGO, the conclusion was that in those areas home composting is a common practice. Moreover, increasing the collection frequency there would only result in higher costs for the company and not necessarily higher revenues. Furthermore, in the Z-zone and apartments, houses are smaller and therefore, the space is limited to store waste. This, in combination with the smell related to VFG waste, are good justifications for this decision.

EIS 4: Production of Black Soldier Flies from VFG for fertilizer, feed and food purposes
The novel process is based on the bioconversion of the Black Soldier Fly (BSF) in order to obtain valuable products. At this stage, it is assumed that all the SC-VFG in the focus area ends up at the BSF treatment facility, no longer undergoing anaerobic digestion and composting. Dried BSFs contain around 40 – 50% protein on a dry matter basis (Inagro, 2019). The BSF is also known to have fats embodied up to 49% (%DM) and contain many nutrients, such as calcium and manganese (Wang & Shelomi, 2017) that are important if the insects are used for feed and/or food purposes (Smetana *et al.* 2019). Optimum conditions for the rearing of these flies include a temperature range between 29-31 °C, humidity around 50-70% and an adequate oxygen supply (Salomone *et al.*, 2017). Several studies suggest that the overall range of organic waste reduction, depending on the feeding regime and type of waste, varies between 20 – 80%, on a dry matter basis (Joly & Nikiema, 2019). Therefore, breeding BSF can be extremely beneficial when valorizing municipal organic waste (Diener *et al.*, 2011; Wang & Shelomi, 2017; Dortmans *et al.*, 2017).

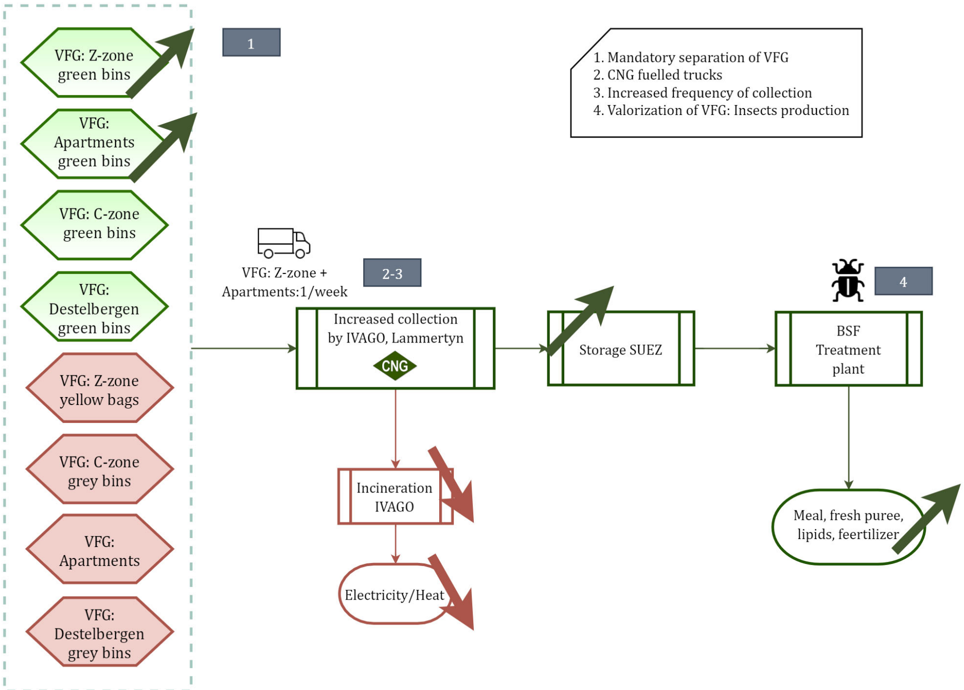


Figure 3, Main strategy, Ghent case, integrating four single solutions. The green thick arrows indicate the flows that are expected to increase with the implementation of this strategy, while the red thick ones, the flows that are expected to decrease compared to the Status Quo.

Figure 3 - 4 provide a simple process scheme of the main strategy, which is a combination of four solutions. The objective is to assess the performance of the whole strategy and compare it to the *Status Quo*. This combination includes the use of CNG as fuel in the collection trucks, having a mandatory separation of VFG for the Z-zone and apartments and increasing the frequency of collection. Finally, all the SC-VFG will be taken to SUEZ, where it will be stored until it is transported to a hypothetical BSF plant, where it will be valorized into several products. This study is the result of adapted datasets from a BSF production and processing

facility called Protix, in the Netherlands. The process consists of several phases. First, in order to prepare the substrate for the flies, the VFG is transported to the plant, where it is shredded, mixed and stripped from impurities. Next, the VFG stream enters a pasteurization step to treat possible contaminants present in the waste. At this stage, the biowaste stream is also watered in order to achieve the minimum moisture requirement, which is at least 70%, to become a suitable feed for the BSF (Pleissner & Smetana, 2020). After this, the BSF are fed with the mixed substrate, until their migration point is reached. When harvested, the larvae are separated from their biological residue via sieving. The residue is then dried and treated to be sold as organic fertilizer, with 85.5% of organic matter on a dry matter basis (Smetana et al., 2019). This product is known to have the potential to replace conventional fertilizers already existing (Diener *et al*., 2011; Choi *et al*., 2009), therefore, the substitution has been performed based on Tonini *et al*., (2020), and similarly to the *Status Quo*. The separated larvae are grinded and dried, and treated for the production of three more products. Furthermore, fresh purée with a moisture, protein and fat content of 70%, 17% and 10%, respectively is produced (Smetana et al., 2019). The avoided product related to purée is chicken meat. Even though it presents differences in the sensory and physical properties, according to Smetana et al. (2019), it remains the most comparable in terms of nutritional properties and can be intended for food and for pet food. The BSF protein concentrate meal produced after the treatment contains 56.3% of proteins and 13.7% of fats and can reduce the need of other products, such as soybean protein and rapeseed oil ingredients. Heat and electricity could be substituted on a 1-to-1 energy basis. Bottom ashes are replaced by natural gravel on a 1-to-1 kg basis, in line with Allegrini *et al.* (2015).

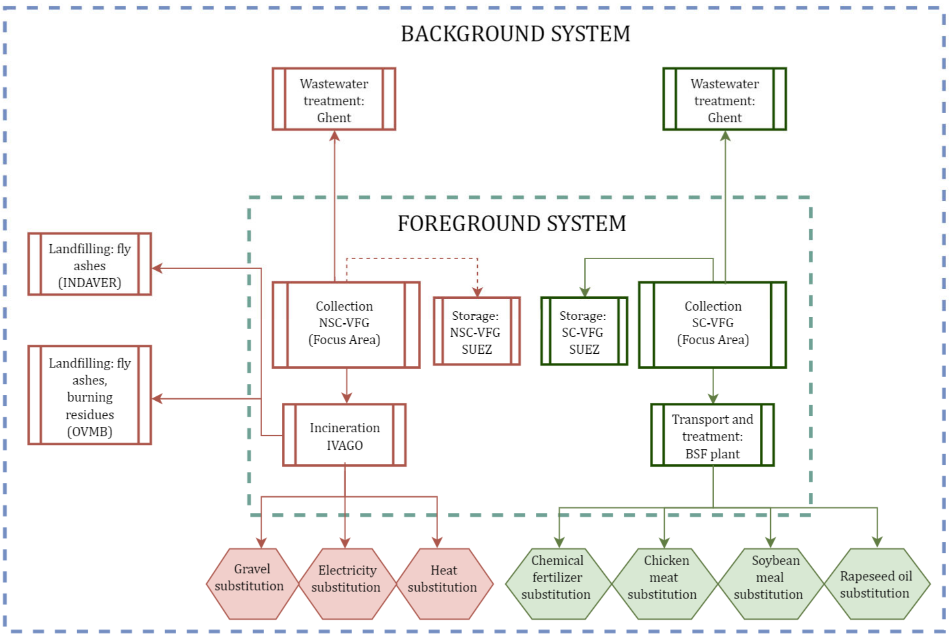


Figure 4, Main strategy, Ghent case. Processes included in the foreground and background system. The SC-VFG is represented in green, while the NSC-VFG in red. Substituted products are also visualized.

To better understand the contribution of each single EIS, we have also assessed separate strategies, see Table 3. Strategy S1 includes mandatory separation of VFG and CNG fuelled trucks. Strategy S2 includes the same EISs and in addition the increase in frequency of collection. For this, different capture rates are considered: 10%-20%-30% (Strategy S2A, S2B, S2C). Strategy S3 focuses on the introduction of the BSF plant (plus CNG fuelled trucks) and strategy S4 represents the main strategy combining all 4 EIS.

Table 3, Strategies developed (S1-S4), Ghent case, reflecting different EIS (or combinations thereof). Changes compared to the Status Quo are mentioned, either at the separation, collection and/or valorisation steps.

	Separation	Collection	Valorization
S1	**Mandatory** VFG bins for the entire FA.	**CNG** fuelled trucks.	
S2A	**Mandatory** VFG bins for the entire FA.	**CNG** fuelled trucks, increased frequency of VFG collection to a **weekly** basis. Assumed **VFG capture rate increase: 10%.**	
S2B	**Mandatory** VFG bins for the entire FA.	**CNG** fuelled trucks, increased frequency of VFG collection to a **weekly** basis. Assumed **VFG capture rate increase: 20%.**	
S2C	**Mandatory** VFG bins for the entire FA.	**CNG** fuelled trucks, increased frequency of VFG collection to a **weekly** basis. Assumed VFG **capture rate increase: 30%.**	
S3		**CNG** fuelled trucks.	BSF treatment plant
S4	**Mandatory** VFG bins for the entire FA.	**CNG** fuelled trucks, increased frequency of VFG collection to a **weekly** basis.	BSF treatment plant

2.2. Naples

2.2.1. *General*

The FA selected for this case study is represented by a portion of the Metropolitan Area of Naples formed by the following municipalities: Acerra, Afragola, Caivano, Casalnuovo di Napoli, Casoria, Cardito, Cercola, Crispano, Frattaminore, Naples (more in depth, the following areas: Poggioreale, Industrial Zone, Ponticelli, San Giovanni a Teduccio, Barra) (Figure 5).

The assessment was facilitated with the software EASETECH (Clavreul *et al.*, 2014). For background datasets, ecoinvent 3.6 database was used (Ecoinvent centre, 2019). For the case of food waste, the indicator "Landscape Disamenities" was excluded due to lack of reliable data, as the collected food waste is mostly shipped off the local FA and treated all over the Italian territory. For the same reason, we did not collect primary data on the technologies and processes involved in the Naples food waste case. Instead, we modelled processes and technologies using as a proxy of the data obtained from the pilot case of the Amsterdam Metropolitan Area (Deliverable D4.8; Tonini *et al.*, 2020). For Construction and Demolition Waste some indicators, that are generally calculable in relation to food waste, have been excluded because they are not relevant for this waste flow (effectiveness in achieving behaviour change, public acceptance/NIMBY syndrome, accessibility of WM systems, private space consumption).

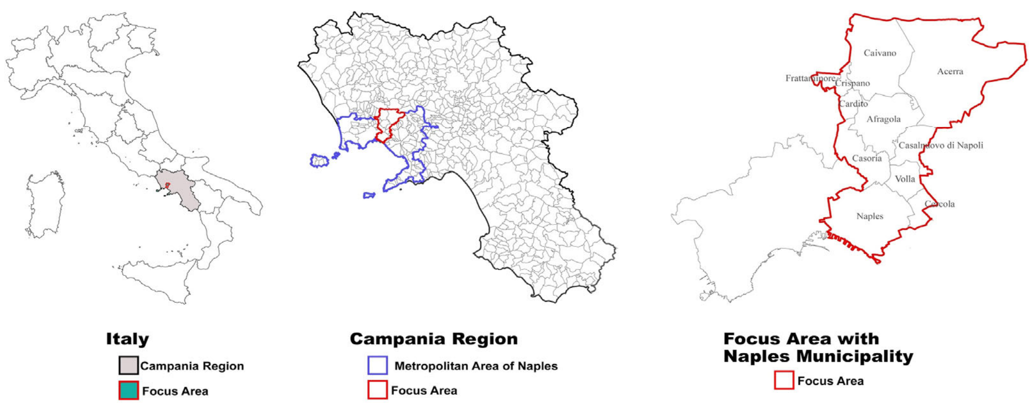


Figure 5, Naples case study: from country to Focus Area.

2.2.2. Key waste stream: construction and demolition waste

Construction and Demolition Waste (CDW) is classified as Special Waste and is a significant waste flow in Europe, Italy and Campania Region. Indeed the Regional Plan for the Management of Special Waste estimates an annual production of about 3 million tonnes, i.e. about 40% of the total and this is also confirmed by the most recent reports (ISPRA, 2019; 2020). Given this, CDW is a priority waste stream for European Union, that has recently developed the EU Construction and Demolition Waste Protocol and Guidelines, proposing the following targets (European Commission, 2018b) :

1) improved waste identification, source separation and collection;
2) improved waste logistics;
3) improved waste processing;
4) quality management;
5) appropriate policy and framework conditions.

Further, the Directive 2008/98/EC establishes the target to recover 70% of the total CDW flow by 2020 and the Circular Economy Action Plan considers CDW as a priority for closing the loop thanks to its recycling potential (European Commission, 2015b).

The FU of the assessment is the management of 1 t of CDW generated in the FA; the assessment is based on the framework developed in Taelman *et al.* (2020). The CDW flow is generated during the life cycle of a building, which can be summarised in four main activities:

- Construction and demolition activities;
- Activities of micro renovations carried out independently;
- Other activities dealing with construction materials.

Status Quo

The *Status Quo* (Figure 6) assesses the environmental, social and economic impacts coming from the treatment of CDW generated in the FA using as a reference the 2015 official data transmitted by the regional agency for environmental protection of Campania Region (in Italian: Agenzia Regionale per la Protezione Ambientale della Campania – ARPAC). Local primary data have been collected on CDW composition, flows and treatment technologies in terms of input-output data on material flows, energy use and emissions. As mentioned earlier, primary data have been complemented with Ecoinvent 3.6 datasets and recent literature sources. The amount of CDW generated in the FA was quantified based on elaboration of the NACE 41, 42, 43 statistics (Statistical Classification of Economic Activities in the European Community), considering also that there could be other economic activities that produce CDW even if they do not belong to the construction sector. The composition has been approximated with selected material fractions from the EASETECH database (Figure 7) and is based on the elaboration of the European Waste Catalogue (EWC) code 17.

Some fractions are subject to specific regulations and have the potential to establish useful practices of recycling and territorial regeneration (an example is represented by waste coming from excavation activities). As far as data traceability is concerned, it is possible to collect information on waste streams through the analysis of the so-called Environmental Declaration Model (in italian "Modello Unico di Dichiarazione ambientale" - MUD).

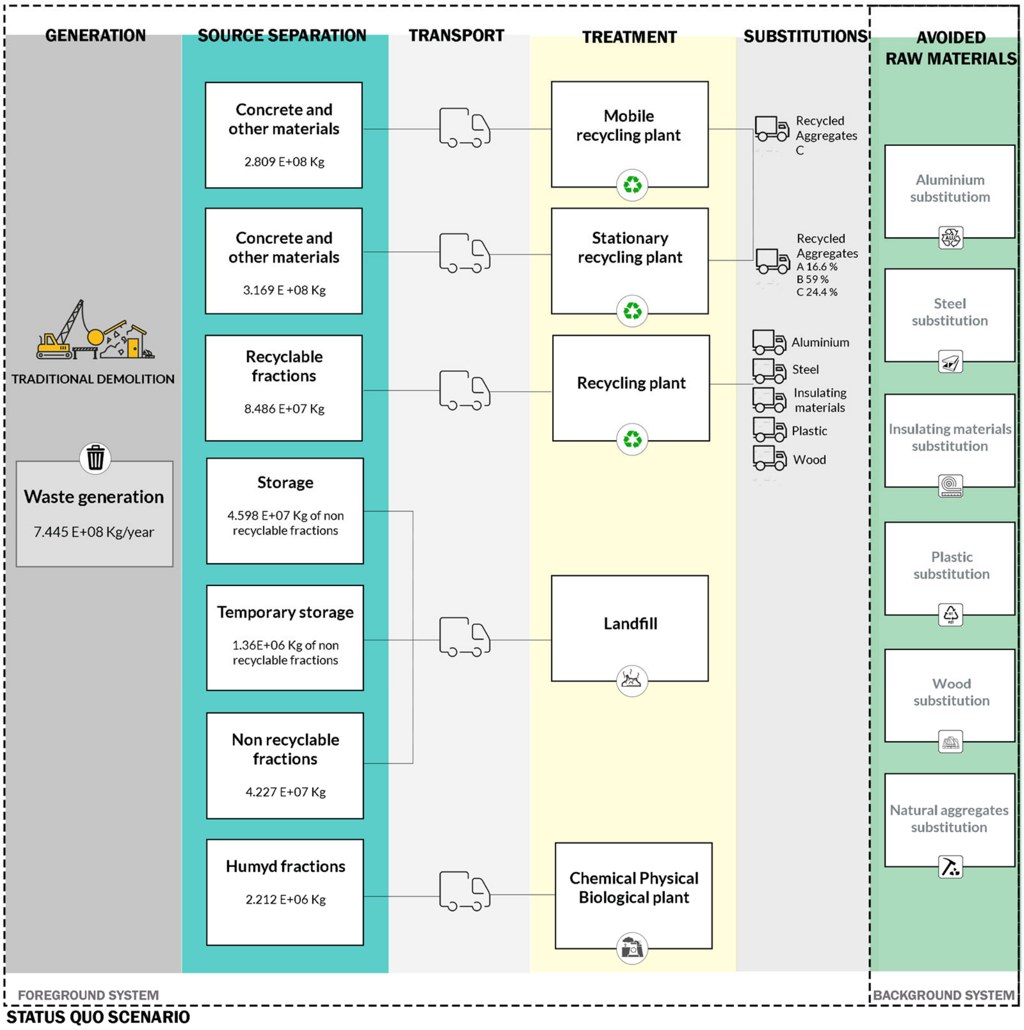


Figure 6, Status Quo scenario for the case study on CDW in the Focus Area.

As illustrated in Figure 6, the treatment facilities identified for Naples case study are represented by three categories of recycling plants.

i) Stationary recycling plants that treat the inert fractions for the production of Recycled Aggregates (RAs). These types of plants are usually characterized by the presence of higher level technology as well as sorting equipment used for the separation of unwanted fractions (Blengini and Garbarino, 2010). Stationary recycling plants are able to produce three qualities of RA: high quality (A), medium quality (B) and low quality (C). Through a survey to the main stationary plants located in Campania Region, it was possible to assess the rate of production of the three qualities: i.e. 16.6% for high quality RAs (type A), 59 % for medium quality RAs (type B) and 24.4% for low quality RAs (type C).

ii) Mobile recycling plants usually treat smaller CDW quantities in temporary demolition worksites through the use of basic technologies. Mobile plants produce low quality RAs (type C) (Blengini and Garbarino, 2010).

iii) Recycling plants that treat other recyclable fractions constituting the flow (plastic, metals, glass, wood, insulation materials).

Apart from the above mentioned recycling plants, in the *Status Quo* there are also other two types of treatment technologies:

i) Landfill, for the non-recyclable portions of the waste flow;

ii) Chemical-Physical-Biological plant, for a small humid component. In general there is no direct emission from CDW and the generation of leachate can be considered negligible, while we account for the emissions coming from consumption of energy, land use and infrastructure (Penteado and Rosado, 2015).

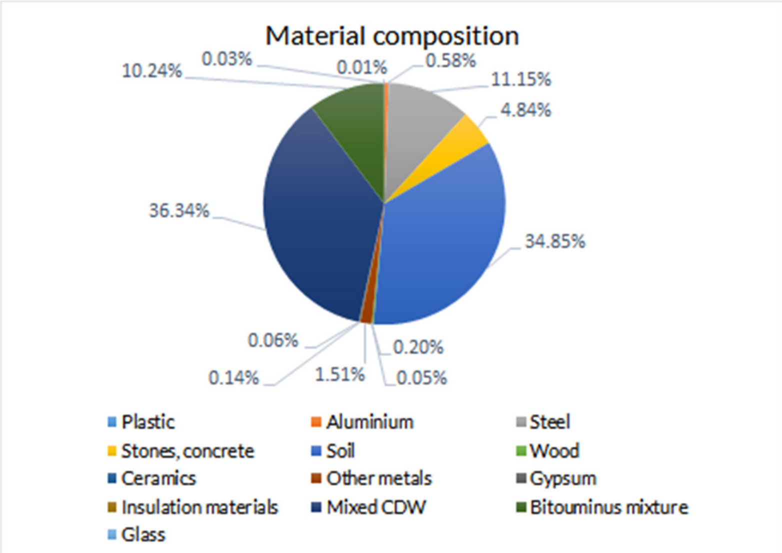


Figure 7, Status Quo CDW composition for the Focus Area.

The system boundary includes all the activities involved in the life cycle of the generated waste, i.e.: collection, transport, treatment, transportation of treatment residues and/or products to end-use or further application and eventual final disposal through landfilling. In addition, the substitution of raw materials thanks to the production of RAs and to the recycling of some fractions has been taken into account. This way, the impacts related to the production of RAs and the impacts related to limestone extraction (natural aggregates, NAs) during mining activities are compared, in order to account for the avoided extraction of raw materials, leading to a gradual reduction in the extractive activity from quarries. As a matter of fact, CDW can be turned into secondary products known as Recycling Aggregates (RAs) thanks to the recycling processes (Blengini and Garbarino, 2010; Badino *et al.*, 2007; Borghi *et al.*, 2018), provided that they follow the specific requirements established by the Ministerial Circular n. 5205/2005. The latter identifies three main categories of RA (Blengini and Garbarino, 2010; Borghi *et al.*, 2018):

- Type A: high quality with structural properties able for concrete production and road foundations;
- Type B: medium quality used for road, airport and harbour construction as well as unbound material in the embankment body, in sub-base layer and in layers with anti-freezing, anti-capillary and drainage properties;

- Type C: low quality used for environmental fillings and rehabilitation of depleted quarries and landfill sites.

For the substitution between RAs and NAs the replacement coefficients proposed by Borghi et al. (2018) have been adopted. These coefficients take into account the quality of RAs and their market demand (Table 4). More specifically, the replacement coefficients are calculated with the following formula:

R = Q1 * Q2 * M

Where Q1 is the quality in terms of purity of the flow while Q2 is linked to the technical characteristics of RAs compared to those of the substituted material. Finally, M is the market coefficient, i.e. the ratio between the amount of RAs sold and produced in a recycling plant in a defined period. M usually varies between 0 and 1 according to the market attractiveness and for the present case study it is assumed equal to 1. For type A, a replacement coefficient equal to 1 has been adopted.

Table 4, Replacement factor for RAs of type B and C.

RA quality	Q1	Q2	M	R
B	0.97	1	1	0.97
C	0.97	0.89	1	0.86

LINEAR ECONOMY STRATEGY (S1): LANDFILL

In order to illustrate the benefits from avoiding landfilling operations, a "Linear Economy Strategy" (S1) has been assessed (Figure 8). This strategy is based on the hypothesis of sending the total flow to landfill, without any distinction. The analysed waste flows comprise direct flows, that are directly sent to plants and secondary ones that derive from intermediate management operations. As a matter of fact, some portions of the fractions are sent to storage and temporary storage before being landfilled. Storage is always a temporary (more or less time consuming) operation; waste can be stored for a maximum of one year before being sent to recovery or disposal.

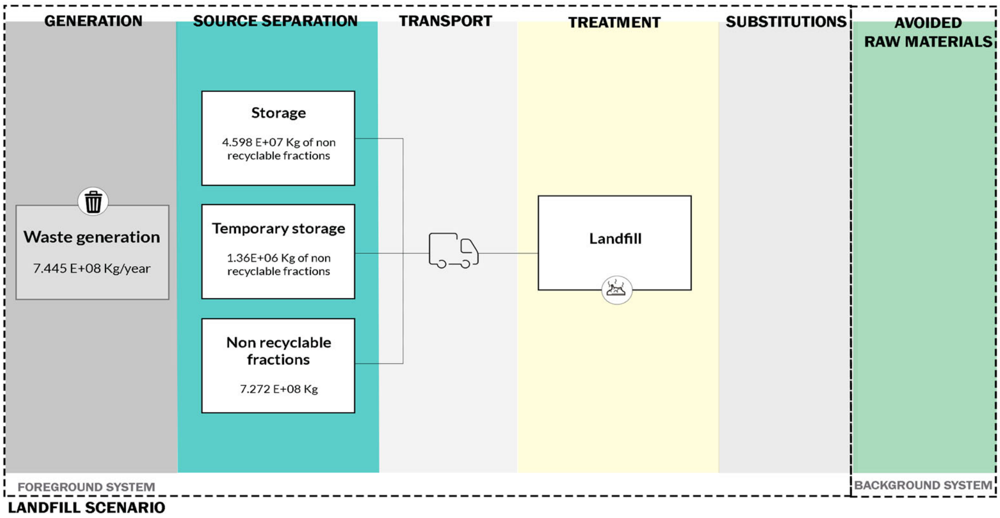


Figure 8, Landfill scenario for CDW management in the Focus Area.

Beyond INERTia. Circular supply chain for CDW: Improvement Strategy (S2)

The Beyond INERTia strategy, developed in Russo *et al.* (2018), aims at triggering some weak points in the current RA supply chain, improving their recovery and recycling rates, especially for what concerns the production of RAs. Among the various EIS, the ones that have been taken into account for the development of this strategy are described herein.

EIS 1: Quarry tax

This solution aims at increasing the Regional Concession Fee on quarries. RAs are able to replace NAs coming from mining activities, or can be used in joint combination. According to the Regional Plan for mining activities (in Italian: "Piano Regionale Attività Estrattive" – PRAE) (2006), it is necessary to pursue a progressive reduction in the collection of natural materials from quarries as the exploitation of raw materials from quarries causesa real degradation and impoverishment of the territory. Currently, there is no taxation on mining activities and this solution should address this issue.

EIS 2: Select

This solution aims at providing incentives to companies that use "selective demolition", also known as "construction in reverse" or "deconstruction" (Pantini and Rigamonti, 2020). This kind of demolition is still rarely applied, but holds a great potential. The difference between the traditional demolition lies in the separation of waste from the place of production thanks to a sequence of demolition activities that allows the separation and sorting of building components and materials (Pantini and Rigamonti, 2020), increasing the level of recyclability. On the other hand, the traditional demolition consists in the production of waste that is largely sent to landfill and minimally recovered. In Italy, selective demolition practices at the construction site, even if not widespread yet, could be useful in increasing the waste quality and purity, enhancing CDW diversion rate from landfill and preserving further land use consumption. Yet, the greater quantities of CDW sent to recovery plant are still represented by mixed CDW, which is treated in combination with minor flows, such as bituminous mixture, gypsum-based waste as well as waste containing cement, bricks, tiles and ceramics (Borghi et al., 2018). Mixed CDW is a mixture of non-hazardous CDW, i.e. a set of waste belonging to the various EWC codes of the non-hazardous component. With this in mind, the present EIS wants to boost selective demolition practices, as experience shows that nature and characteristics of the CDW flow in input into the recovery facilities significantly influence the characteristics and final performances of the resulting RAs.

EIS 3 – 4: B€ST and CERT

These EISs aim at inserting RAs in tender specifications and at activating a regional sustainability certification for RAs. Currently different factors hinder the widespread use of RAs, like the distrust of construction companies against recycled materials due to their origin from waste, a lack of knowledge of their real performances but also the low cost and the wide availability of virgin materials in the territory. Indeed, mining activity in the Campania region is very intense and characterized by the opening of new mining sectors and also by the increase in extraction in the existing ones. It would, therefore, be necessary to encourage the use of RAs (Borghi *et al*., 2017) by making operational some regulatory instruments, such as DM 203/2003, which imposes the use of a minimum amount of 30% of recycled materials in the construction of public works. It is also important to share information on the technical performances of RA in order to improve the awareness (Borghi et al., 2017).

From the joint combination of the above described EIS, an “Improved Strategy” (S2) has been built (Figure 9), based on the following assumptions:

1) Selective demolition: this implies some adjustments in the flow composition, based on an average between the elaborations of Metabolic (2020) and Lavagna *et al*. (2018) that specify the CDW content for buildings, in order to define the maximum rate of each fraction when applying selective demolition. According to these adjustments, the new composition is represented in Figure 10, where one of the most relevant changes is the composition of stones and concrete, that can allow a maximization in the production of high quality RAs. Other important changes regard the composition of plastic, insulation materials, wood and glass (Table 5). Sorting and recycling efficiencies developed in Pantini and Rigamonti (2020) and Faraca *et al*. (2019) have been adopted for the material substitutions. Furthermore, the inventory for wood recycling and substitution comes from Faraca *et al.* (2019). Selective demolition implies also a different electricity and diesel consumption, and the reference for the new values is represented by Pantini and Rigamonti (2020).

2) Increased quantity of Type A RAs production (high quality; Table 5), the maximum production of concrete from selective demolition is 53.44 % and this is reflected in the production of the same quantity of high quality of RAs (from the previous rate of 16.6 % to the improved one of 53.44 %). As stated by Di Maria *et al.* (2018, p. 4), the high-quality use is «an important contribution toward the closure of construction materials cycles, as it decreases the amount of residual CDW to be managed, increases the economic value of the recycled material and reduces the quantity of NA used». Figure 9 summarises all the assumptions.

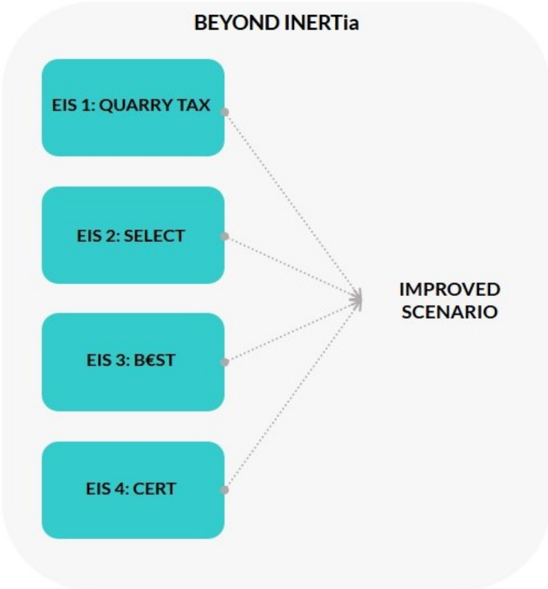


Figure 9, Improved strategy for CDW management in the Focus Area.

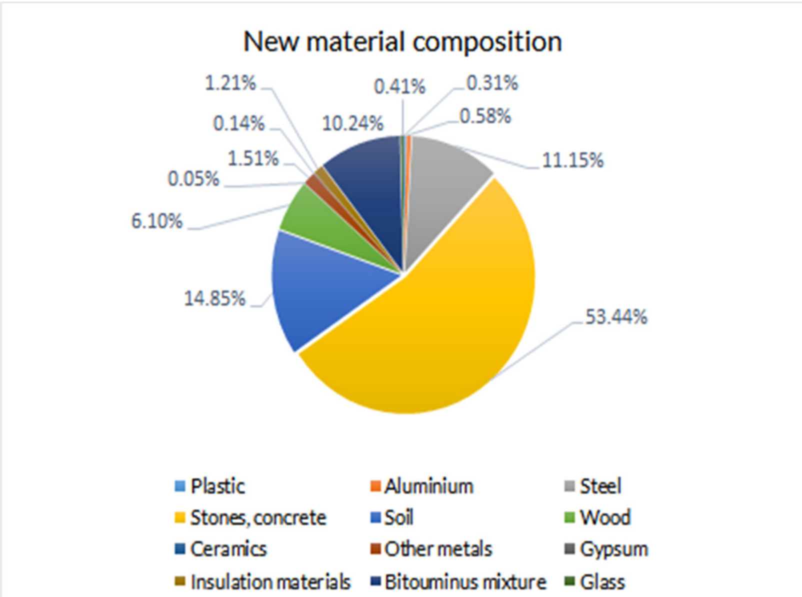


Figure 10, New CDW composition in the Focus Area assuming selective demolition practices.

Table 5, Material fractions for the Focus Area: from traditional to selective demolition.

Material fractions	% traditional demolition	% selective demolition
Plastic	***0.01***	***0.31***
Aluminium	*0.58*	*0.58**
Steel	*11.15*	*11.15**
Stes and concrete	***4.84***	***53.44***

Soil	***34.85***	***14.85***
Wood	***0.20***	***6.10***
Ceramics	*0.05*	*0.05*
Other metals	*1.51*	*1.51*
Gypsum	*0.14*	*0.14*
Insulation materials	***0.06***	***1.21***
Mixed CDW	*36.34*	*0*
Bituminous mixture	*10.24*	*10.24*
Glass	***0.03***	***0.41***

**We did not increase the collected amount of metals in selective demolition because we exclude metals from our boundaries.*

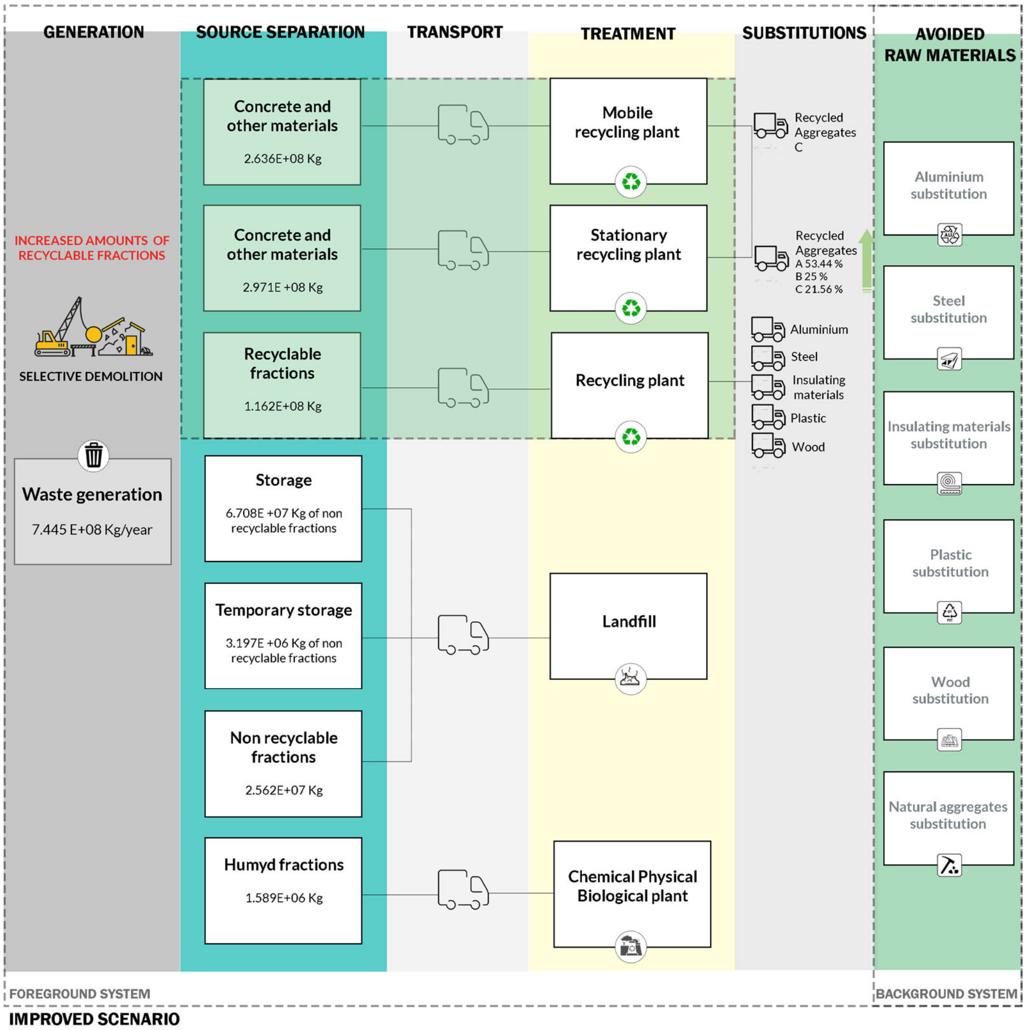


Figure 11, Improved scenario for the case study on CDW in the Focus Area.

2.2.3. *Key waste stream: household food waste*

Household food waste is one of the main focus of local authorities and stakeholders as, while the current capture rate is relatively high (44% of the food waste generated is collected separately), much of the material collected is then transported out of the region for subsequent treatment due to insufficient capacity in the region. The FU utilized in the assessment is the management of 1 t of food waste generated in a year by the households and small-and-medium-enterprises (SMEs) in the FA under assessment. The specific physico-chemical composition was assumed as that of the Netherlands (ca. 80% vegetables and 20% meat products; Tonini *et al.*, 2020). As short- and mid-term solutions to the current situation, building local capacity and avoiding shipping are the alternatives proposed for the management of the (collected) food waste by the PULLs (Strategies 1-to-3).

Status Quo

Description

The food waste generated in 2015 equals 1,362,398 t (wet weight, ww) per year. About 44% of the food waste is collected separately through "door-to-door" (82%) or "bring" schemes (18%). The collected food waste is only partly treated locally, as a consistent share is shipped off the Campania region for further processing in anaerobic digestion with post-composting (42% of the total; 141 km hauling based on weighted average) or direct composting plants (58% of the total; 297 km hauling based on weighted average). The food waste non-separately collected (56% of the generated) is sent to mechanical-biological treatment (98% of the total, 24 km hauling on average) for aerobic stabilisation prior to disposal in a landfill. The remaining 2% is treated through direct incineration with energy recovery (24 km hauling on average). Detailed data are available under request.

System boundary

The boundary of the system includes all the activities involved in the life cycle of the waste, i.e. collection, transport (hauling), treatment, and subsequent disposal and/or use on-land. Any co-product generated alongside the management of the waste is credited to the system by expanding it to account for the substitution of corresponding (conventional) market products. These products/services were identified in the market marginal products/services for the area under assessment, i.e. those that are capable to respond to changes in demand (Weidema *et al.*, 2003; 2009). On this basis, electricity provision was assumed as the future Italian marginal mix (Ecoinvent centre, 2019); likewise, a marginal heat mix was elaborated on the basis of a recent study for Italy and EU14 (European Commission, 2018). With respect to production of gaseous fuel, such as upgraded biogas (natural gas-quality, injected into the gas grid), we assumed a 1-to-1 energy-basis substitution of natural gas extraction, (long-distance) distribution, and combustion on the basis of the energy content. With respect to NPK mineral fertilisers, we relied on the choices justified in previous studies (Tonini *et al.*, 2016), assuming urea-N, diammonium phosphate, and potassium chloride as marginal mineral fertilisers. The actual nutrient substitution was quantified following the commonly applied maintenance principle as illustrated in Vadenbo *et al.* (2016) and as applied in a number of recent LCAs (e.g. De Vries *et al.*, 2012; Hamelin *et al.*, 2014; Styles *et al.*, 2018). Details on the calculation methods can be found elsewhere (e.g. Tonini *et al.*, 2019). Use of aged bottom ash as road sub-base was assumed to substitute for natural gravel extraction and production, on a one-to-one mass basis.

Inventory

With respect to the life cycle inventory of technologies and processes, we did not collect primary data on the technologies and processes involved in the Naples case. The reason for this is that the waste from the region is shipped and treated all over the Italian country in a number of many different plants. Instead, we modelled these plants based on their process type (e.g. composting, digestion, incineration) using the available data from the pilot case of the Amsterdam Metropolitan Area (Deliverable D4.8; Tonini *et al.*, 2020). On this basis, the anaerobic digestion with post-composting was proxy with the inventory for the plant located in “Middenmeer” (capacity 79,000 t per year; see Tonini *et al.*, 2020; Appendix C). The direct composting plant was proxy with the inventory for the plant located in “Middenmeer” (118,000 t per year capacity; see Tonini *et al.*, 2020; Appendix C). The incineration plant was proxy with the inventory for the waste-to-energy plant ‘Acerra’ (located in the focus area; A2A Ambiente 2019). The mechanical-biological treatment (MBT) plant was modelled using the inventory reported for state-of-the-art MBT plants in Montejo *et al.* (2013). Transport processes were also modelled as in Tonini *et al.* (2020) assuming similar distances for the transport of compost to use on-land (20 km) and fly ash to disposal (500 km). Stabilised organic material after MBT was assumed to be transported 50 km prior to disposal in a landfill site. All the individual costs for products, electricity, natural gas, heat, etc. were based on italian prices wherever possible. The methodology for cost calculation (e.g. amortization, annualisation, etc.) was based on Martinez-Sanchez *et al.* (2015). The reader is referred to the original publications and related supporting information material for additional details. The background datasets to model electricity provision, natural gas supply, as well as the supply of chemicals and products necessary for the technologies involved in the foreground system are retrieved from ecoinvent 3.6 (consequential system version).

Strategy S1: No shipping (Local treatment)

This strategy represents the combination of avoiding shipping and installing local capacity of anaerobic digestion coupled with post-composting (to treat 42% of the total) and direct aerobic composting (to treat 58% of the total) treatment in place of using similar plants located outside the region. The only difference with the *Status Quo* is therefore the hauling distance (25 km instead of 438 km, where the hauling distance is defined as the distance from the centre of the waste collection area to the subsequent treatment plant, i.e. digestion or composting). The remaining assumptions and treatment flows are precisely the same as the *Status Quo*. See Figure 12.

Strategy S2: No shipping and installation of local anaerobic digestion & post-composting capacity

This strategy represents the combination of avoiding shipping and installing local anaerobic digestion coupled with post-composting capacity. The differences with the *Status Quo* are therefore the following:

- 100% of the food waste generated is assumed to be treated locally through anaerobic digestion followed by composting of the digestate to achieve a compost-like material for subsequent use in agriculture.
- We considered a hauling distance of 25 km instead of 438 km (hauling distance is the distance from the centre of the collection area to the subsequent treatment plant, i.e. digestion or composting).

The remaining assumptions and treatment flows are precisely the same as the *Status Quo*. See Figure 12.

Strategy S3: No shipping and installation of local (direct) composting capacity

This strategy represents the combination of avoiding shipping and installing local composting capacity. The differences with the *Status Quo* are therefore the following:

- 100% of the food waste generated is assumed to be treated locally through direct composting to obtain a compost-like material for subsequent use in agriculture.
- We considered a hauling distance of 25 km instead of 438 km (hauling distance is the distance from the centre of the collection area to the subsequent treatment plant, i.e. digestion or composting).

The remaining assumptions and treatment flows are precisely the same as the *Status Quo*. See Figure 12 for an overview.

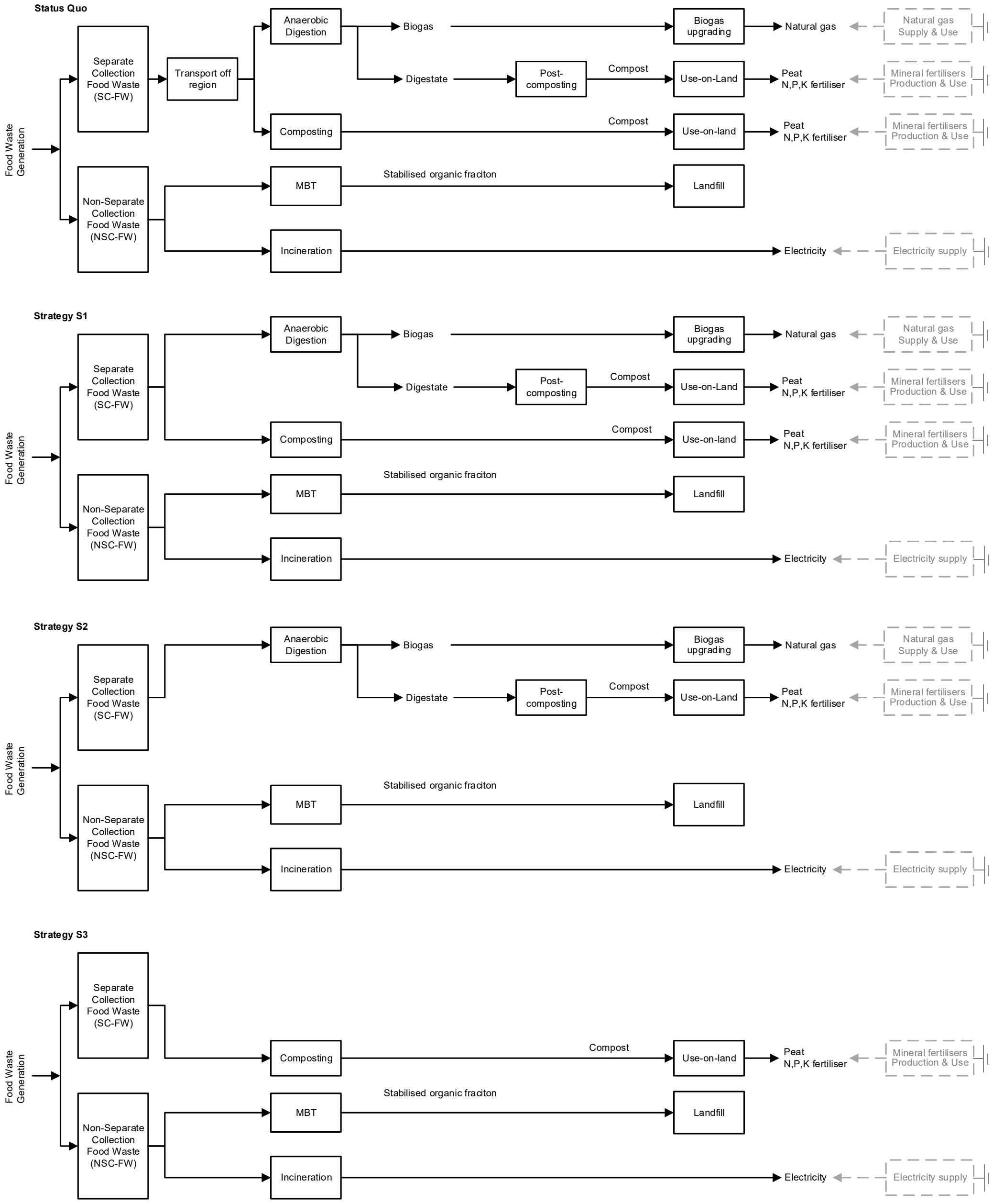


Figure 12, Illustration of the Status Quo and of the three strategies for the management of food waste in the Focus Area.

2.3. Hamburg

2.3.1. General

The FA for Hamburg is composed of two separate entities, namely Altona District and Pinneberg County. The two entities belong to two different Federal States, Free and Hanseatic City of Hamburg and Schleswig-Holstein respectively. However, reflecting the interest of the local stakeholders, the Life Cycle Assessment was conducted only for Altona District (cf. Acke *et al.*, 2019). From now on, the FA will refer exclusively to Altona District.

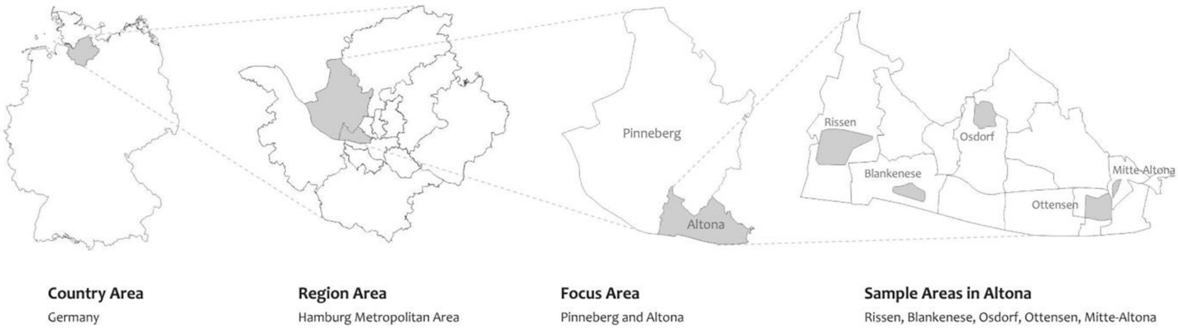


Figure 13, Hamburg case study, from country to Focus Area and sample areas in Altona.

Altona District is one of the seven districts in the Federal State of Hamburg: legally and politically, the districts can be assimilated to a municipality (Figure 13). Altona has 273.731 inhabitants (Statistikamt Nord, 2019) and is divided in quarters (*Stadtteile*) which present very diverse economic and social characteristics as well as different urban structures (cf. Arlati *et al.*, 2018). As City State, Hamburg uses its city-owned public waste management company, Stadtreinigung Hamburg (SRH), "which is responsible for the management of the waste coming from private households, street cleaning, winter service, and public toilets. Moreover, SRH owns and manages 12 recycling stations all over Hamburg" (Arlati et al., 2018, p. 43).

Further, five smaller areas, the "sample areas", were chosen for a more detailed and space-based investigation (Figure 13). The selection of these areas for REPAIR was defined together with the key stakeholders such as SRH, the City of Hamburg and HCU. For a detailed explanation of the characteristics for the five sample areas, refer to Arlati *et al.* (2018) and Obersteg *et al.* (2020). The LCA-related indicators of the sustainability analysis were implemented with Easetech software v3.1.6 and, in order to model the background system, the life cycle Ecoinvent 3.5 database was used.

2.3.2. Key waste stream: Biowaste

In line with the EU waste hierarchy guidelines, Germany has developed its own 2012 Circular Economy Act (KrWG). The main aim of the act was to set a strategy to reduce the landfilling of the biodegradable waste, including both biowaste and paper waste, by enhancing their separated collection from households. In the REPAIR context, after several interviews and meetings with the local stakeholders, improper biowaste management was identified as a main problem. Therefore, the case of Hamburg diverted its attention on improving the current biowaste stream. More specifically, the kitchen and garden waste generated at household level have been considered.

In the case of Altona district the FU is the management of 1 t of biowaste generated from households in the FA Altona during one year. The specific physico-chemical composition was derived from a study conducted for the German Federal Ministry of Food and Agriculture (Bundesministerium für Ernährung und Landwirtschaft) regarding the consumption behaviors of German households, i.e. ca. 85% vegetables and fruit and 15% animal food (including fish and meat) products (GfK SE, 2017). The solutions designed by the students at the HCU and refined with the local stakeholders during the PULL workshops (cf. Obersteg et al., 2020) can be subdivided in centralized and decentralized solutions (End-of-Pipe strategies) and economic measures (biowaste prevention and better separation measures) directed to a) trigger behavioural change, b) prevent waste generation, and c) a better separation.

Status Quo

Description

The collection, transport and treatment of the biowaste in the FA of Hamburg is managed for the majority by SRH. Hamburg households can profit from a four bin system (yellow for recyclables, blue for paper, black for residual and green for biowaste), although it has been calculated that, on average, around 25% of the households do not have access to a bio bin yet. For the management of other waste types, please refer to Arlati *et al.* (2018).

In general, the bio bin is collected by SRH and brought to the Biogas and compost facility BKW Bützberg located north of Hamburg just outside the city border in Schleswig-Holstein (ca. 33 km hauling[2]). There, the waste is treated to produce biogas and digestate (see System boundary section for more details). The residual waste, always collected by SRH, is brought to the incineration plant located in the east side of Hamburg at a hauling distance of ca. 20 km. The other two waste fractions (paper, recyclables) fall under the responsibility of the Extended Producer Responsibility scheme and therefore are managed by other companies. The yellow bin is collected by WERT GmbH for a consequent recycling. The biowaste as described in point A (below) follows the aforementioned processes. The blue paper bin was hence not considered.

The biowaste generated from households consists of different types (kitchen waste and garden waste) and is collected in three ways:

A. Regular collection from households (with the bin system or in few areas residual waste bags): kitchen waste, kitchen waste not compostable, garden waste (herbaceous and woody), and food packaged waste. Ca. 93 %; a considerable part is thrown in the residual waste, a smaller part in the bio bin[3], and a tiny part in the yellow bin, as described in the next paragraph),
B. Seasonal (1st October till 31st December) collection in garden waste bags: garden waste, herbaceous (mainly leaves), (ca. 1 %), and
C. Bringing system (transported directly from the households to the nearest recycling station): garden waste, woody, (ca. 6 %).

[2] The geographical centre of Altona District was chosen as the starting point.
[3] Additionally, the biowaste in the bio bin is composed mostly by garden waste, see Table 6.

In the FA Altona, the main problems that were identified refer to the first category of biowaste (A). Concerning the waste collection at household level, from the biowaste that is generated ca. 47% on average is disposed of in the residual bin (kitchen waste having the highest share), whereas the bio bin is mainly used for disposing garden herbaceous and woody waste. This is considered not optimal by SRH, being the garden waste not fully appropriate for the production of biogas and digestate.

In this report, the results are delivered as the average for the entire District of Altona, but the data for waste generation were specific for four different housing typologies, namely single-family, multi-family, mixed use and large housing estate (SRH, 2019b).

Table 6, Waste generation in kg year^{-1} for housing typology for a total of 36,897 t year^{-1} (HCU Team, 2020).

	Single-family	*Multi-family*	*Mixed use*	*Large housing estate*	*Tot per organic fraction*
Inhabitants (n)	*20275*	*74173*	*107596*	*71658*	***273702***
Kitchen organic (t yr^{-1})	1232.31	5839.64	11092.07	7309.83	**25473.86**
Garden organic, herbaceus (t yr^{-1})	1768.39	424.27	666.02	212.82	**3071.50**
Garden organic, woody (t yr^{-1})	236.20	135.74	3.23	0.00	**375.17**
Packaged food (t yr^{-1})	381.17	1232.76	1278.24	1752.75	**4644.92**
Organic non compostable (t year^{-1})	27.17	56.37	110.82	1190.24	**1384.60**
Leaves bags (t year^{-1})	44.00	160.96	0.00	0.00	**204.95**
Green waste self brought (t year^{-1})	373.87	1367.75	0.00	0.00	**1741.62**
Collection ratio (residual - bio) (%)	100 - 95	100 - 95	100 - 55	100 - 55	**100 - 75.16**

System boundary

Collection processes, transport (hauling), incineration of biowaste, anaerobic digestion of biowaste and subsequent disposal/treatment of residues (e.g. wastewater treatment and ashes disposal) were the processes included in the foreground system. Figure 14 provides a schematic representation of the processes included in the system boundary. Two main processes are of importance for the biowaste flow. The incineration at MVB (Müllverbrennungsanlage Borsigstraße) and the anaerobic digestion at BKW Bützberg (Biogas- und Kompostwerk Anlage Bützberg). The incineration process contains 10 stages: waste bunker, furnace, separation of ferrous metals from bottom ashes, boiler, filter, HCl washing and processing, sulphur dioxide washing, gips processing, stack. The anaerobic digestion consists of 10 stages: first separation between kitchen and garden waste, incineration of garden waste for heat in fermentation, kitchen waste undergoes a refined screening for the separation of impurities, fermentation for methane production, storage of methane, cleaning of gas to produce biomethane, incineration of biogas in a combined heat-and-power (CHP) unit, the residues go to a composting plant, preparation of the fertilizer, wastewater treatment.

The impacts of the co-products generated during the two processes are credited to the system by means of substitution which correspond to the respective market product as described in Tonini *et al.* (2020). Through the incineration process, at the MVB only heat is generated from the incineration of waste in line 1 and 2 (SRH, 2019a)[4]. According to the Heat Roadmap for Germany, the heat produced from waste incineration is expected to substitute the one generated from industry and fossil fuel (Pardekooper, 2018). Gypsum and metal scraps are also generated as co-product. For these, it was assumed that they serve as a substitute for virgin materials in the construction sector and as input for other industries (SRH, 2019a). Co-

[4] Production of electricity happens in line 3 but not from waste input.

products of the anaerobic digestion process are biomethane and compost. The biomethane is used to generate heat and electricity that is distributed to Hamburg households through the energy grid (SRH, 2013). These are expected to substitute the generation of heat from industrial processes and fossil fuel; and the generation of electricity from brown coal (Bundesnetzagentur, 2016), which has still a big share in the Germany energy market. The compost generated is used to substitute peat (5-10%), industrial fertilizers in the agricultural sector (70-80%), and for private households (10-25%). The average EU mix for NPK substitution has been considered.

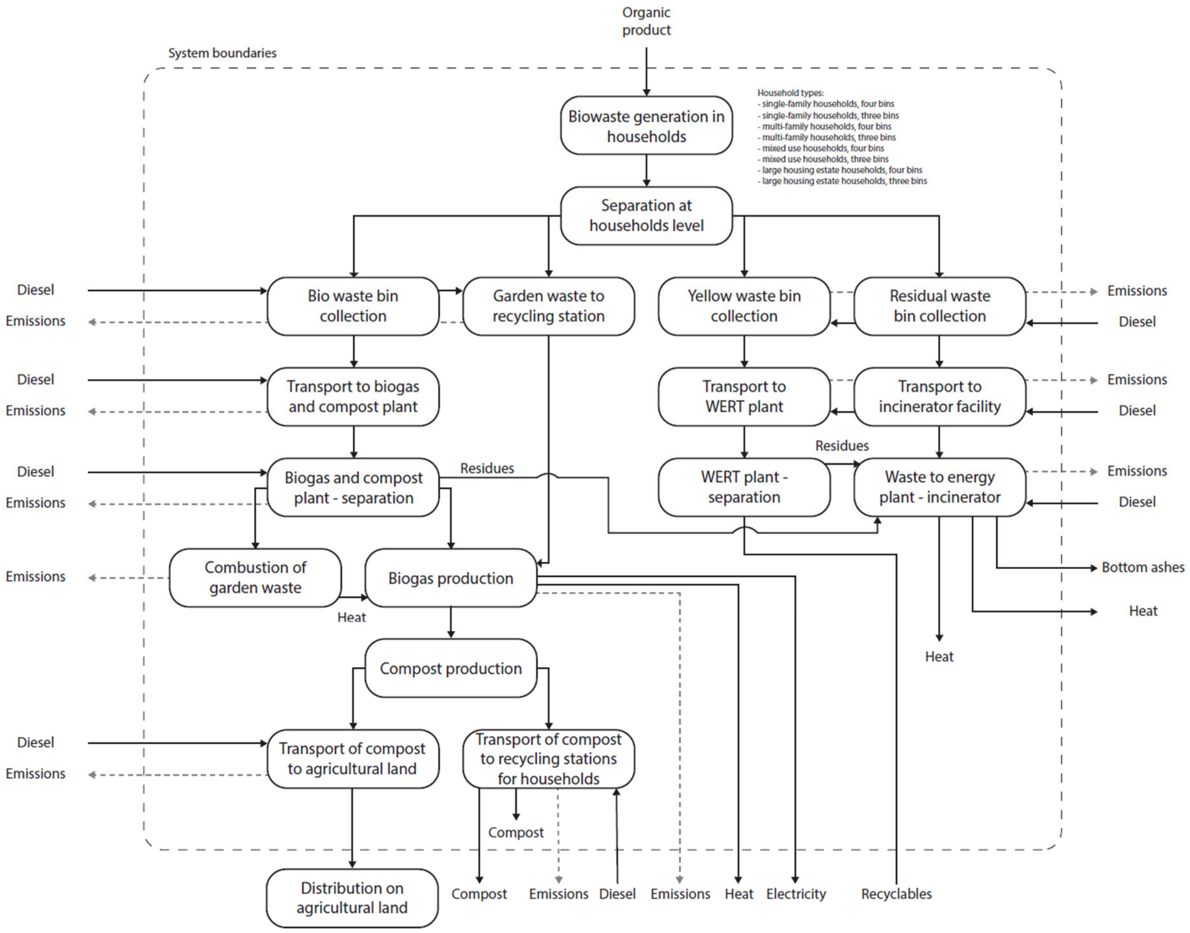


Figure 14, System boundary of the Hamburg case study for the collection of biowaste (HCU Team, 2020).

Data inventory

In general, data for the assessment for the foreground processes are site-specific, obtained both from local documents (e.g. laws, reports) and via direct communication with the local partners (e.g. SRH). To compensate for data gaps, similar processes from LCA databases and literature were considered and adapted to the local specifications. The composition of the biowaste generated at household level was derived from a sampling study requested by SRH. This provided diversified composition for four different housing typologies, which characterise the FA Altona urban structure: single-family, multi-family, mixed-use, and large housing estate households. The ratio between animal food waste and vegetable and fruit is 15% and 85% respectively (GfK SE, 2017). Further data were taken from the pilot case study of Amsterdam Metropolitan Area (Tonini *et al.*, 2019, Tonini *et al.*, 2020) was used for some specific information on labor and technical details for the anaerobic digestion plant. Table 7 reports more precise information on the separation habits per household typology in the FA Altona.

Table 7, Different compositions for the household typologies of the biowaste and the residual waste bin the four bins system in kg person-1 year-1 (HCU Team, 2020; from SRH, 2019b).

Typology		Waste Bins	Kitchen Organic	Kitchen organic non compostable	Residual waste	Garden Waste (herbaceous and woody)	TOT
Lockere Bebauung	Single-family	Plastic	1.40	3.40	2.60		7.4
		Paper			0.60		0.6
		Residual	51.80	16.70	18.30	1.40	88.2
		Bio	7.50		0.20	97.50	105.2
		TOT	**60.70**	**20.10**	**21.70**	**98.90**	**201.4**
Mehrfamilienhaus	Multi-family	Plastic	0.10	0.50	1.70		2.3
		Paper		0.30	0.20		0.5
		Residual	57.50	16.50	33.20	2.30	109.5
		Bio	21.10	0.10	0.10	5.30	26.6
		TOT	**78.70**	**17.40**	**35.20**	**7.60**	**138.9**
Kerngebiet	Mixed used	Plastic	0.20	0.10	0.30		0.6
		Paper		0.20	0.10		0.3
		Residual	65.20	12.70	45.30	2.20	125.4
		Bio	37.60		0.20	4.00	41.8
		TOT	**103.00**	**13.00**	**45.90**	**6.20**	**168.1**
Großsiedlung	Large housing estate	Plastic	0.20	0.20	0.90		1.3
		Paper		0.80	4.90		5.7
		Residual	90.30	40.00	61.10	2.40	193.8
		Bio	11.50	0.10	0.10	0.50	12.2
		TOT	**102.00**	**41.10**	**67.00**	**2.90**	**213**

Concerning the social assessment part, for most impact categories the data were based on primary data from SRH. As in the AMA case study, the stakeholder involvement for the *Status Quo* was considered to be equal to zero. Landscape disamenities were left 0 because the plants under consideration are all located in a distance greater than 5 km, as described in Taelman et al. (2018). Spatial data were derived from the Hamburg Geoportal and the HCU Geoportal.

The LCA-related indicators of the sustainability analysis were implemented with Easetech software v3.1.6 and, in order to model the background system, the life cycle Ecoinvent 3.5 database was used.

END-OF-PIPE STRATEGIES

The end-of-pipe strategies in this part are two and are divided in centralized and decentralized solutions. The first one is related to EIS 6 with the objective of realising a new plant which will be able to receive unsorted municipal waste and function as an incinerator and an anaerobic digestion. The second strategy refers to the EIS 5, which consists in the implementation of community gardens for the composting of biowaste from households. Table 8 shows the list of strategies assessed and the EIS considered in each strategy. The recycling offensive is an initiative launched by SRH in 2009 and pointing at two goals: a) increase the coverage of the four bin collection system, and b) promote better separation at households level (Freie und Hansestadt Hamburg, 2018). This initiative was applied as 'default' to each strategy beside the *Status Quo*. The effects of the offensive were modelled as an increase in the number of households that have four bins and a decrease of biowaste in the residual bin: these were calculated based on the relative changes recorded from 2009 to 2015 (latest recorded data in the report) and projected to 2018.

Table 8, EIS for each strategy assessed.

	EIS combination
Strategy S1	*recycling offensive + Mechanical separation of residual waste for biowaste valorisation - anaerobic digester and incinerator (ZRE)*
Strategy S2	*recycling offensive + Collection of biowaste in community gardening*
Strategy S3	*recycling offensive + Targeted events for prevention + Information campaign for better separation*
Strategy S4	*Strategy S1 + Targeted events for prevention + Information campaign for better separation*
Strategy S5	*Strategy S2 + Targeted events for prevention + Information campaign for better separation + Reward mechanisms through point system*

Strategy S1 - Centralized waste management system

As previously mentioned, this strategy considers the realisation of the new centre for resources and energy (ZRE). The ZRE is a plant park built in the area of the former and now demolished incineration plant in Schnackenburgallee 100, in the north of the FA Altona. The ZRE is also presented as EIS 6 in Obersteg et al. (2020). ZRE will receive the following waste flows to be processed in the different facilities of the plant park: municipal waste from households, bio and garden waste from households, woody waste and biomass not coming from households. The plant park of ZRE will have the following facilities with the related functions:

A mechanical sorting facility that will be able to separate municipal waste into fermentable biogenic waste, recyclable materials and residual waste. Recyclables are paper, cardboard, cartons, glass, metal and polyolefins.

Two fermentation plants where a) the biogenic waste coming from the mechanical sorting and b) separately collected bio and green waste from households are fermented to obtain biomethan. Both fractions will be treated separately, because the biogenic waste is too impure to be composted after the fermentation, while the separately collected biowaste will be composted after the fermentation phase. The methane that is produced in both fermentation plants will be cleaned and used as biogas for heat and electricity production.

A drying facility in which the output of the fermentation of sorted biogenic waste, which is not sent to the fermentation process together with other biomass waste, is dried to obtain a fuel-like feedstock for the biomass incinerator.

A composting plant: bio and green waste together with the woody waste are sent in the composting plant after the biogas generation (just for bio and garden waste). The compost is supposed to substitute peat and fertilizer for agriculture and private households.

A cogeneration plant with two sections, one for biomass and one for refuse-derived fuel incineration. The biomass incineration section will receive non compostable residuals from the fermentation process of the woody waste and the bio and green waste as well as the residual of the dried biomass waste after the fermentation process . The refuse-derived fuel section will receive the residual waste that was mechanically sorted out of the municipal waste. The cogeneration plant generates heat to be delivered to the district heating system and electricity to be integrated into the electricity grid. This strategy avoids the complete coverage of the FA Altona by the bio bin collection scheme. As stated in Arlati et al. (2018) and Acke et al. (2019) a 100% coverage is unlikely to happen due to the specific urban structure of certain housing typologies. Moreover, as shown in Arlati et al. (2018, p. 19) , the Hamburg population seems to have a low level of waste sensitivity.

The data available regarding the ZRE functioning are mainly related to mass flows. No technical data were found. In this sense, the same technical data used for the MVB and the BKW were used. The generation of electricity and heat through the process of incineration and from the biomass cogeneration plant were assumed to substitute the electricity produced by hard coal, brown coal and oil, as for the MVB (see system boundary). The methane produced from the fermentation process is then processed to generate biomethan and used as a substitute of heat and electricity, as for the BKW. Figure 15 represents the flow changes due to the application of the strategy to the *Status Quo*.

Further, the ZRE will be located closer to the FA Altona, which will result in a reduction of the hauling distances and its related impacts. The Strategy S1 linked to this EIS (S1) includes also a change in the waste separation pattern as resulting from the recycling offensive reported in Freie und Hansestadt Hamburg (2018).

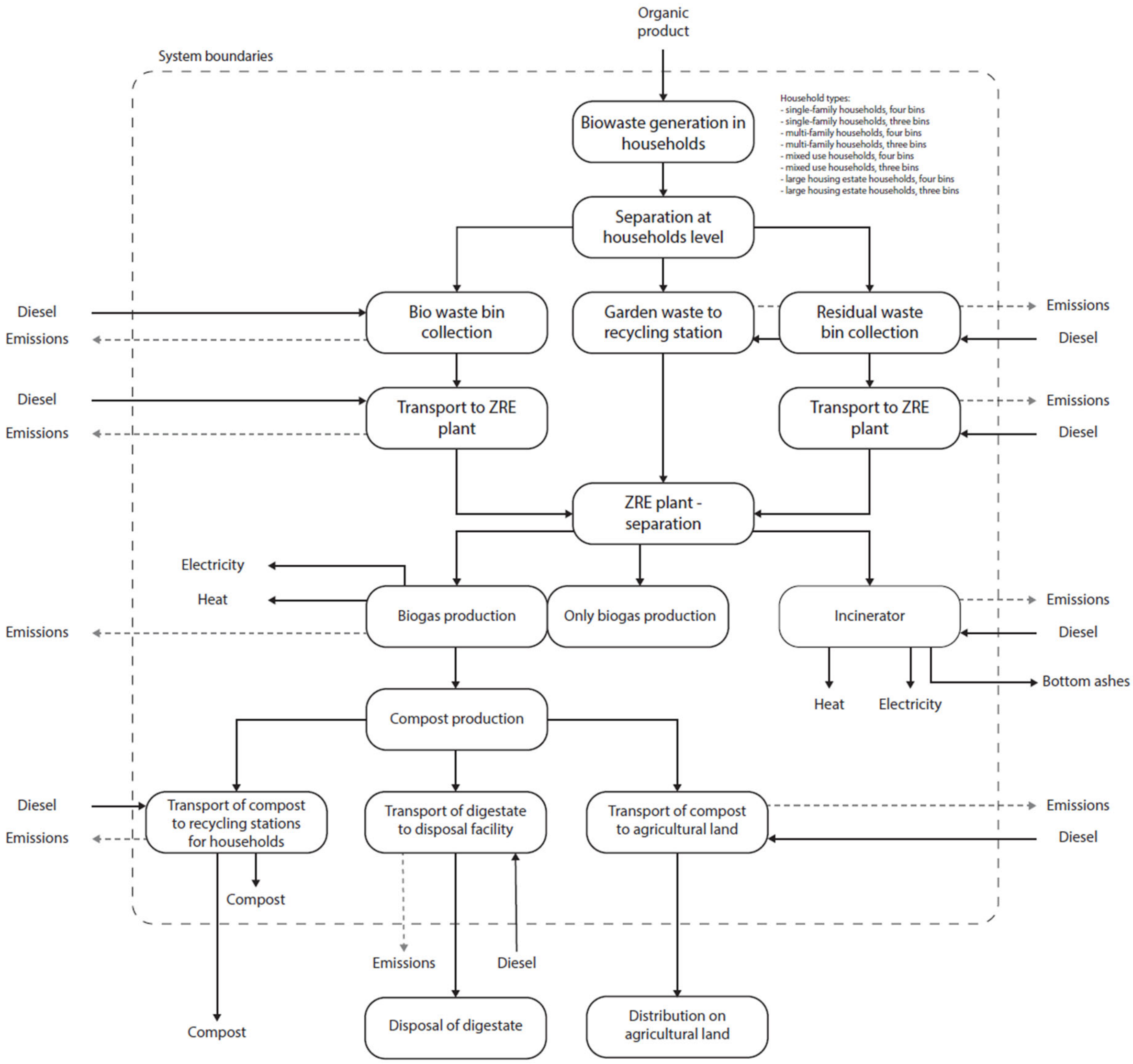


Figure 15, Changes in the flows due to the application of strategy S1 to the foreground system (HCU Team, 2020).

Strategy S2 - Decentralized solution for biowaste collection from households

Strategy S2 refers to the development of community gardening (CG) initiatives on the territory. The CG was modelled according to a similar initiative already present in the neighborhood of Ottensen in Altona. The strategy S2 corresponds to EIS 5 in Obersteg et al. (2020) and includes the possibility for the CG to receive the kitchen and garden waste especially (but not exclusively) from those households who cannot have access to the bio bin for several reasons. From this waste, the CG will produce compost to be used as fertilizer for the garden. The fruits and vegetables grown in the CG will then be distributed to the members who adhere to the initiative.

Further, it was assumed that households with a garden will be inspired by this initiative to start to compost by their own a certain amount of garden waste and vegetable and fruit waste (25% as in Boldrin *et al.*, 2009) as "lesson learned" from the CG initiatives. The bio bin in this scenario is collected as described in the *Status Quo* scenario, as well as for the residual bin. Beside the diversion of part of the biowaste to the CG initiative, the content of biowaste in the residual bin is supposed to be further reduced as for strategy S1 in accordance with the recycling offensive.

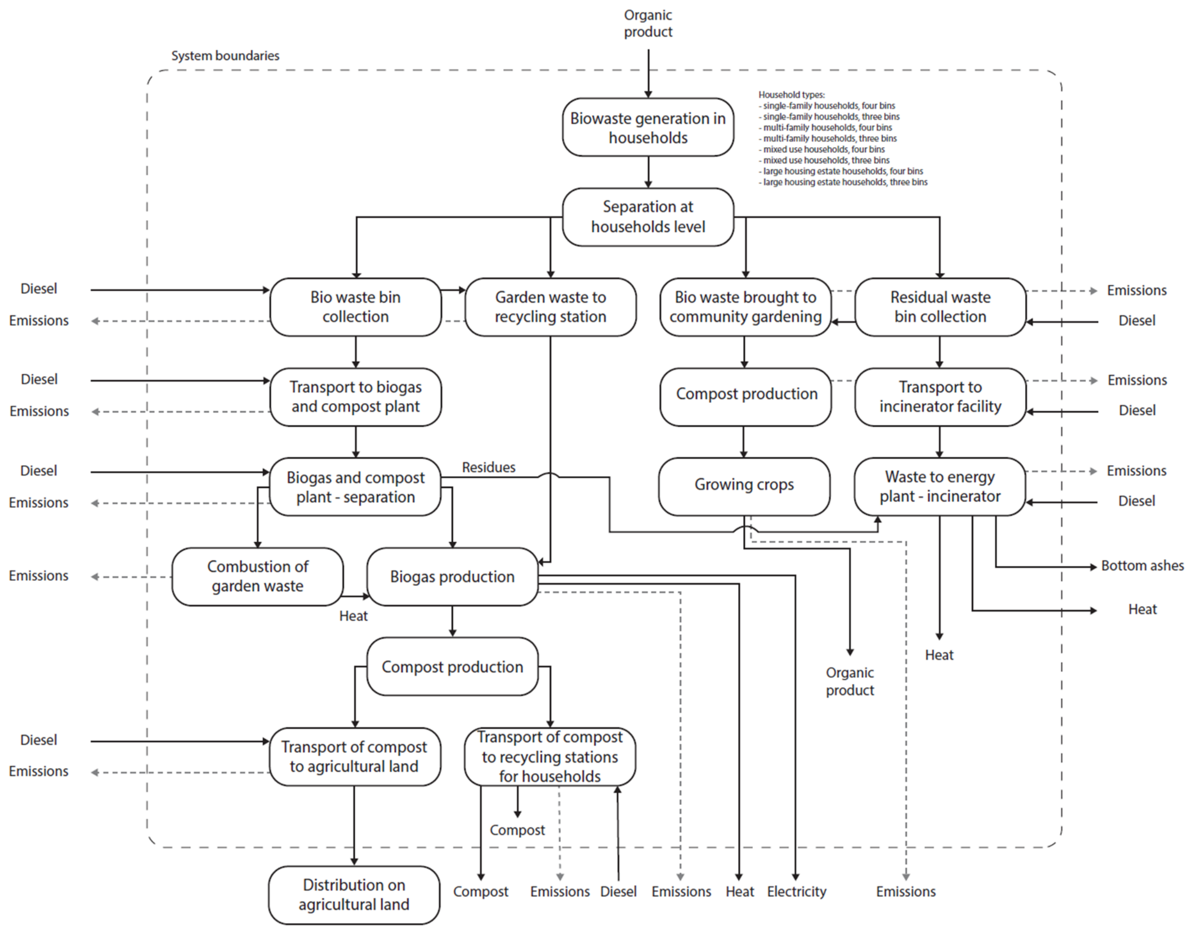


Figure 16, Changes in the flows due to the application of strategy S2 to the foreground system.

FOOD WASTE PREVENTION AND BETTER SEPARATION STRATEGIES

The food prevention strategies are subdivided into three Economic Measures developed on the basis of three different goals: a) trigger behavioural change, b) prevent waste generation, and c) a better separation. The following three measures are the translation of the EIS 1 (here divided into EIS 1a and EIS 1b) and EIS2 in the LCA modelling as described in Obersteg *et al.* (2020). These two EIS have the goal of improving waste avoidance and separation also by involving actively the residents (cf. Obersteg *et al.*, 2020). These three measures for food waste prevention were then applied to the *Status Quo*, Strategy S1 and S2, for a total of five strategies as shown in Table 8. Their impacts on the *Status Quo* are expected to reduce the amount of waste that has to be managed otherwise. In the following paragraphs, the three measures (i.e. EIS 1a, EIS 1b and EIS 2) are described in detail. After, Strategies S3-to-S5 are presented.

EIS 1a: Food waste avoidance through single events

This EIS refers to the organisation of targeted events for sensibilisation of citizens towards sustainability topics. This has been translated in savings in animal food production and the relative costs for the waste management. According to Caldeira *et al.* (2019), the initial investment for such events has been determined. One event was considered to last two full weeks in a year (which might be distributed over the year or as a single event). This results in a reduction in the emissions for the production and distribution of animal food waste (as described in Tonini *et al.*, 2018). The waste prevention was considered also as a change in the consumption pattern, reducing therefore the ratio of animal food waste generated. The animal food waste that could be potentially avoided through such events was calculated to be ca. 400 t year^{-1} in the five sample areas for a total revenue of 1.4 million euro year^{-1}.

EIS 1b: Incentives for a better separation through information campaign

SRH has conducted an information campaign for rising awareness towards waste separation. This measure was considered as an awareness/education campaign according to the categorisation of Caldeira *et al.* (2019). This translated in a better separation in the household typologies, i.e. in an increase in the biowaste content in the bio bin and its consequent decrease in the residual bin. An office with three persons will be in charge of organising the campaign. Given the fact that the results from SRH on the improved waste separation behaviour are not available yet, these have been derived from Caldeira *et al.* (2019). As a result, around 570 t year^{-1} in the five sample areas are supposed to be better separated, i.e. an increase of the biowaste content in the bio bin.

EIS 2: Subsidies for behavioural change through point system

The EIS 2 is focused on introducing rewarding systems for waste avoidance and good separation behaviour. In the model, this has been translated in a coupon-like initiative. Most likely, this solution will be linked to the community gardening project as an additional measure to push residents adhering to the initiative. The initiative is supposed to provide the user with a coupon per kg of bio-waste brought. This biowaste consists of green waste and fruit and vegetable waste (as for a home composting practice). With the coupon it will be possible to obtain discounts by zero waste shops, organic food shops, and other similar initiatives in the area. The initial investment for this initiative has been derived by Caldeira *et al.* (2019). The operational costs have been accounted to the system as subsidies considering 2 persons as starter of the initiative and the costs for the coupon (WallStreetMojo, 2020). Assuming that a share of the waste generated by households without the bio bin will be brought here as in EIS 5, an additional 32% as in Caldeira *et al.* (2019) has been considered as effect of the initiative, for a total of ca 860 t year^{-1} in the five sample areas (around 6% of the total biowaste generated in the FA Altona). All three measures are applied simultaneously for the strategies S3, S4, and S5 as described below and reported in Table 8.

Strategy S3 - SQ + EIS 1a and EIS 1b: effects of information campaigns and single events

Strategy /s3 represents the application of the Economic Measures EIS 1a and EIS 1b to the *Status Quo* in combination with the recycling offensive. The two EIS as described above are bringing a reduction of animal food waste generation (EIS 1a) and a better separation behaviour at households level (EIS 1b).

Strategy S4 - Strategy S1 + EIS 1a and EIS 1b: effects of information campaigns and single events combined with the centralized strategy

As for strategy S3, this strategy takes strategy S1 as base and applies the EIS 1a and EIS 1b as described above as further measures for reducing the waste managed by the system and increasing better separation behaviour. These two measures combined with the strategy S1 reduce the emissions of the ZRE for the mechanical separation process and increase the amount of compost produced as co-product.

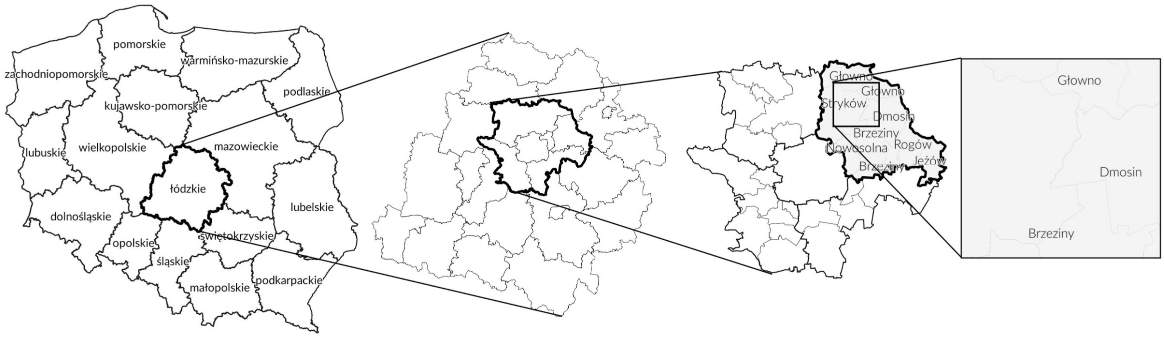
Strategy S5 - Strategy S2 + EIS 1a, EIS 1b and EIS 2: effects of information campaigns, single events and point system combined with the decentralized strategy

As opposed to the previous strategy, strategy S5 takes strategy S2 as base and applies the EIS 1a, EIS 1b and additionally the EIS 2. The EIS 2 describes the point system which is linked to the Community Gardening initiatives. This last measure results in a diversion of part of the kitchen waste from the conventional waste management system and contributes to an additional production of compost.

2.4. Łódź

2.4.1. General

We focus on the management of biodegradable municipal waste, including vegetable, fruit and garden fraction (VFG) from households generated in a selected area of Poland, i.e. Łódź Metropolitan Area, from now onwards referred to as the Focus Area (FA; see Figure 17). It consists of six municipalities, including Brzeziny (urban and rural), Głowno (urban and rural), Jeżów, Nowosolna, Rogów and Stryków.



COUNTRY AREA	REGION AREA	FOCUS AREA	SAMPLE AREA
Poland	Łódzkie voivodeship	Six municipalities within Łódź Metropolitan Area (ŁOM): Brzeziny (urban and rural), Głowno (urban and rural), Jeżów, Nowosolna, Rogów, Stryków	

Figure 17, Łódź case study, from country to Focus Area and sample areas.

The first definition of the Łódź case study area has been formulated in a pre-Lab participatory process, led by the IGiPZ PAN (Institute of Geography and Spatial Organization, Polish Academy of Sciences) and PHH (Pheno Horizon) in collaboration with other local partners and User Board Members.

The Łódź Metropolitan Area (Łódzki Obszar Metropolitalny) is located in central Poland. The ŁMA is made up of thirty-one local self-government units in five districts: the City of Łódź, Brzeziny County, Lodz–East County, Pabianice County and Zgierz County. One of the primary objectives between the five districts is to promote socio-economic development of the Łódź Metropolitan Area through ITI Association (Integrated Territorial Investment). The total population of the ŁMA is about 1.1 million. The region is responsible for a range of policies, including economic development, public transport and aspects of spatial planning related to suburbanisation, infrastructure and waste management. ŁMA is divided into 3 municipal waste management regions (so-called RGOKs) and the chosen focus area belongs to one of them.

The EASETECH software was used to facilitate LCA modeling (Clavreul et al., 2014). Primary data was collected and calculated using open databases and data provided by the Marshall Office and local authorities (municipal waste management reports).

2.4.2. Key waste stream: Vegetable, Fruit and Garden (VFG) waste

Considering the indications of the User Board members, PULL workshops' participants and bearing in mind the challenges facing the Łódź agglomeration in the field of sustainable waste management, it was decided to focus on the Vegetable, Fruit and Garden (VFG waste) fraction (see Deliverable 3.5). The FU of the assessment is 1 t of VFG waste generated by households in the FA (the reference year is 2016).

The inventory data with respect to VFG waste management in the FA involves local primary data complemented with literature data and available LCI databases (EASETECH database and Ecoinvent datasets). We managed to collect the primary data on the quantity of VFG waste generated by households in the FA with the division into individual municipalities, waste flows (waste collection and transportation) and finally waste treatment technologies, being applied in the Łódź Metropolitan Area. Data regarding both separated and non-separated waste flows: amount of treated waste, category and subcategory of waste, waste treatment plants (locations, type of facility, treatment process), were collected from municipalities' databases (municipal waste management reports) and structured for the LCA purposes. All datasets used as a proxy for the composition of vegetable and food waste were obtained from the database of food products provided in Tonini et al. (2018), whereas the composition of garden waste was derived from the EASETECH database. Background data for modelling of energy, material, fuels and resource provision was acquired from the relevant LCI databases, consequential system.

There was also additional background data collected, which was used to calculate primary indicators. Households data – type of building (single-family, multi-family, semi-detached houses) were obtained from Topographic Objects Database (BDOT10k), which was shared by the Marshall Office of Łódzkie Voivodship. Cadastral data was employed as a supplementary for analyses on single-family and semi-detached houses, because plots were treated as an additional space possible to be used for waste collection. These data were applied for calculation of Private Space Consumption indicators. The number of flats were estimated using data on the average size of flats in each municipality (based on data from the Central Statistical Office – Local Data Bank). Data regarding nominal space consumption of containers were collected from waste management companies. Public space consumption of the waste management system was estimated based on municipal databases (above mentioned reports) and cadastral division provided by the GUGiK (Head Office of Geodesy and Cartography). Calculations for spatial indicators were conducted involving Quantum GIS and ArcGIS software. Costs were estimated by own calculations and data from the reports (European Commission, 2009). To determine the loss value of properties, data from the leading real estate agencies was used (www.otodom.pl, www.morizon.pl, www.domiporta.pl, www.dom.gratka.pl, www.klikmapa.pl). Data regarding locations provided in advertisements of properties for sale were employed for conducting analyses in buffer zones of: 0-1 km, 1-2 km, 2-3 km, 3-4 km, 4-5 km. Coherent selection criteria were assumed to achieve a comparable database for each buffer zone. Regarding the accessibility to waste management indicators, where 8 buffers were predefined, no calculation was needed. Due to the specificity of Polish spatial planning all containers and infrastructure for waste collection from households are located in the vicinity to the buildings and not exceeding 50 m. All socio-economic indicators were calculated using methodology described in Deliverable 4.4. Supplementary data were collected from Local Data Bank and websites, which provide data from regional waste management installations –RIPOK:

(http://www.rceeplock.nazwa.pl/blizejsmieci/index.php/wykaz-i-mapa-ripok-ow).

Detailed identification of EIS appropriate for the Łódź Metropolitan Area was carried out based on discussions held during the 3rd and 4th PULL Meetings as well as subject literature overview along with selection of best practices from Poland.

Status Quo

Based on workshops with key stakeholders, as well as a preliminary territorial study, we selected the focus area of Łódź Metropolitan Area as the north-eastern part of the ŁMA – communes located within two suburban belts - national road 14 and 72, with a particular attention to the communes of Stryków and Brzeziny. Municipalities within the FA belong to 2 RGOKs (Fig. 18).

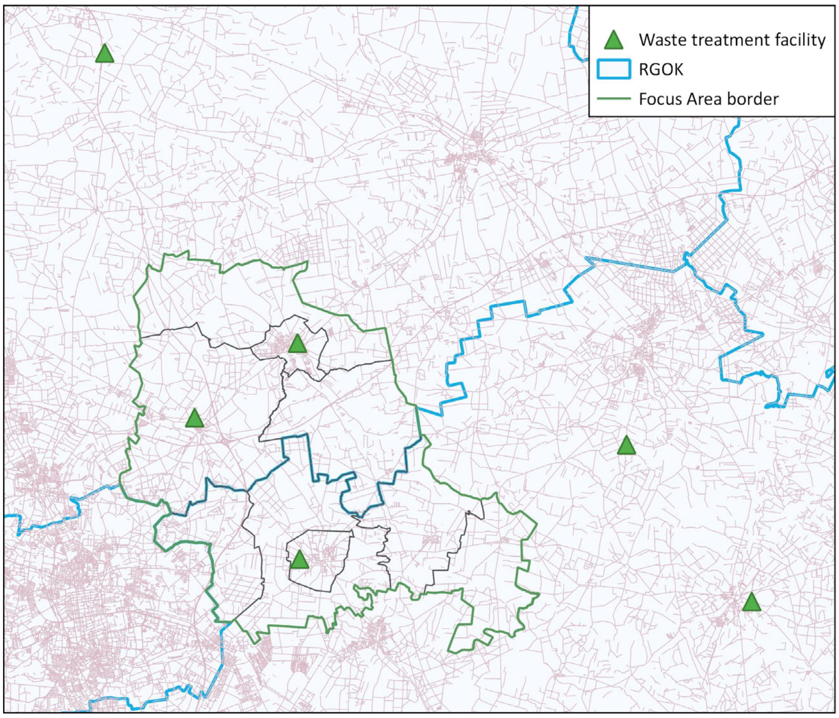


Figure 18, Location of waste treatment plants and division on RGOKs.

The FA is serviced by 5 waste management companies:

1. Municipal Plant in Głowno,

2. Composting and storage plant in Brzeziny,

3. Waste Management Plant AQUARIUM SP. Z O.O. PUKININ

4. EKO-REGION Sp. Z o.o. in Julków,

5. Waste Management Plant (Regional Installation of Communal Waste Treatment, in Polish RIPOK) in Krzyżanówek, TONSMEIER CENTRUM SP. Z O.O. (now PREZERO sp. z o.o.)

Tonsmeier Centrum Sp. z.o.o. is the biggest company from the list above, and is responsible for the treatment of about 46,6% of waste generated within the FA. Only the first two companies are located within the FA. According to the Act of Waste (2012), which is one of the most important acts regarding waste management recently issued in Poland, waste should be treated inside the region where they are generated. Therefore other companies are located within RGOK and are servicing neighboring municipalities.

Within the FA there are also 2 selective municipal waste collection points (in Polish PSZOKs). There is a possibility to leave separated fractions of waste (in the FA only 0,5% biowaste goes to PSZOKs). This waste finally goes to waste treatment facilities, where it is mostly composted. Polish law forces local authorities to establish such facilities as PSZOKs, to increase the amount of waste collected and transported by individual inhabitants.

The collection of waste in Poland is described in the Act of Waste (2012). It states that each of the five fractions (biowaste, metal and plastic, glass, paper and mixed) has to be collected separately to different containers. During and after the transition towards a more separate collection system, people's awareness of appropriate sorting did not follow the new regulations as it was expected and a part of the analysed biowaste (VFG) fraction (as it was described in Deliverable 3.5) ended up as mixed waste. As over 70% of waste collected in 2016 in the Łódź Metropolitan Area was classified under the mixed waste category, it was decided to estimate this value based on nationwide data and information obtained from communal reports on implementation of tasks related to municipal waste management concerning mass of biodegradable waste collected from municipal waste stream within commune's area in the accounting year, transported for storing.

The mass flows of household waste generated within the FA are presented in Table 9. In total, 89% of VFG waste is composted and reused (e.g. as a fertilizer). The greatest amount of waste is generated in single-family houses. It is strictly connected with a settlement structure of the FA, which is mostly represented by rural areas, and secondly by small cities where the settlement has a similar character.

Table 9, General statistics of waste generation and treatment by municipality within the FA

Municipality	**Mass of waste treated (t/year)**		**Total mass of VFG waste (t/year)**	**Mass of waste generated by type of household (t/year)**		
	Recycling / composting	**Storage**		**Single-family**	**Semi-detached**	**Multi-family**
Brzeziny (urban)	581		581	404.25	0.00	3.67
Brzeziny (rural)		252	252	263.23	0.13	192.58
Dmosin	78		78	47.42	0.00	0.57
Głowno (urban)	456		456	294.29	0.67	40.01
Głowno (rural)	48		48	564.28	0.00	17.67
Jeżów	43		43	89.75	0.00	162.20
Nowosolna	408		408	70.00	0.00	7.51

Rogów	35		35	39.57	0.00	3.26
Stryków	335		335	33.36	0.00	1.22
FA	1984	252	2236	1806.17	0.80	428.68

In the FA 2236 t of VFG waste in 2016 was collected. The system of collection and treatment is shown in Figure 19. Separately collected waste is transported to mechanical and biological treatment (MBT) and composted. The compost is used as a fertilizer. One of the examples is the Waste Management Plant AQUARIUM SP. Z O.O. PUKININ, which produces fertilizers called "Pukininek" (according to the official website of the company). Part of the VFG waste, due to low ecological awareness, is available in the mixed fraction. These are sorted and transported to a MBT plant or simply landfilled. About 0,5% of VFG waste, as mentioned earlier, is transported by individuals to PSZOK from where it goes to a proper treatment installation.

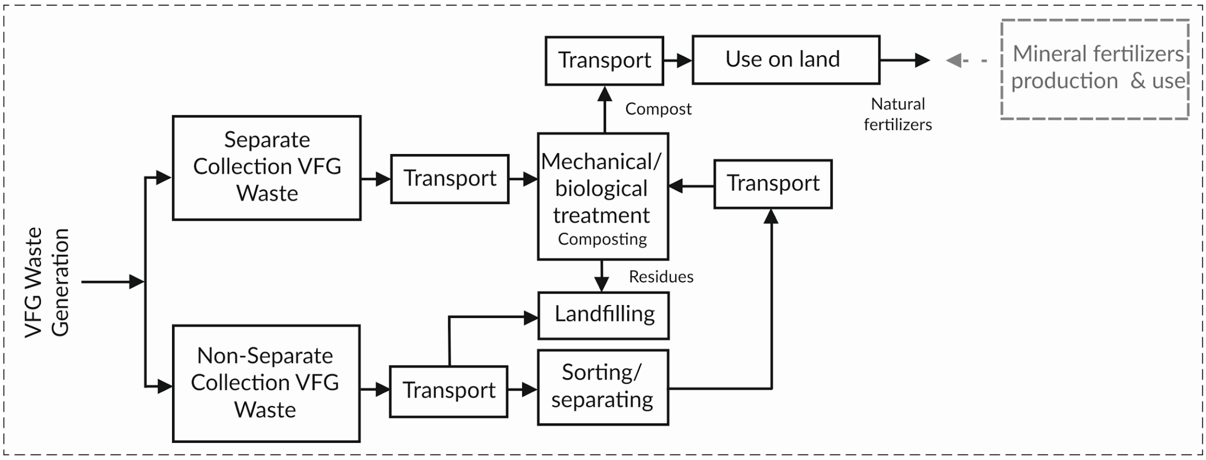


Figure 19, System Boundary of Focus Area of ŁMA – Status Quo.

STRATEGIES

S1. Home composting & Centralised composting

The strategy S1 involves aerobic home composting of the separately collected VFG waste for all households with gardens. Additionally, it involves centralized aerobic composting of the remaining selectively collected VFG waste from the households without gardens. Considering the structure of the FA (basically rural areas) and the type of buildings, it was assumed that 19% of VFG waste can be composted by inhabitants.

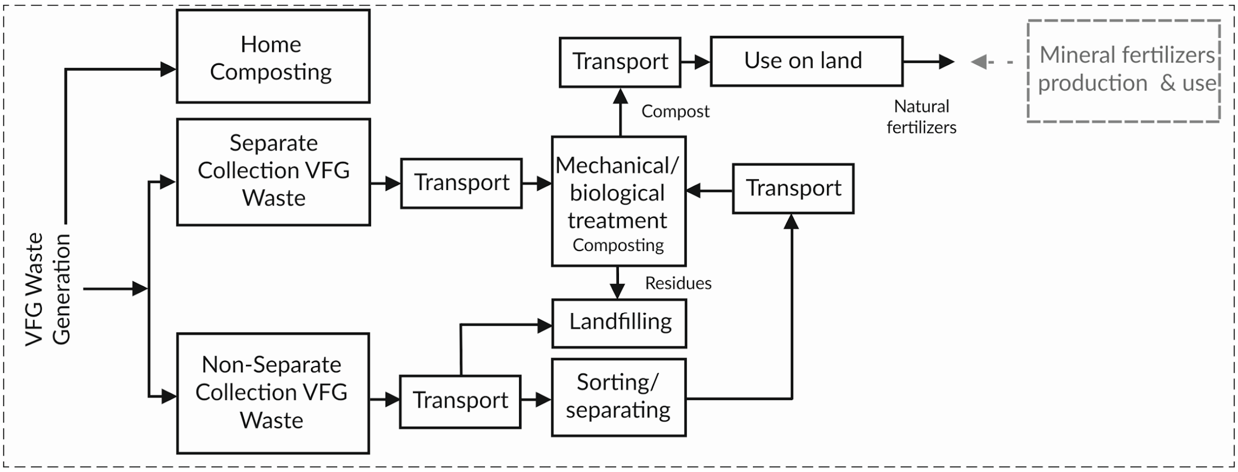


Figure 20, Strategy S1 Home composting & Centralised composting.

S2. Centralized Anaerobic digestion

The strategy S2 involves centralized anaerobic digestion followed by a post-composting of the selectively collected VFG waste.

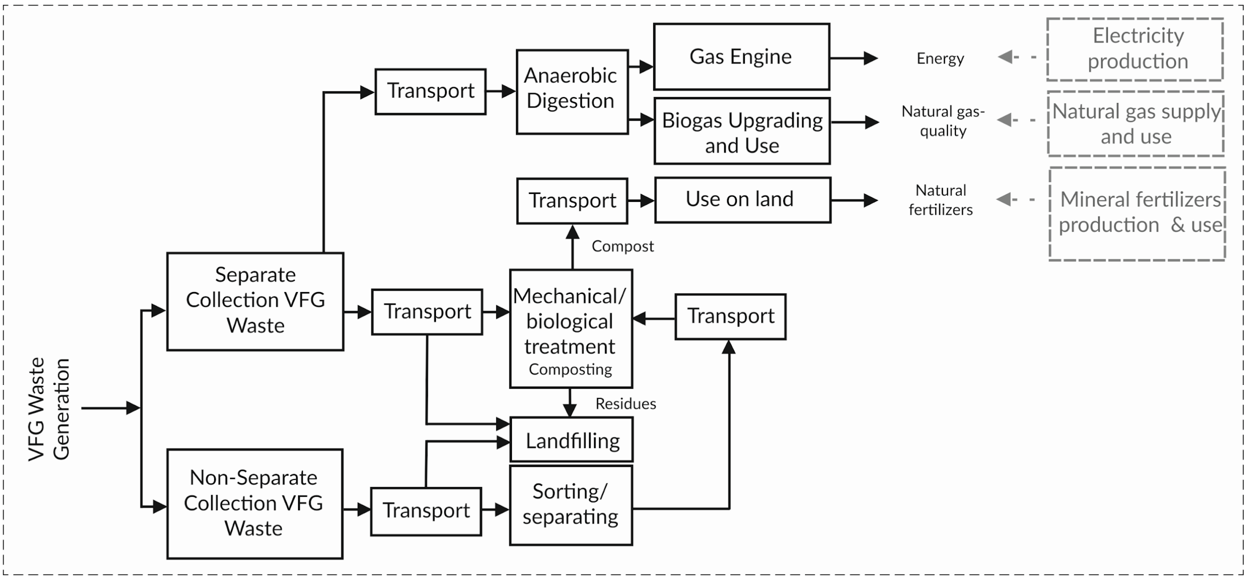


Figure 21, Strategy S2 Centralised Anaerobic digestion

S3. Home composting & Centralised Anaerobic digestion

The strategy S3 involves aerobic home composting of the separately collected VFG waste for all households having private gardens. Additionally, it involves centralized anaerobic digestion of the remaining selectively collected VFG waste from the households without gardens. Considering the structure of the FA (basically rural areas) and the type of buildings, it was assumed that 19% of VFG waste can be composted by inhabitants.

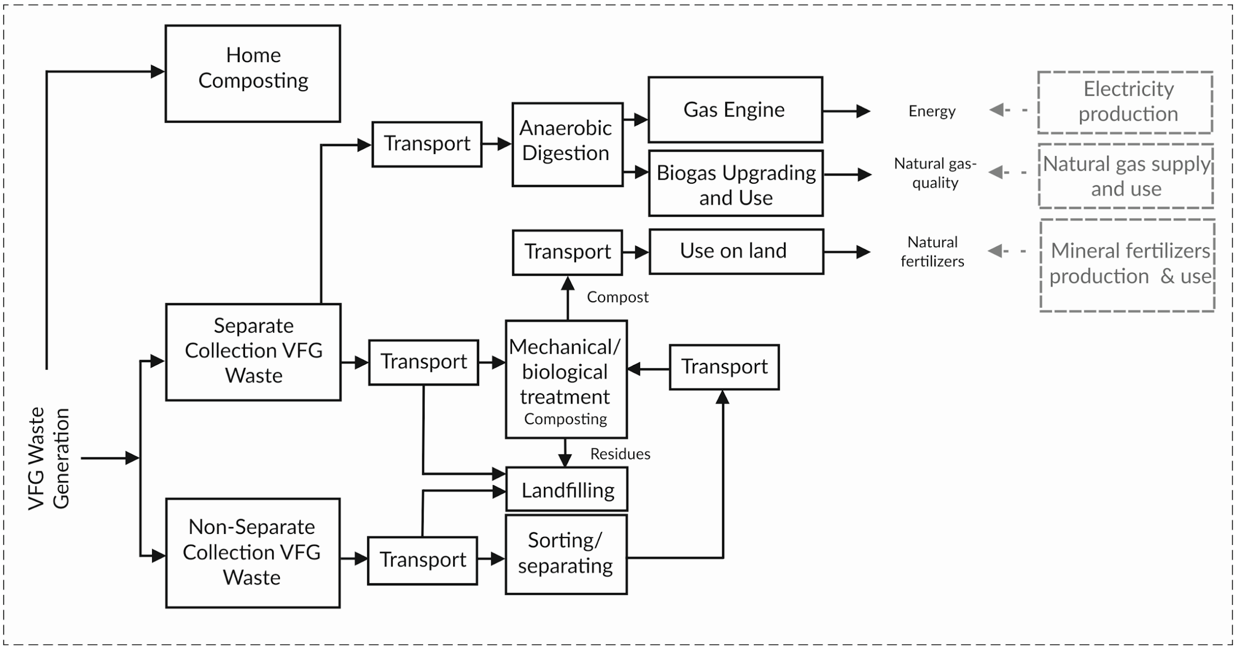


Figure 22, Strategy S3 Home composting + Centralised anaerobic digestion

2.5. Pécs

2.5.1. General

Figure 23, Pécs case study, from country area to Focus Area.

The Pécs FA includes Pécs city and 40 neighboring settlements in the Baranya county, in the South-West part of Hungary, close to the Croatian border (Figure 23). Despite the fact that each municipality is responsible for its own waste management, only regional companies certified by the national authority are allowed to offer Waste Management (WM) services for households and small businesses. The certified company in Pécs FA is Dél-Kom, which is owned by BIOKOM, hence we use BIOKOM in this report when referring to the service provider. Restaurant & canteen food waste is collected by independent actors.

The LCA-related indicators of the sustainability analysis were implemented with openLCA software v1.10.2, while the life cycle ecoinvent v3.5 (student) database was used to model the background system. Data inventory for the *Status Quo* consists mainly of primary site-specific data, provided by local actors. All indicators of the REPAiR framework (Taelman *et al.*, 2020) were applied to the Pécs case.

2.5.2. Key waste stream: Organic Waste (OW)

The PULL workshops organized in Pécs focused mainly on organic and plastic waste, as these are the most important material streams that prevent fulfilling the recycling and landfilling targets set by EU directives, which were recently revised in 2018. The OW related solutions, proposed by workshop participants, fall under both prevention and recycling categories of the WM hierarchy: reduction of food waste and separate collection of food and garden waste is both targeted. Organic waste is defined in the case of Pécs as: organic fraction of municipal solid waste (of MSW), garden waste, unsold food, restaurant & canteen food waste and christmas trees.

The FU considered in this study is the management of 1 t of organic waste (OW) generated by households, small-and-medium-enterprises (SMEs), as well as by school canteens, large marketplaces and shops in the FA per year. Any (co-)product generated alongside the management of the waste is credited to the system by expanding it to account for the substitution of corresponding (conventional) market products.

Status Quo

Description

The organic waste management in the Pécs FA consists of three door-to-door collection method, which is accessible for citizens in different parts of the area, according to the geographical and demographical characteristics:

i. non-separate collection of OW (i.e. collected with the MSW);

ii. non-separate collection of OW (i.e. collected with the MSW) + separate collection of garden (and uncooked food) waste;

iii. non-separate collection of OW (i.e. collected with the MSW) + home composting.

Depending on the combination of collection methods in place, including separate collection of packaging, the FA is broken down into 8 districts (see Figure 24; details in Deliverable 3.7).

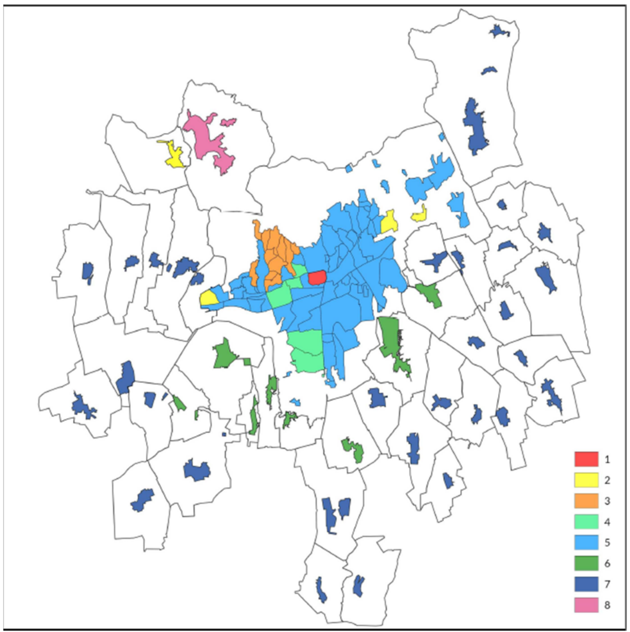


Figure 24, Typology of waste collection districts of the Pécs Focus Area.

For consistency reasons in this report, the organic waste fraction of mixed municipal solid waste is referred to as non separately collected (NSC)-OW, while separately collected organics are SC-OW. Gray or black bins, containing mixed MSW, are emptied once or twice a week, while brown bins full of garden waste are emptied once every two weeks. WM public service integrates both commingled and separate collections, citizens and SMEs pay according to the grey/black bin volume. No weighing or RFID customer identification is available, since these are irrelevant in the invoicing process. In the late 90's, when separate collection was introduced, downsizing of the grey/black bin resulted in some financial advantage, but almost every household pays for the minimum volume possible today, i.e. economic incentives are non-existing in this case.

Garbage trucks transport NSC-OW directly to the MBT plant near Pécs, where the treated waste (Compost-Like-Organic, CLO) is landfilled. Based on regular waste composition analyses, 1.22E+7 kg of NSC-OW was present in the MSW entering the MBT plant in 2017. The organic fraction of the residual waste is assumed to be 31.55% (macroscopic composition analysis shows 26,2% of the total input material, which has to be adjusted taking into account the total organic content of the fine fraction). The treatment site also hosts a composting plant, where green wastes from households and public parks (also collected by BIOKOM) are composted together. The end product is used on agricultural land as fertiliser. In 2017, the green waste collected from households and public parks totalled at 6.0E+6 kg and 3.3E+6 kg, respectively.

Restaurant & canteen food waste (1.6E+4 kg) is collected by independent companies and delivered at biogas plants near Pécs and in Budapest. Christmas trees (2.6E+4 kg) are separately collected and burned in the local biomass power plant, in a fluidised bed boiler to produce electricity and district heat. No MSW incinerator is available to treat waste produced in the FA. Organic waste in the *Status Quo* represents 2.208E+7 kg in total. Table 9 shows the breakdown by treatment options.

Table 9, Treatment pathways of organic waste in the Status Quo (mass of OW per FU).

Treatment	Mass (kg)
MBT	554.34
Composting	421.23
AD	23.25
Incineration	1.18
TOTAL	1,000

System boundary

Collection processes (NSC and SC), mechanical-biological treatment (MBT) of NSC-OW, composting, incineration and anaerobic digestion of SC-OW, and subsequent disposal of residues (e.g. landfilling of CLO and plastic impurities) were the processes included in the foreground system while further treatment of some recovered resources from the treatment processes was not. Economic, material flow and energy data were available from the treatment processes at plant level. Social and collection data were gathered on municipality level inside the FA. The foreground and background systems are shown in Figure 25.

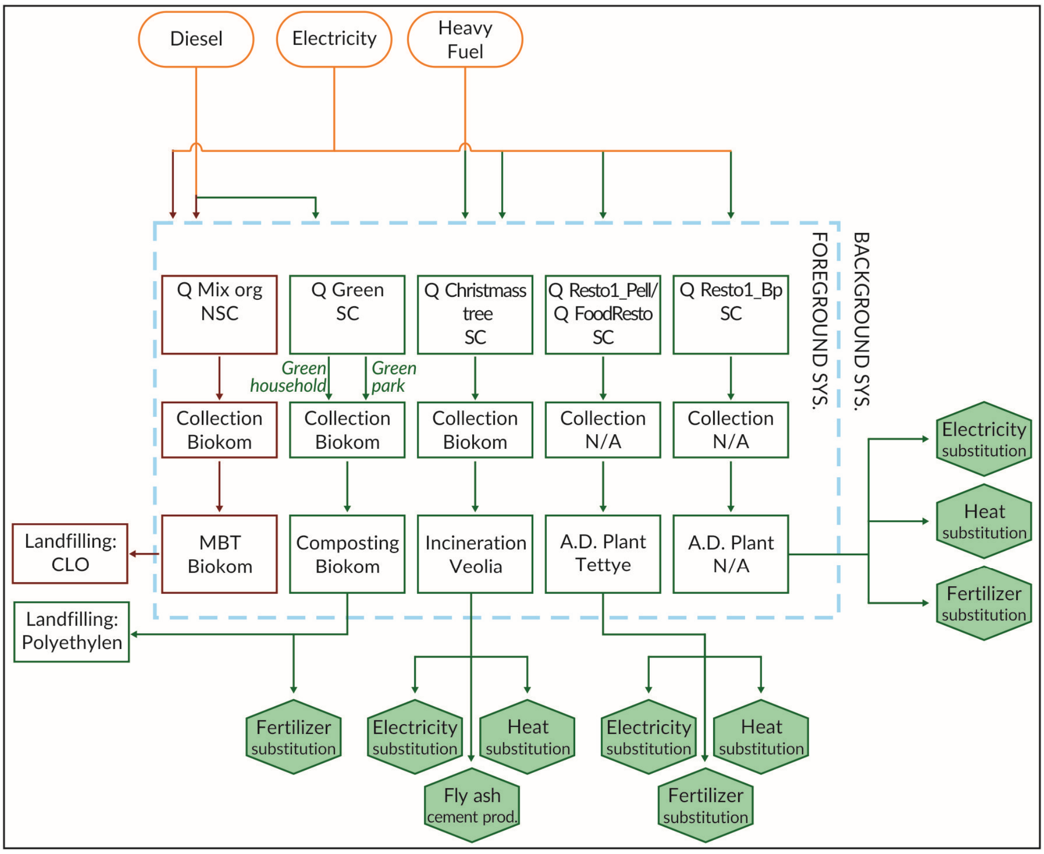


Figure 25. Processes in the foreground and background systems collecting and treating OW, its residues and avoided products in Pécs FA. The selective collected waste streams are represented in green, while the non-selective collected waste streams in red. Required energy carriers are represented in orange. Arrows indicate material flow directions only.

The co-products generated during the treatment of organic waste are credited to the system by substitution of conventional (primary) products. Aerobic and anaerobic treatment processes produce compost. Since it was unknown for which purposes the compost is applied (e.g. as substitution for peat), the substitution has been performed based on Tonini et al., (2020), assuming an average EU mix for the substitution of NPK mineral fertilisers. This mix includes 24.5% urea, 27% ammonium nitrate, 33% calcium ammonium nitrate and 15.5% urea-ammonium nitrate, diammonium phosphate and potassium chloride. Electricity and heat are the end products of christmas tree incineration in the local power plant. The same applies for the anaerobic treatment of restaurant & canteen food waste. This energy replaces energy produced by other technologies that use uranium, natural gas and coal. It was assumed that low voltage electricity from the Hungarian market (including own production and import) and heat from the combination of a +100 MW natural gas fuelled CHP unit and district heating plant are avoided this way. It was also assumed that fly ash from christmas tree incineration substitute market ready cement, pozzolana and fly ash (11-35%) product.

Data inventory

Since one of REPAiR project's beneficiaries is BIOKOM, responsible for the waste management of the FA, the most reliable data was provided by its controlling department for the year 2017. The dataset included: mass of collected waste streams, distances covered, diesel and electricity consumption, macroscopic composition of mixed MSW, client data, end product mass, industrial land area occupied, employment, wages, CAPEX, OPEX, EOLEX, tarifs, revenues, bin dimensions, accidents. The macroscopic composition of mixed MSW in Pécs FA was defined following quarterly sampling during 5 consecutive years, performed by BIOKOM. The particle size distribution and total organic content of the fine fraction (< 20 mm) were investigated by the University of Miskolc (Hungary), in cooperation with the WM company (2018).

Veolia, owner of the local power plant provided information related to the amount of electricity and heat sold, primary energy carrier consumption, as well as other operational and financial data (2017, 2018). Biofilter and other independent actors gave information concerning the collection of restaurant & canteen food wastes (mainly mass and frequency, 2017). Tettye Forrásház, operator of the local biogas plant, provided operational and financial information related to the anaerobic treatment process (2017). The same figures were used to describe the AD plant at Budapest, where the collection distance makes the only difference. Emissions from composting and anaerobic digestion are based on Amlinger et al., (2008), as well as on the IPCC guidelines of 2006. As a consequence, biogenic CO_2 emissions are not taken into account in the burdens of a given process. All background data originate from the life cycle ecoinvent v3.5 (student) database.

Strategy S1: Separate collection of kitchen waste followed by centralised composting and Anaerobic Digestion (Q kitchen)

The strategy S1 (Figure 26) involves separate collection of the food waste in households. Detailed calculations revealed that an average of only 3 liters (i.e. 1 kg) of food waste could be collected each week per household, thus the implementation plan was reduced to those two districts where high collection efficiency can be obtained. In district 3, where green waste is already collected separately in brown bins, kitchen waste is supposed to be put in this bin, to be treated in the Composting plant. In district 4, which is characterized by high-rise buildings and high population density, kitchen waste should be pre-treated in standardized, small, odourless kitchen bins inside the flats. A group of 15 to 20 households would use one 120 L bin (placed outside the building) allowing separate collection and further treatment in the local Anaerobic Digestion plant (operated by Tettye Ltd. in Pellérd). End products are electricity and digestate. Organic waste in the S1 amounts to 2.208E+7 kg in total. The amount of altered waste is 4.178E+6 kg. As the functional unit is 1 metric t of organic waste treated annually, Table 10 below shows the breakdown by treatment options.

Table 10, Treatment pathways of organic waste in strategy S1 (mass of OW per FU).

Treatment	Mass (kg)
MBT	365.13
Composting	443.87
A.D.	189.82
Incineration	1.18
TOTAL	1,000.00

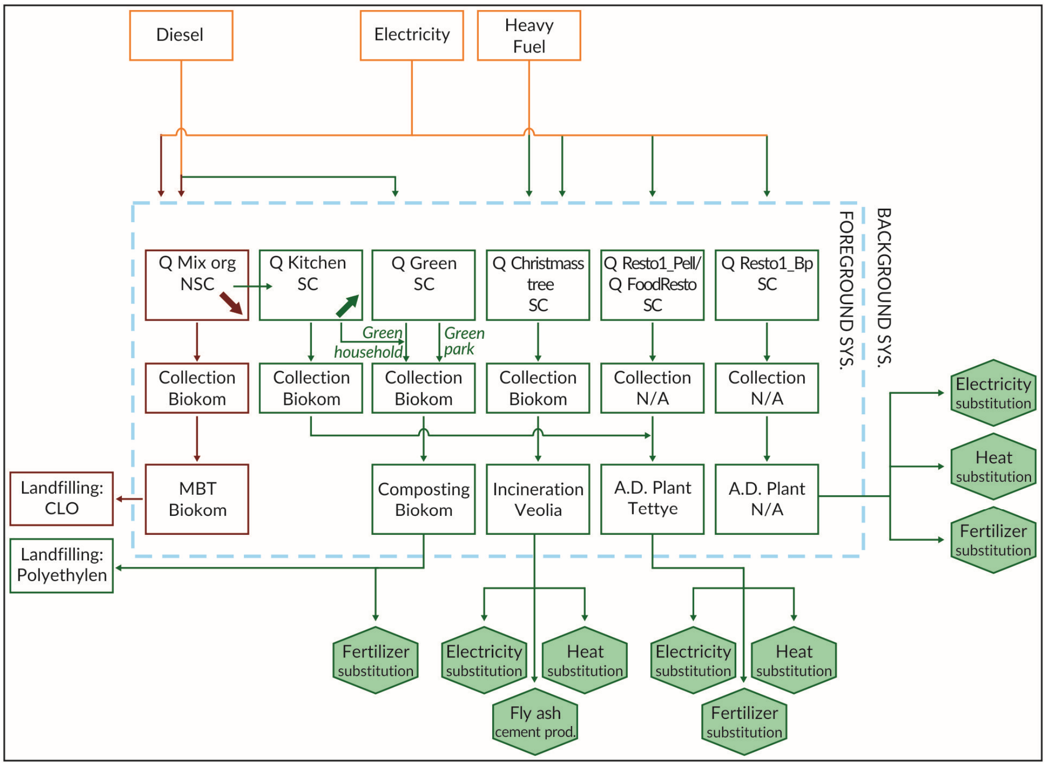


Figure 26 Strategy S1, Pécs case. The green thick arrow indicates the flow that is expected to increase with the implementation of this solution, while the red thick one indicates the flow that is expected to decrease compared to the Status Quo.

Strategy S1 is based on two pillars:

- About 5.0E+5 kg of household kitchen waste is planned to be collected together with green waste. Citizens in district 3 will be asked to boost separate collection simply by adding their kitchen waste to their yard waste. As seen on the figure above, this will raise the amount of material entering the composting facility. The same collection distances are applied for the t*km calculation in case of residual waste and green waste (40km), identically to the Status Quo.
- About 3.678E+6 kg of household kitchen waste is planned to be collected in a novel way: citizens in district 4, where high-rise buildings are dominant, will use a special home equipment to pretreat their kitchen waste aerobically. After 2 weeks, all households in a given building block (15-20 families) will put the pretreated material in one single 120 L bin. 20 km collection distance is applied for the t*km calculation to bring the kitchen waste from district 4 to the AD plant. Other waste streams are unchanged. Data sources and substitution choices are identical to the *Status Quo*.

Strategy 2: Food Rescue Program

The strategy S2 (Figure 27) involves the collection of meals and foodstuff suitable for human consumption from restaurants, public catering and retailment (shops and markets) and distribution to those in need through official caritative institutions or voluntary organizations. Organic waste in the EIS2 represents 2.106E+7 kg in total. The amount of waste production prevented is 1.39E+6 kg. Table 11 shows the breakdown by treatment options.

Table 11, Treatment pathways of organic waste in strategy S2 (mass of OW per FU).

Treatment	Mass (kg)
MBT	540.45
Composting	441.02
A.D.	17.29
Incineration	1.24
TOTAL	1,000.00

The amount of food rescued is composed of:

- 8.8E+5 kg of food from shops
- 1,5E+5 kg of food from restaurants
- 1,4E+4 kg of food from marketplaces

It is assumed that 20 km of collection distance is needed, using a lorry with a refrigeration machine. 2.08E+4 kg of PLA-based packaging is supposed to be used for the redistribution process, which ends up in the MBT plant.

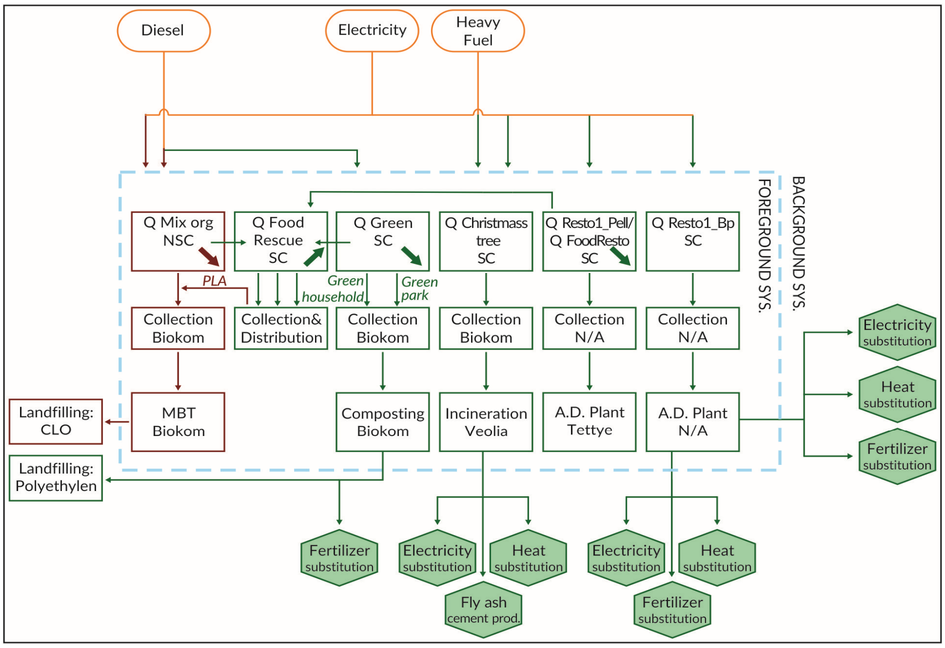


Figure 27, Strategy S2, Pécs case. The green thick arrow indicates the flow that is expected to increase with the implementation of this solution, while the red thick one indicates the flow that is expected to decrease compared to the Status Quo. Decrease in "Q Mix org NSC" originates from shops, "Q green SC" from marketplaces, "Q FoodResto SC" from restaurants. Other waste streams are unchanged. Data sources and substitution choices are identical to the Status Quo.

Strategy S3: Public Catering Improvement (Menzaturbo)

The strategy S3 involves the reduction of wasted food in school canteens by the following interventions: improvement of the quality and aesthetics of food served in the canteens, flexible portioning to better adapt to individual appetite, more adequate information about the number of portions to be consumed (see Figure 28). Removal or reformation of school vending machines, regulation and reformation of food and drink offer in school buffets. Organic waste in the EIS3 represents 2.2078E+7 kg in total. The amount of waste production prevented is 1.6E+4 kg. Table 12 shows the breakdown by treatment options.

Table 12, Treatment pathways of organic waste in strategy S3 (mass of OW per FU).

Treatment	Mass (kg)
MBT	554.46
Composting	421.32
A.D.	23.04
Incineration	1.18
TOTAL	1,000.00

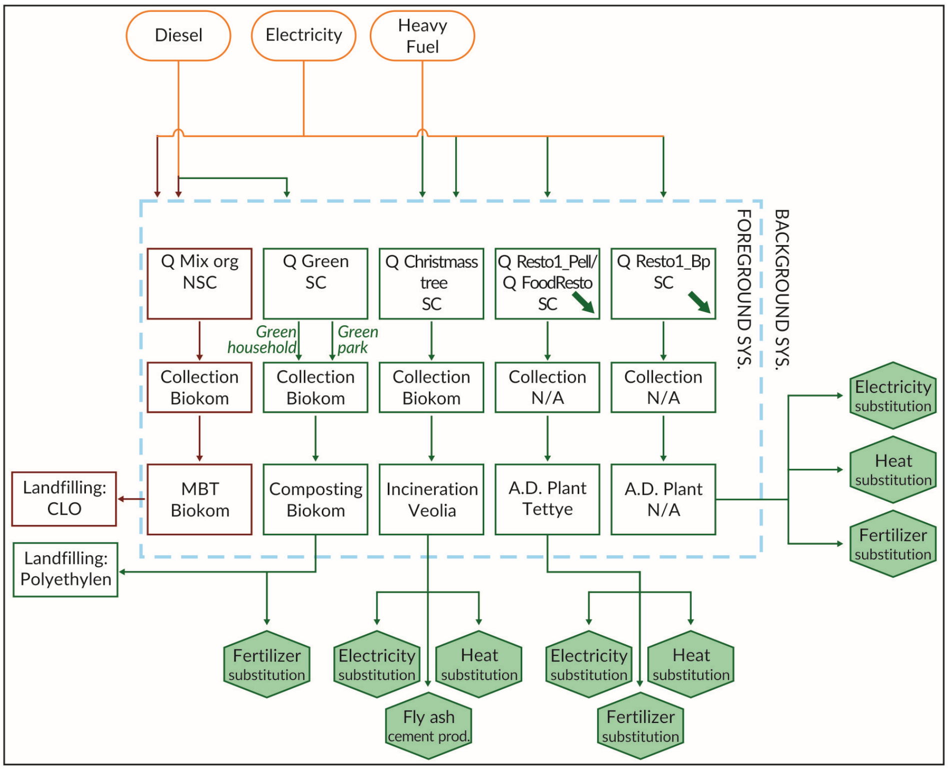


Figure 28, Strategy S3, Pécs case. The green thick arrow indicates the flow that is expected to increase with the implementation of this solution, while the red thick one indicates the flow that is expected to decrease compared to the Status Quo. Since the only change in Strategy 3 is the decrease of food waste ending up in the AD plant, other waste streams, data sources and substitution choices are identical to the Status Quo.

3. Results of the sustainability impact assessment

Results of the application of the sustainability framework are shown first at the endpoint level, per AoP, as obtained after aggregation (applying the MCDA; Taelman et al., 2020) providing a synthetic overview of the performance of each strategy as compared to the correspondent *Status Quo*. This is directed to decision- and policy-makers that search for a final aggregated synthesis of the information.

For a more detailed analysis of the results, the reader is directed to the breakdown at the midpoint impact categories level, where the comparison is made between the strategies and correspondent *Status Quo*. Such level of detail is especially interesting for experts in the field of sustainability analysis. The breakdown of the impact is displayed in Annex B-to-G.

3.1. Ghent

3.1.1. Vegetables, Fruit and Garden Waste

ENDPOINT RESULTS

In total, 7 strategies have been analysed (including each *Status Quo*) with the MCDA technique developed within the REPAiR project (D4.5). The endpoint results are illustrated in Table 13, where the ranking of scenarios is done per AoP. Strategy S6 (BSF plant as valorization), followed by scenario S7 (the strategy containing all EIS), performed best of all scenarios in the AoPs ecosystem health, human health, human well-being and prosperity. On the other hand, the Status Quo performed better than all scenarios in the AoP natural resources, i.e. fossil depletion category. The remaining scenarios, S2A, S2B and S2C, performed worse (or equal) than the Status Quo in all AoPs, except for human health.

Overall, it can be observed that valorisation through insects has a better overall performance (except for the AoP prosperity, so fossil depletion), also the transition to CNG fuelled trucks. Furthermore, it appears that increasing the frequency of collection (S2A, S2B, S2C) and making the separation of VFG mandatory for the whole focus area, does not contribute significantly in a positive way to any AoP, but human health. It could be concluded that reducing the valuable outputs of the incineration plant (electricity, heat, bottom ashes) cannot be compensated by more substituted products at the AD&C plant (fertilizers, electricity). Therefore, exploring new ways of valorising organic waste is the recommended path to take. However, a point of attention is the AoP natural resources, where the BSF valorization (S3+S4) scores worst because of the high amount of natural gas and electricity consumed during the rearing and drying of insects.

Table 13, Endpoint results. SQ: Status Quo, S1: mandatory separation + CNG, S2A-C: mandatory separation + CNG + increased collection frequency (different capture rates), S3: CNG + BSF plant, S4: all EIS (the strategy). Green colours indicate a better performance than the Status Quo, while red colour represent a worse one. Comparable performances are shown in yellow.

Strategy	Ecosystem health	Human health	Human well-being	Natural resources	Prosperity
SQ	*2*	*5*	*3*	*1*	*3*
S1	2	3	4	2	5
S2a	5	5	4	3	4
S2b	5	3	4	4	5
S2c	7	5	4	5	7
S3	1	1	1	6	1
S4	2	2	1	7	1

MIDPOINT RESULTS

The results are displayed for all midpoint indicators analysed in Annex B, grouped according to the five AoPs.

For the impact categories ecotoxicity, marine eutrophication and land use, strategy S4 performed best for all scenarios. This can be explained due to the production of insect puree and meal through the BSF valorisation, which implies having chicken meat and soybean meal as avoided products, that have a high burden in these categories (due to the feed for chickens and the emissions of pesticide/fertilizer use for soybean cultivation, and the related cultivation surface needs). The change to natural gas fuelled collection trucks compared to the *Status Quo* has a positive effect in all EIS scenarios. The opposite trend is visible for freshwater eutrophication, where S3 and S4 score worse than the *Status Quo*. Although the avoided material impact at the BSF plant is significant, the burden (mainly at the product management stage due to the use of ethanol and electricity) of the valorization plant is similar, generating a net impact of 6.37E-04 kg P_{eq} and -1.24E-03 kg P_{eq} for S3 and S4, respectively.

When it comes to global warming potential, S2C shows the worst performance. This is mainly explained by the reduction of waste going to incineration, consequently generating less avoided products of heat and power, which decreases the avoided impact from -1.15E+02 kg $CO_{2\,eq.}$ in the *Status Quo* to -6.73E+01 kg $CO_{2\,eq.}$ in S2C. A significant difference can be observed between S3 and S4, which is explained by the lower frequency of collection in S3, which results in a lower collection rate. In S4, the increase in the need for natural gas for the collection trucks doubles the global warming potential generated by the collection, compared to S3. The BSF plant in scenario 4 accounts for 4,09E+02 kg $CO_{2\ eq.b}$, generated mainly at the rearing and breeding step where high amounts of natural gas are needed. This is also reflected in the category fossil depletion. A similar trend can be seen for ozone formation where S3 and S4 have the largest impacts because of the use of natural gas.

For water use, S3 and S4 scored worst, with a respective water consumption of 6.37E+03 l and 7.04 l per FU. The amounts of water used at the plant are for moisture control of the substrate (VFG), for the insect nursery, mainly for cleaning, as well as in the processing and management of the products. On top, avoiding protein feed also generates a high water burden. When the process 'Protein feed, 100% crude {GLO}| soybean meal to generic market for protein feed | Conseq, U' is investigated it has an avoided burden for water consumption. Because of the consequential approach applied, this becomes a positive impact in S3 and S4.

In the human toxicity categories, S3 and S4 score best. The substituted products from the BSF plant contribute most to the avoided impacts, more specifically the avoided soybean meal and related pesticide emissions. The landfilling of residues and fly ashes at the incineration process in the *Status Quo*, makes the latter process score the worst at these impact categories, contributing approximately 40% (cancer) to 75% (non-cancer) of the total impacts. A same trend can be seen with particulate matter formation. For the category stratospheric ozone depletion again S3 and S4 score best, due to the avoidance of rapeseed oil and nitrogen fertilizers. The *Status Quo* performs the worst at this category, mainly impacted by the use of diesel in the collection step, which is compensated by the avoided heat and electricity in the incineration process and the avoided electricity and fertilizers in the AD&C. For the category ionizing radiation, again the avoidance of products (-3.58E-01 kg $Co_{60\ eq.}$ for S4) at the BSF plant is what contributes the most to this category.

S3 and S4 score best for urban space consumption, explained by the change of treatment process for the SC-VFG. AD&C have a total area of 6480 m^2a while the hypothetical bioconversion plant only occupies 1136 m^2a. This calculation was based on an existing commercial bioconversion plant and its capacity (see section 5.3). Private space consumption, on the other hand, increases from 0.09% in the Status Quo, to 0.14% in S1, S2(A-C) and S4 where it is mandatory to have a separate bin for VFG which takes space. For both total employment and occupational health, S4 scores best. The amount of employees that work in the BSF plant resulted in 2.04E-03 employees $tne{\cdot}VFG^{-1}$, higher than within incineration of AD&C. The BSF plant has also reported the lowest amount of accidents (4.11E-05 per FU) compared to the other scenarios. Also for the odour footprint, S3 and S4 perform best with a value of 2.29E-02 kg H_2S eq. and 2.86E-02 H_2S eq., respectively. The BSF plant has not a significant impact on odour.

In the category effectiveness in achieving behaviour change, S2C performed the best compared to the other scenarios, because it had the highest recycling rate. The SC-VFG in the *Status Quo* represents 60% of the VFG generated in the focus area, while in scenario 2C this increases to 83%. As expected, S2C also performs the best in the impact category public acceptance. This indicator measures the relation between the economic incentives and the sorting efficiency of waste, and even though the financial fee was higher for scenario 2C than, for instance, the *Status Quo*, the sorting efficiency was highly increased in this scenario.

Stakeholders participation was the same for all scenarios as it was not possible to make a distinction between the type of solutions, resulting in a value of 71%. Regarding the accessibility of waste management systems, this was assumed to be the same in all scenarios and the *Status Quo*, as the collection is always door-to-door. Landscape disamenities did not significantly vary between the scenarios.

Regarding the costs, S4 resulted in the highest OPEX, while the reference scenario has the lowest value. This is mainly explained by the high operational costs of the BSF plant, which is around 80% of the total OPEX of the waste management system, mainly because of the large consumption of natural gas for climatization purposes. On the other hand, the CAPEX was highest in the *Status Quo* with a total value of 4.40E+01 € t^{-1} VFG, mainly because in the other scenarios, the cost of incineration is lower and this reduction is higher than the increase in cost by using more capacity from the AD&C plant. For OELEX, S3 performs best. Changing the AD&C plant by the BSF plant significantly reduces this expense. S3 and S4 resulted in the highest revenues. The BSF plant has a high potential to be a good investment when it is compared to AD&C, due to the value of the outputs produced. The market prices for fishmeal and soybean meal have been rising due to increasing demand and thus, the industry is consistently looking for other sources of protein, especially if they can serve as additives or substitution for more conventional sources (Joly & Nikiema, 2019).

3.1.2. Key conclusions and limitations

Changes at the household separation, collection and valorization of organic waste have been evaluated for the cities Ghent and Destelbergen. It can be concluded that the new insect breeding valorization plant has a significant potential to mitigate especially social and environmental impacts, mainly due to the substitution of more impacting conventional products, such as chemical fertilizers, soybean meal and chicken meat. Producing high value products, for feed and food purposes, from organic waste streams is an excellent option for waste treatment, although it is limited by other factors such as regulations and public acceptance. Moreover, the BSF processing plant also comes with economic benefits, as the market using BSF larvae is expected to increase in the following decades.

Overall, strategy S3, a combination of two EIS (CNG trucks and BSF valorization), performed best in all AoP (followed by S4, all EIS), except for natural resources. This is mainly because of the high energy demand and decreased electricity/heat production via incineration. In order to improve the score of S3 and S4 where lots of natural gas is used, changes in the energy source towards more renewable ones could improve the overall sustainability. Changes in the collection step were mostly attributed to the change of diesel-fuelled trucks to CNG fuelled trucks. All indicators related to the collection performed better once this fuel was introduced, which proves that it is an excellent decision for the waste collection.

A limitation of this study was that the data of the BSF plant was found for lab-scale setups only. Even though the use of Hermetia illucens to treat organic matter is currently developed at industrial scale in some countries (e.g., AgriProtein in South Africa, Enterra in Canada) it is still considered an emerging technology in Belgium (Lohri *et al.*, 2017).

3.2. Naples

3.2.1. *Construction and Demolition Waste (CDW)*

ENDPOINT RESULTS

In total, 2 different strategies plus the *Status Quo* have been assessed with the MCDA technique developed within the REPAiR project (D4.5; Taelman *et al.*, 2020). The endpoint results with the ranking of scenarios according to AoPs are illustrated in Table 14. It is possible to observe that strategy S2, i.e. the improvement strategy based on the inclusion of all the EISs, performs better across all AoPs (Ecosystem Health, Human Health, Human well-being, Natural Resource, Prosperity). Strategy S1, i.e. a "Linear Economy Strategy" built in order to demonstrate the importance of landfill avoidance, performs worse across all AoPs, demonstrating the importance of avoiding landfilling.

Table 14, Endpoint results. SQ: Status Quo, S1: Linear Economy Strategy, S2: Improvement Strategy. Green colours indicate a better performance than the Status Quo, while red colour represent a worse one. Comparable performances are shown in yellow.

Strategy	Ecosystem health	Human health	Human well-being	Natural resource	Prosperity
SQ	*1*	*1*	*2*	*2*	*1*
S1	3	3	3	3	3
S2	1	1	1	1	1

MIDPOINT RESULTS

The midpoint results are displayed for the 22 indicators analysed in Annex C, grouped according to AoPs and the key differences between the strategies assessed and the *Status Quo* can be observed. In particular, in the *Status Quo*, for most categories, the management of CDW always resulted in a net impact, i.e. the savings determined by recycling operations were not enough to compensate for the burdens incurred by management and treatment processes. For this reason, an improvement strategy formed by the combination of different EISs has been introduced and the results illustrate the benefits of this strategy. For example, for the indicator "Global Warming", by introducing selective demolition and improving the amount of high quality Recycling Aggregates we move from 4.98 kg CO2-eq. to -18.70 kg CO2-eq. (obtaining overall a saving of 23.68kg CO2-eq. per each tonne managed). The same applies for all the remaining indicators of the AoP "Ecosystem Health". With respect to the individual contributions to the impact breakdown (see Annex C), the main contribution to the burdens were CDW processing and transport, while the most important contributions to the savings were the avoided products and related processing (the recyclable materials and the avoided extraction of raw materials from quarries), avoided transport and land use changes.

For benchmarking, a "Linear Economy Strategy; S1" has also been modelled: this strategy reflects the impact of landfilling 100% of CDW. The results further stress the benefits arising from avoiding landfilling (see indicators in annex C). With respect to the AoP "Prosperity", it is noticeable that significant revenues can be obtained in the improved strategy S3 thanks to the increased material recycling.

3.2.2. Household food waste

ENDPOINT RESULTS

The results of MCDA (Table 15) illustrate that strategy S2 (i.e. avoiding shipping of the waste while implementing local treatment capacity for anaerobic digestion) scored best in three out of four AoPs. strategy S3 (i.e. avoiding shipping of the waste while implementing local treatment capacity for direct composting) scored best in Prosperity due to reduced OPEX, CAPEX, and OELEX. No comparison and ranking could be performed for the AoP Human Well-being due to the fact that most indicators had the same score across the scenarios investigated, i.e. they were not affected by the solutions proposed (see also Midpoint results).

Table 15, Endpoint results. S1: No shipping and installation of the AD and composting capacity needed to treat the food waste at a local level (in the same proportion as the current treatment operated outside the region); S2: No shipping and installation of AD capacity locally; S3: No shipping and installation of composting capacity locally. Green colours indicate a better performance than the Status Quo, while red colour represent a worse one. Comparable performances are shown in yellow. AD: anaerobic digestion; CP: composting.; n.r.: not relevant.

Strategy	Ecosystem health	Human health	Human well-being	Natural resource	Prosperity
SQ	*3*	*3*	*n.r.*	*3*	*4*
S1	2	2	n.r.	2	2
S2	1	1	n.r.	1	2
S3	3	3	n.r.	4	1

MIDPOINT RESULTS

The midpoint results are displayed for the 27 indicators analysed in Annex B, grouped according to AoP. The key differences between the strategies assessed and the *Status Quo* are observed for the indicators Global Warming, Fossil Resource Depletion and the cost indicators belonging to the AoP Prosperity. With respect to Global Warming, simply avoiding shipping of the waste off the region (while maintaining the same proportion between composting and digestion plants, but built locally; S1) saved 4. 4 Mkg CO_2-eq. each year (ca. 23,800 t in *Status Quo* versus 19,400 t). Avoiding shipping while building local capacity for 100% anaerobic digestion (S2) appeared to be the best from a GHG-mitigation perspective incurring an annual reduction of CO2 quantified to 9.4 Mkg CO_2-eq. each year (ca. 23,800 t in *Status Quo* versus 14,400 t). Instead, a strategy based on building local capacity for 100% direct composting led to a decrease of GHG emissions compared to the *Status Quo* of 2.3 Mkg (ca. 23,800 t in *Status Quo* versus 21,500 t) but to an increase of the GHG emissions compared to the two remaining strategies assessed. This is expected owing to the net energy consumption of the composting process and the low recovery of effective nutrients as illustrated in Tonini et al. (2020) for the case of Amsterdam. The same trend in the results was observed for the indicator Fossil Resource Depletion. The remaining energy-related indicators such as Particulate Matter and Tropospheric Ozone Formation mostly reflected the trend observed for Global Warming. As opposite to this, no significant variations were observed in the indicators toxicity and eutrophication as these are mostly affected by nutrient and metals behaviour following use on-land of the compost, which is the same across all the four strategies investigated (i.e. no change is assumed in application techniques and leaching behaviour).

With respect to the cost, as compared to the Status Quo, simply avoiding shipping (S1) incurred a reduction of ca. 8.4 M€ per year, corresponding to 42 €/t of food waste generated in the Focus Area. An EIS based on local anaerobic digestion (EIS II) increased the savings to 9.5 M€ per year, thanks to the additional revenues from energy recovery through biogas production, corresponding to 47 €/t of food waste generated in the FA. S3 (direct composting) led to a saving of 7.5 M€ per year, corresponding to 36 €/t of food waste generated in the FA. Overall, it is estimated that the current management of one tonne of food waste generated in the Focus Area costs about 505€ (summing CAPEX, OPEX, OELEX and revenues throughout the waste life cycle, from collection to use on-land and/or disposal), corresponding to a total of 102 M€ required to manage the food waste generated annually.

The social indicators Effectiveness in Achieving a Behaviour Change, Public Acceptance, and Accessibility of Waste Management System were the same for *Status Quo* and strategies proposed as they are not affected by the strategies proposed (they are only related to changes in the collection system which here instead remains unvaried between *Status Quo* and strategies). Similarly, negligible differences between *Status Quo* and strategies were observed for Private Space Consumption and Urban Space Consumption as the processes and technologies involved occupy comparable urban land per input-waste treated. For Total Employment, a decrease of employment was observed because of the avoided shipment of the food waste off the region which reduced transport activities in the waste life cycle. This reduction of employment was quantified in the order of 84-100 employees-year depending on the solution. This came together with a reduction of accidents (about 2 accidents/year).

It should be noticed that these results all refer to the FU of the assessment defined as “management of the waste generated in the Focus Area during one year” and therefore do not distinguish between geographical areas (or actors in the waste life cycle management chain) that gain (employees, money, or any other quantifiable benefits) and those that lose.

3.2.3. Key conclusions and limitations

With respect to **CDW**, the results indicated that improving the recyclability of some fractions (i.e. wood, plastic, insulation materials, glass and concrete, thus reducing the mixed fraction) by applying the selective demolition, not only allows to avoid the market production of the same materials, but also to increase the production of high quality recycling aggregates. In conclusion, one advantage of recycling is landfill avoidance, which implies saving of waste dump capacity, i.e. space: a very important and scarce resource nowadays in Italy» (Blengini and Garbarino, 2010, p. 1021). Indeed, land is becoming an ever increasing scarce resource (Munafò, 2019) and the avoided landfilling of demolition waste represents a very important environmental and economic benefit (Blengini, 2009) alongside the reduced quarrying activity. Best practices involve the reduction of waste generation, the minimization of transport impacts, the maximization of reuse and recycling through the improvement of the quality of second raw materials as well as the optimization of the environmental performance of the methods of treatment (Gálvez-Martos et al., 2018). In addition, reducing transport by incentivizing local treatment and market for recycled aggregates appears desirable in order to further improve the environmental performance and likely decrease overall multidimensional costs. It is important to bear in mind that circular economy-inspired actions can facilitate the achievement of higher and better quality recycling and can be facilitated by sharing information on the potential value of CDW, overcoming uncompetitive pricing and the luck of trust in the quality of secondary materials (Wahlström et al., 2020). All in all the results confirm the economic, social and environmental benefits associated with landfill avoidance and the necessity of promoting recycling practices, saving non-renewable natural mineral resources and reducing the economic and environmental impacts due to mining activities.

With respect to the management of food waste, the results indicated that avoiding waste shipping off region and building local capacity for anaerobic digestion is the preferred option among the strategies investigated. This can potentially save 9.4 Mkg CO2-eq. and 9.5 M€ per year relative to persevering with the *Status Quo*. A solution based on building local capacity for (direct) composting is not recommendable as savings compared to the *Status Quo* are limited and this alternative ultimately appears the worst among those analysed.

3.3. Hamburg

3.3.1. Vegetable, Fruit and Garden Waste

ENDPOINT RESULTS

A total of 5 strategies plus the *Status Quo* were analysed with the MCDA method developed in the REPAiR project. Table 16 illustrates the results of the analysis. It is interesting to notice that none of the alternative scenarios shows a clearly better performance, when compared to the others. Strategy S1, except for Human well-being (which has the same score as SQ), is clearly the least performing. Strategy S2 performs best on ecosystem health, human health and human well-being. The costs of these initiatives are rather high and reflected in a worse score in prosperity. Strategies S3 and S4 perform generally worse than the SQ.

As a first conclusion, SQ performs relatively well in comparison to the alternatives. The reason lies in the too tiny dimension of the solutions proposed in the scenarios. The community gardening initiative proves to be the most suitable alternative (S3).

Table 16, Endpoint results. SQ: Status Quo, S1: ZRE, S2: Community gardening, S3: SQ + Economic Measures, S4: ZRE + Economic Measures, S5: Community Gardening + Economic Measures. Green colour indicates a better performance than the Status Quo, while red colour represents a worse one. Comparable performances are shown in yellow.

Strategy	Ecosystem health	Human health	Human well-being	Natural resources	Prosperity
SQ	4	4	6	3	1
S1	6	6	5	6	5
S2	4	4	1	4	4
S3	1	2	1	2	3
S4	2	3	4	5	6
S5	2	1	3	1	1

MIDPOINT RESULTS

The midpoint results are shown in Annex D organised in the different AoPs. For the impact categories ecotoxicity, marine and freshwater eutrophication, the *Status Quo* performs best among all scenarios. The reason for this lies in the fact that all scenarios include processes which affect these impact categories, as for compost production in S2 and S5. Concerning water usage, strategy S1 scores worst. This is due to the fact that the new plant needs a high amount of water for cleaning the machinery for the mechanical separation. This results in the same for S4, but the reduction of badly separated waste shows a decrease in the water usage. The community gardening in S2 needs a lot of water per FU, both for the composting process and for gardening activities. However, the results show that this solution performs better than the *Status Quo*. For Global Warming potential, S3 performs best, followed by S5. The two differ from the other scenarios for the compost production in the community gardens, which do have an impact in terms of emission, even though they are not generated from fossil sources. In both cases, however, the *Status Quo* performs best, because it does not involve composting. As expected, for the categories of fossil depletion, tropospheric ozone and particulate matter formation, the scenarios involving the ZRE construction perform worst. The same is valid for Human toxicity, both cancer and non-cancer. S2 performs best in terms of ozone depletion, being the scenario with the higher production of fertilizer substitutes.

In general, S2 and S4 perform environmentally worse compared to the other scenarios, as the two envision the realisation of the ZRE plant and thus results in more emissions. Urban space consumption is increasing in all scenarios in comparison with the *Status Quo*, as all scenarios propose the realisation of a project, e.g. a plant or a community garden. The private space consumption results show an opposite trend. This might be linked to the better separation behaviours introduced in S1 and S2, and supported by the economic measures in S3, S4 and S5.

The impact category Effectiveness in Achieving Behaviour Change increases slightly from the *Status Quo* to the strategy S5. This is due to the increase of the separation behaviour due to the recycling offensive (in S1 and S2) with the addition of the economic measures (in S3, S4 and S5). Stakeholders' participation was set at a higher level in the community gardening scenario as it is necessary there to involve more local stakeholders. The other scenarios perform equally (except for the *Status Quo*, where it is equal to 0). The accessibility was increased in all scenarios in respect to the *Status Quo*, because as a result of the existing recycling offensive the number of bins distributed at household level is supposed to grow, i.e. in a higher door-to-door collection ratio. Landscape disamenities were not considered as all the facilities are located at least five kilometres from the FA Altona.

Concerning the economic indicators, it is clear that the realisation of the new ZRE results in a much higher CAPEX value. The community gardens also contribute in increasing the CAPEX, although slightly. The three scenarios including the economic measures do bring an increase in this category value for the actual initiation of the initiatives. Same reasoning can be done for the OPEX impact category. In terms of OELEX, S5 performs the best, as the combination of community gardening and economic measures contribute in reducing expenses. S4 provides the highest revenue. This is due to the versatility of the ZRE in producing substitute outputs, both for material and energy. The revenues are generally high in S3, S4 and S5 due to the economic measure EIS2a, which foresees an overall reduction in the production of waste and therefore in the costs for its management.

3.3.2. Key conclusions and limitations

The EIS for Hamburg envisioned changes in two different directions: i) improvements at the 'end-of-pipe' (the first two scenarios) and ii) upstream, i.e. the economic measures for waste prevention. It can be stated that the end-of-pipe solutions bring important improvement in terms of well-being and prosperity, meanwhile contributing negatively to the environment. Especially for what concerns the new ZRE, although it can solve the problem of bad separation and at the same time producing more co-products, the emissions and the costs for its realisation, operation and OELEX impact severely on the final result. The reduced distances also contribute in reducing the emissions, but they do not account much on the total.

The economic measures pointing at increasing separation and improving consumption behaviour have an important impact as they relieve the system from a considerable amount of input waste. This proves that prevention measures are an overall good alternative in terms of impacts by tackling the waste problem since the very beginning, avoiding it to enter into the system. As a general conclusion, strategy S5, which envisions a combination between community gardening initiatives and waste prevention measures, appears to be the preferred option.

3.4. Łódź

3.4.1. Vegetable, Fruit and Garden Waste

ENDPOINT RESULTS

A total of 3 strategies plus the *Status Quo* were analysed with the MCDA method developed within the REPAIR project. The endpoint results with the ranking of strategies according to AoPs are illustrated in Table 17. It is worth to note that, in general, the proposed alternative strategies perform better in the environmental AoPs, except for S1 in the AoP Ecosystem health, and worse in the AoP Prosperity and Human Well-Being. An in-depth analysis of reasons is provided in the Midpoint results section.

Table 17, Endpoint results. SQ: Status Quo, S1: Home composting & Centralised composting ; S2: Centralised Anaerobic digestion , S3: Home composting & Centralised Anaerobic digestion . Green colour indicates a better performance than the Status Quo, while red colour represents a worse one. Comparable performances are shown in yellow.

Strategy	Ecosystem health	Human health	Human well-being	Natural resources	Prosperity
SQ	*3*	*4*	*1*	*4*	*1*
S1	3	3	2	3	3
S2	1	1	2	1	4
S3	2	1	4	2	2

MIDPOINT RESULTS

The midpoint results are displayed for the 27 indicators analysed in Annex C, grouped according to AoPs. In most cases, positive values indicate burdens, whereas negative values indicate savings.

With respect to the AoP ecosystem health, the strategies involving anaerobic digestion (S2 and S3) give more desired results in the majority of impact categories. This is the case of: Climate Change, Water Use, Freshwater Eutrophication and Land Use thanks mainly to the energy substitution. The only two categories, where strategies include composting (the *Status Quo* and S1) give better results are Marine Eutrophication and Ecotoxicity. In those two cases, the credits associated with fertilizer substitution compensate the burdens bound predominantly to the use-on-land operations.

With respect to the AoP human health, the strategies including solely composting (the *Status Quo* and S1) give better results in the majority of impact categories. This is the case of: Particulate Matter Formation, Tropospheric Ozone Formation and Human Toxicity (Cancer and Non-Cancer). The only two categories, where strategies relying on anaerobic digestion (S2 and S3) give better results are Ozone Depletion and Infrared Radiation. In those two cases, the credits associated with either fertilizer substitution or energy substitution surpassed the burdens associated with the remaining waste management stages.

Although the environmental impact analysis for all proposed strategies give better results then the SQ, the economic costs of implementation are higher. Also the AoP human health shows an overall worse performance than the SQ for all strategies, although a clear positive change could be observed for the categories Effectiveness of Achieving Behaviour Change, Stakeholder Involvement, Urban Space Consumption, Accessibility to the Waste Management System and Total Employment.

With respect to the AoP natural resources, the strategies including anaerobic digestion (S2 and S3) performed far better to the corresponding *Status Quo* and S1. In both cases though the credits associated with energy substitution overwhelmed the burdens associated with the remaining waste management stages. The achieved results are in line with the results of the Global Warming category, since these two impact categories are both largely affected by the consumption and savings. In our case the energy of fossil fuels is substituted by the energy derived from VFG waste.

All strategies seem to have potential when purely looking at the economic revenues. However, despite the rise of revenues, also the costs (especially OPEX) were rising because of the implementation of the strategies and were larger than the revenues. Concerning OPEX, S1 has the lowest value, because of low costs of transformation of the system while implementing home composting.

S2 will bring the most positive benefits considering all sustainability indicators. It is worth to underline that the implementation of two combined EIS in S3 is more profitable than S2, but S3 scores worse (in general) for the socio-environmental indicators than S2. Better results in comparison to *Status Quo* can be observed for S3 in prosperity but then is scores worse for the AoP Human Health. S1 has the worst innovative potential from the proposed strategies. Its impact on the environment is positive, but not as good as S2 or S3. This also applies to revenues and costs (OPEX and OELEX), but the biggest difference is visible in CAPEX.

3.4.2. *Key conclusions and limitations*

Despite the fact that during the last three decades the Polish municipal waste management sector was completely revolutionized, there are still many challenges before decision-makers can handle with respect to achieving sustainability. Our analysis proved the lack of adequate monitoring of the VFG waste generation, low quality of the selectively collected VFG waste and, finally, still inefficient mechanical-biological treatment of VFG waste that leads to numerous environmental issues. Consequently, implementation of any technology that may increase the production of market value products out of VFG waste is highly recommended. However, taking into account problems related to compost selling, due to its low quality, and the benefits of energy production, the strategies including anaerobic digestion and home composting are recommended.

3.5. Pécs

3.5.1. *Organic Waste*

ENDPOINT RESULTS

The MCDA results are illustrated in Table 18. Strategy S2 (Food Rescue Program) performs best in three Areas of Protection: Ecosystem health, Human health and Natural resource, due to avoided impacts related to agricultural production. S1 (Separate collection of kitchen waste) achieves the highest score in Human well-being and economic prosperity. S2 (Food rescue) and S3 (Public Catering Improvement) fall short behind SQ in Prosperity: collection of edible food with refrigeration vehicles implies somewhat higher expenditures, and avoided canteen food waste slightly decreases revenues (-0,03%) compared to SQ.

Table 18, Endpoint results. SQ: Status Quo, S1: Separate collection of kitchen waste; S2: Food Rescue Program, S3: Public Catering Improvement. Green colour indicates a better performance than the Status Quo, while red colour represents a worse one. Comparable performances are shown in yellow.

Strategy	Ecosystem health	Human health	Human well-being	Natural resource	Prosperity
SQ	*3*	*4*	*4*	*4*	*2*
S1	2	2	1	2	1
S2	1	1	2	1	3
S3	3	2	3	3	3

MIDPOINT RESULTS

The midpoint results are displayed for the 27 indicators in Annex F. Positive values indicate burdens, while savings are illustrated as negative figures.

Analysing the results of the AoP Ecosystem Health and Human Health, S2 (Food Rescue Program) performs better than the remaining strategies in almost all categories. The only exceptions are the *Ionizing Radiations* and the *Freshwater Eutrophication*, closely related to renewable electricity produced after the Anaerobic Digestion of separately collected household kitchen waste in S1.

The strategy S2 involves the collection of meals and foodstuff suitable for human consumption from restaurants, public catering and the retail sector (shops and markets) and distribution to those in need through official charity institutions or voluntary organizations (see detailed description in 2.6.2). The outstanding environmental performance of S2 is explained by the amount of avoided food production: it is assumed that 1.39E+6 kg of food is not wasted, thus the agricultural production of the same amount of food can be prevented (11,3% meat, 12,1% dairy products, 33,3% bakery, 13,5% fruits and 30% vegetables). Aiming at assessing the real environmental savings of food rescuing, so called “market processes” were used in LCA models, which include diesel consumption for crop production, fertilizers, pesticides, land use, animal feeding, transport, cooling, etc. See details in Annex F, where avoided food production is marked with purple (“Material Substitution / Prevention” in the legend).

S1 also shows significant savings in many indicators, compared to the SQ (cf. tables at the end of Annex F). In case of *Global Warming Potential* for example, it offers more than 48 million kg of $CO_{2\text{- eq.}}$ savings . There are two important contributing factors: first, the mass diverted in S1 is much higher than in any other case. On the other hand, biogas production and its use in the CHP unit leads to avoided electricity with high nuclear and fossil components (production and combustion of lignite, brown coal, natural gas and uranium have a substantial impact in many environmental midpoint impact categories). The combination of the increased quantity of digested kitchen waste and the avoidance of the impacts from fossil-based electricity leads to savings in these indicators.

Although S2 outperforms all other strategies from an environmental point of view, it seems to be the best choice when analysing socio-economic indicators. Since the altered amount of kitchen waste (AD instead of MBT+landfilling) represents 30% of the organic part of municipal solid waste, S1 results in an important change in the collection and MBT plant related figures: decrease in urban space consumption, occupational health, CAPEX, OPEX and revenues (the latter being disadvantage here), but increase (in absolute value) in effectiveness in achieving behaviour change (gain here), landscape disamenities and private space consumption (the latter two being disadvantage here). We also have to note that the calculation method of individual indicators (PA, OD, AWMS, etc.) are ruther irrelevant for food rescue program (S2). E.g., Public Acceptance is closely related to the change in waste management fee paid by citizens that has been frozen in Hungary in the last eight years, thus being irrelevant for food donation. Odour footprint is only considered in high population density areas, but agricultural production happens far from the settlements, thus does not appear in the savings. Accessibility of Waste Management System is irrelevant in case of prevention, when edible food donation is in focus.

The sum of the three cost indicators shows a slight decrease for S1 compared to SQ, due to the fact that this imply the reduction of residual waste treated in the most cost-intensive infrastructure (MBT plant and the landfill). The same applies to the employment indicator: the organic part of the residual waste follows alternative paths that are less labour-intensive than the SQ. The change in economic performance of S2 and S3 compared to SQ is nearly unnoticeable: less than 1 and 0.1 percent in expenditures, and 1.8 and 0.03 percent in revenues, respectively. The revenue increase of S2 is attributed to the subsidy given by the state and non-governmental entities for the local charity organizations, dedicated to cover the costs of the food rescue program.

3.5.2. Key conclusions and limitations

The implementation of Food Rescue program (S2) conveys the most advantages for the environment, in compliance with the EU waste hierarchy, the avoidance being the most favourable approach.

Selective collection and anaerobic treatment of kitchen waste (S1) achieves the highest score in Human well-being and economic prosperity, due to the potential of avoiding the production of fossil and nuclear power.

The quality improvement of public catering in schools (S3) has only marginal effects on the system's performance, due to the low amount of waste avoided, which is three orders of magnitude less than the amount of organic waste generated in the FA.

4. Discussion

4.1. Take-home results

The results of the six case studies on the five Focus Areas highlight that no solution could be clearly singled out as the best across all the five Areas-of-Protection considered in our framework. Trade-offs were almost always present, except for the case of the management of food waste in Naples where one strategy (avoiding waste shipment off the region while installing local anaerobic digestion coupled with post-composting capacity) clearly stood out as the best strategy across all Areas-of-Protection. However, this was mainly due to the exceptionally poor performance of the *Status Quo* management in the region (waste shipment, with high costs and impacts) rather than to the intrinsic value of the winning strategy itself.

Overall, strategies based on organic waste prevention (Pécs, Hamburg) or valorisation into high-value products (e.g., production of animal feed) stood out as the best option across most of the Areas-of-Protection, and also generally performed better compared with anaerobic digestion coupled with post-composting and direct centralised or domestic composting. This was illustrated well for the case of animal feed production (VFG treatment in a black soldier fly plant) in Ghent and for the prevention strategies evaluated in Hamburg and Pécs. Nevertheless, some trade-offs could still be observed, e.g. the strategy for animal feed production performed worse than the remaining energy/compost-focused alternatives in the Area-of-Protection “Natural Resources” due to the high natural gas needs during insect rearing and drying. This AoP, however, focusses on the assessment of fossil resource scarcity and gives low importance to potential energy-resource savings related to biomass, land or other similar biotic resources. In this respect, future methodological improvements of this indicator may give more importance to the biotic resource savings, hence also influence the trend of the sustainability assessment results. Our findings further indicate that, if strategies aiming at prevention, redistribution or higher-value products (e.g. feed) could not be implemented, then anaerobic digestion coupled with post-composting should be prioritised as next in line as this perform generally better than incineration with energy recuperation. This treatment produces valuable nutrients and stable carbon for the soil in the form of compost and ensures a maximum recovery of energy from the degradable portion of the carbon as opposite to direct centralised or domestic composting. Notice that this ranking also generally applies to the case of the Amsterdam Metropolitan Area (see deliverable D4.8), albeit at the expenses of increased costs (mainly due to higher collection efforts) compared with direct incineration. While not tackled in this deliverable, in the particular context and market of the Netherlands, supporting the production of more targeted NP fertilisers instead of digestate/compost is however highly recommended to maximise benefits for plant uptake under the current conditions (Huygens et al., 2019; Tonini et al.; 2019).

The results of the case study on construction and demolition waste conveyed three main messages: i) while current practices may already involve high recycling rates, substantial improvement potentials exist as often the quality of the recyclates is low or the full potential of the recyclable material in the building is not captured at the demolition stage (i.e. upstream); ii) savings per tonne of construction and demolition waste are typically low, when compared to other waste types (e.g. for CO_2, savings around 5-20 kg CO_2 per tonne managed are typical under best practices, against 50-400 kg CO_2 per tonne MSW managed; Garbarino *et al.*, 2009; Tonini *et al.*, 2013); iii) total annual savings are, however, substantial as CDW is the largest portion of waste generated in Europe. This means that little improvement potentials at the single tonnage level translate into substantial savings when the full extent of the waste generation is considered. In the broader context of the REPAiR H2020 projects, these results are communicated to stakeholders during dedicated workshops/meetings (e.g. PULL workshops) using the geodesign decision support environment (GDSE) as the main medium. More information regarding the sustainability assessment results for Ghent, Hamburg and Pécs is also to be found in Sanjuan-Delmás et al. (submitted).

4.2. Reflection on the sustainability assessment framework and results

Upon consideration of the numerous feedbacks received throughout the project (from the steering and evaluation committee as well as from the scientific peer-review process), a broad reflection can be drawn on the sustainability assessment applied and the results derived. While a general remark is directed to the use of life cycle thinking based methods for assessing circular economy and support long-term policy, the vast majority of the criticisms ultimately pinpoint to assumptions and scenario definitions, which are inevitable in any sustainability assessment. With respect to the first critique, we have elaborated a specific reflection under section 4.2.1. With respect to definition of assumptions and scenarios, we believe that a broader *participatory process* actively involving experts and stakeholders (e.g. steering committee as well as final evaluators) in the definition of *future scenarios* with related sound assumptions (see work from Bisinella *et al.*, 2017) would help overcoming such criticisms. Such participatory process to specifically support future scenarios definition at the detailed level required for the sustainability assessment was not originally envisioned in the REPAiR project. Fully acknowledging the intrinsic limitations of LCA and broader sustainability assessments, we firmly believe that these are the best available tools to assess sustainability and that challenges and nuances highlighted in this research can be overcome with targeted improvement actions. These include better defining future scenarios and conditions, improving indicators of impact assessment (local to global effect, circularity indices), and providing additional knowledge on the long-term effects of circular products, e.g. compost or biochar. For the sake of simplicity, we articulate our reflexion via the following five sub-sections, each tackling a specific issue:

i. Life Cycle Assessment as a tool for assessing circular economy
ii. The limits in relation to generalising our results
iii. Deviations from the waste hierarchy: direct and home composting in the AMA
iv. The limitations in terms of impact indicators
v. When/How to use this framework

4.2.1. Life Cycle Assessment as a tool for assessing circular economy

LCA and other life cycle thinking based tools are typically used along with cost-benefit analyses to support impact assessment studies for 'better regulations' (European Commission 2021), also in the field of circular economy (Sala *et al.* 2016). Despite science- and evidence-based policy is at the foundation of the EU policy-making (European Commission 2021), such technique-based regulation process is criticised by some authors (e.g. Perez 2013, Ellul 1964). The main critique lies in the excess of trust in computational models (e.g. cost-benefit analyses, LCA, etc.), which ultimately incurs a delegation of the decision and related consequences from the policy makers to the quantitative science or technique applied. Fully appreciating the views expressed by the authors, we believe that such arguments are excessive. Regulators are not delegating the decisions to technique or science, but rather use the knowledge produced from science to take informed decisions. This is easily demonstrated as policy-makers decisions can disregard the results of an impact assessment, if those are not in line with the direction of the overarching policy direction. While there are many examples that can be quoted, we would like to point to a key episode from the past where the use of life cycle based assessment tools was decisive in steering the policy towards better regulations: the renewable energy directive 2008. This, while aiming for increased penetration of renewables in the energy systems under the equation 'bioenergy equal green' did not sufficiently address land use change and other indirect impacts of biomass. Upon increasing evidences from life cycle based studies (notably Searchinger et al. 2008, 2010), the directive has been amended in 2015 to limit the use of biomass that can incur leakages of carbon and indirect effects. We are now facing similar situations with the circular economy wave: it should be clear that *not* all that is circular is *necessarily* environmentally better. There will be cases that need to be carefully addressed, and we firmly believe that life cycle based tools and their adaptations for circular economy studies (e.g. see Dieterle et al., 2018) are key for this. This reasoning is supported by the fact that the first Circular Economy Action Plan launched by the European Commission in 2015 focussed on the different processes such as production, consumption, waste management, and production of secondary raw materials, very much at the heart of life cycle thinking (European Commission, 2015a)

Circularity can be embedded in life cycle thinking approaches through adapting the functional unit, as CE strategies aiming at maintaining the same function can be considered as a prolongation of the lifetime of a product (e.g. repair, refurbish, etc.) (Niero *et al.*, 2016). For the reuse of parts or components in products of the same or (entirely) different functionality ("second, third, … life"), by contrast, a different approach (than through the FU) is needed (e.g. dedicated indicators). The introduction of dedicated indicators (in addition to the environmental life cycle impact indicators), e.g. weight or volume of a product, percentage (relative to total weight) or amount of recycled or virgin material, percentage (relative to total weight) or amount of recycled or virgin critical raw material, percentage of renewable material, number of re-used components, amount of hazardous substances contained in a product, etc., could be helpful to better grasp the circularity potential (Helander *et al.*, 2019, Dieterle *et al.*, 2018, Moraga *et al.*, 2019, Huysveld *et al.*, 2019), but will not change the outcomes of the consequential LCA study as system expansion can capture the different functionalities. An end-of-life activity is by nature a multi-output processes when combined with valorisation or open-loop recycling processes.

According to Corona *et al.* (2019), substitution has been the most applied approach so far to deal with open-loop recycling, and this approach was followed in the REPAIR project. However, some concerns can be raised. First of all, the understanding of which market products will/can be substituted is crucial. Second, it might be more straightforward to determine the substitution ratio from energy produced from waste streams (1-to-1 fossil versus renewable) than for recycled materials (e.g. compost, metals from bottom ashes) as the latter might be subjected to a change in quality (often decreasing, 'downcycling'). The Circular Footprint Formula included in the Product Environmental Footprint (PEF) Guide (European Commission, 2013) introduces the ratio between the quality of the secondary material (QS) and the quality of the primary material (QP) and this must be determined at the point of substitution and per application or material. Priority is given to quantify it based on economic aspects (or physical ones if the economics are not relevant). As economic indices also have its own drawbacks, Vadenbo *et al.* (2016) proposes to designate the degree of functional equivalence between recovered resources and displaced alternative resources/products for a specific end use based on technical functionality and can include additional constraints. A non-accurate substitution ratio might imply an over- or underestimation of the real benefit/burden of the recycling activities, potentially leading to wrong conclusions and recommendations (Faraca *et al.*, 2019, Rigamonti *et al.* 2020).

4.2.2. Limits in relation to generalising the sustainability results

As a general principle, the results reported in the deliverable D4.8 (pilot case: Amsterdam Metropolitan Area) and D4.7 (follow-up case studies) should always be contextualised taking into account the assumptions and conditions used for the assessment of the specific case study. In this respect, the most important assumption relates to the energy system. We performed the assessment using the forecasts for electricity and heat system in the next decade from the EU Commission GECO report, which reflects the projections of the 27 individual Member States (European Commission 2016). Since fossil sources are expected to remain in the energy mix until the year 2030 (and beyond), this means that the production of energy (e.g. through incineration with energy recovery) from food waste (i.e. biomass) receives environmental credits in the quantitative sustainability assessment because of the savings incurred in the energy sector. We would like to remark that this is fully consistent and in line with international standards. Assuming a CO_2-neutral (or low-carbon) energy system would decrease the performance of incineration.

A practical way forward to define future scenarios in respect to energy mixes (to be used in the assessment) is through a stakeholder consultation where steering committee, evaluators, and relevant stakeholders (e.g. energy authorities) participate and contribute in the definition of the relevant scenarios and assumptions.

4.2.3. Deviation from the waste hierarchy: the case of direct and home composting in the AMA

Direct centralised and home composting achieved an overall worse performance than incineration with energy recovery for the case of the Amsterdam Metropolitan Area. This result is explained by:

- Producing energy from food waste incineration receives environmental credits because of the savings incurred in the energy sector.
- *Direct* composting (aerobic oxidation via forced aeration) is energy-intensive; therefore, the only environmental credits are related to the agronomic value and carbon storage of the final compost.

Our findings simply highlight that a *combination* of anaerobic digestion and post-composting should be promoted instead of *direct* composting, to ensure, along with compost recovery, a maximum harvest of energy from the degradable portion of the carbon (instead of consuming energy to oxidise such fraction). This is in line with a myriad of LCA studies and we believe it is a clear take-home message to ensure the sustainability of biological treatments. This is precisely fitting the ideal of the waste hierarchy (the Waste Framework Directive 2008 clearly says to apply life cycle thinking to pinpoint any possible deviation from the hierarchy).

Also, it should be kept in mind that the current market for compost *in the Netherlands* is poor with values per tonne around -5 to +2 euro and a low agronomic value overall (Huygens *et al*., 2019). The Dutch conditions and market for soil amendments and fertilisers are peculiar because heavily affected by one of the worldwide most intensive agriculture and farming sectors, which demand rather targeted NP fertilisers to maximise plant-uptake and minimise losses, as indicated in recent studies (Tonini *et al*., 2019).

In line with the section above, assuming a CO_2-neutral (or low-carbon) energy system would decrease the performance of incineration and improve that of *direct* composting in the AMA. On top, if compost from food waste could be applied on soil depleted in organic carbon or used in niche applications that would otherwise use fossil peat, e.g. horticulture, it would increase the savings of composting (both *direct* and *coupled* with anaerobic digestion; see Boldrin et al. 2010).Within this study, compost is credited for the substitution of NPK fertilisers and for carbon storage. Other possible benefits (such as increased water retention) are not included due to lack of robust data. Additional benefits of compost should be supported by scientific evidence, currently lacking in the literature. Furthermore, the benefits induced by food waste separation on the recycling of the remaining waste fractions are not taken into account (e.g. better quality of paper, plastics, etc.).

4.2.4. Limitations of the indicators incorporated in the sustainability assessment framework

While we strived to use state-of-the-art indicators of impact assessment in the framework (e.g. recommended by the Product Environmental Footprint or the last version of Recipe, etc.), some of the indicators should be subject to further improvements following development in the (LCA) methodology. For example, the indicator fossil resource scarcity used to express impacts in the Area-of-Protection "*Natural Resources*" shows a higher importance of savings in fossil based energy-resources such as coal, gas, oil, etc. than those related to biomass, land or other similar biotic resources. Future methodological improvements of this indicator may attribute proportionally more importance to the biotic resources. This will influence the trend of the results by placing more emphasis on those scenarios producing higher-value/quality products such as chemicals and feed or redistributing/preventing food wastage. Another indicator that can be subject to improvement is "Landscape Disamenities" (part of AoP Human Well-Being") whereby the impact we accounted for is mainly related to the presence of an incineration or landfilling facility; other aspects, beyond those particular facilities, may be taken into account within the same indicator as well.

4.2.5. How/When to use the sustainability assessment framework

We often observed that the results of the assessment indicate that specific strategies (or single solutions) do not bring any additional advantage relative to the *Status Quo*. This was, for example, the case of many strategies assessed for Hamburg, but was also the case for some solutions proposed for Amsterdam and Ghent. While certainly pinpointing better/worse solutions is one of the goals of a sustainability assessment, we suggest using the sustainability impact assessment also at the beginning of the project for prospective reasons. The advantage of doing so consists in having sustainability assessment results, even if preliminary (e.g. screening exercises), at an early phase of the solutions/strategies development process. This may help in singling out best solutions/strategies, eliminating those that are least attractive from a sustainability point of view, as well as introducing new solutions/strategies based on the results of the preliminary assessment.

References

A2A Ambiente 2019. Dichiarazione ambientale termovalorizzatore Acerra. Available at: https://s3-eu-west-1.amazonaws.com/a2a-be/a2a/2019-05/DA_ACERRA_2019.pdf?null.

Acke, A., Arlati, A., berruti, G., Czapiewski, K., Fraser, T., Heurkens, E., Mezei, C., Obersteg, A., Palestino, M.F. and Taelman, S.E., 2019. D6.4 first application of the decision model in all case studies.

Allegrini, E. et al., 2015. Life cycle assessment of resource recovery from municipal solid waste incineration bottom ash. *Journal of Environmental Management*, 151, pp.132–143.

Andersen, J.K. et al., 2010. Quantification of Greenhouse Gas Emissions from Windrow Composting of Garden Waste. *Journal of Environment Quality*, 39(2), p.713.

Arlati, A., Lopes, A., Obersteg, A., Pascoli, C.C., Bodor, Á. and Grünhut, Z., 2018. D3.6 process model Hamburg.

Amlinger, F., Peyr, S., Cuhls, C. (2008), Green House Gas Emissions from Composting and Mechanical Biological Treatment, in Waste Management & Research, (1):47-60. doi: 10.1177/0734242X07088432.

Badino, V., Blengini, G.A., Garbarino, E., Zavaglia, 2007. Economic and environmental constraints relevant to building aggregates beneficiation plants. In: Carpuz, C. (Ed.), Proceedings of XX International Mining Congress and Exhibition of Turkey, Ankara, Turkey, pp. 197–208.

Benato, A., Macor, A. & Rossetti, A., 2017. Biogas Engine Emissions: Standards and On-Site Measurements. *Energy Procedia*, 126, pp.398–405.

Bisinella (2017). Future scenario development within life cycle assessment. PhD thesis, DTU Environment, Technical University of Denmark, Lyngby, Denmark. https://orbit.dtu.dk/files/133577013/Thesis_online_version_Valentina_Bisinella.pdf (accessed February 2021).

Blengini, G.A. (2009), 'Life cycle of buildings, demolition and recycling potential: A case study in Turin, Italy', Building and Environment, 44, pp. 319–330.

Blengini, G.A., Garbarino, E. (2010), 'Resources and waste management in Turin (Italy): The role of recycled aggregates in the sustainable supply mix'. Journal of Cleaner Production, vol. 18, pp. 1021–1030.

Boldrin, A., Andersen, J.K. and Christensen, T.H., 2009. Environmental assessment of garden waste management in Århus Kommune (Miljøvurdering af haveaffald i Århus Kommune). Copenhagen: Department of Environmental Engineering, DTU.

Borghi, G., Pantini, S., Rigamonti L. (2018), 'Life cycle assessment of non-hazardous Construction and Demolition Waste (CDW) management in Lombardy Region (Italy)'. Journal of Cleaner Production, 184, 815-825.

Brogaard, L.K. & Christensen, T.H., 2016. Life cycle assessment of capital goods in waste management systems. Waste Management, 56, pp.561–574.

Bundesnetzagentur, 2016. Genehmigung des Szenariorahmens für die Netzentwicklungspläne Strom 2017-2030. Bonn: Bundesnetzagentur für Elektrizität, Gas, Telekommunikation, Post und Eisenbahnen.

Caldeira, C., De Laurentis, V. and Sala, S., 2019. Assessment of food waste prevention actions: Development of an evaluation framework to assess the performance of food waste prevention actions. JRC technical reports. Luxembourg: Publications Office of the European Union.

Choi, Y.-C., Choi, J.-Y., Kim, J.-G., Kim, M.-S., Kim, W.-T., Park, K.-H., Bae, S.-W., & Jeong, G.-S. (2009). Potential usage of food waste as a natural fertilizer after digestion by Hermetia illucens (Diptera: Stratiomyidae). International Journal of Industrial Entomology, 19(1), 171–174.

Clavreul, J., Baumeister, H. and Christensen, T. H. (2014) 'An environmental assessment system for environmental technologies.', *Environmental Modelling and Software*, 60, pp. 18–30. doi: 10.1016/j.envsoft.2014.06.007.

Corona, B., Shen, L., Reike, D., Carreón, J.R., Worrell, E. (2019) Towards sustainable development through the circular economy—A review and critical assessment on current circularity metrics. *Resources, Conservation and Recycling*, 151, 104498

De Vries, J. W., Groenestein, C. M. and De Boer, I. J. M. (2012) 'Environmental consequences of processing manure to produce mineral fertilizer and bio-energy', *Journal of environmental management*, 102(0), pp. 173–183. doi: http://dx.doi.org/10.1016/j.jenvman.2012.02.032.

Diener, S., Zurbrügg, C., Gutiérrez, F. R., Nguyen, D. H., Morel, A., Koottatep, T., & Tockner, K. (2011). Black soldier fly larvae for organic waste treatment-prospects and constraints. Proceedings of the WasteSafe, 2, 13–15.

Dieterle, M, Schafer, P., Viere, T (2018). Life Cycle Gaps: Interpreting LCA Results with a Circular Economy Mindset. 25th CIRP Life Cycle Engineering (LCE) Conference, 30 April – 2 May 2018, Copenhagen, Denmark.

Di Maria, A., Eyckmans, J., Van Acker, K. (2018), 'Downcycling versus recycling of construction and demolition waste: Combining LCA and LCC to support sustainable policy making'. Waste Management, 75, 3-21.

Dortmans, B. M. A., Diener, S., Verstappen, B. M., & Zurbrügg, C. (2017). Black Soldier Fly Biowaste Processing - A Step-by-Step Guide.

Ecoinvent centre (2019) 'Ecoinvent v3.5 database'. Zurich, Switzerland: Swiss Centre for Life Cycle Inventories. Available at: http://www.ecoinvent.org/database/ecoinvent-version-3/introduction/.Ellul, J. (1964). The Technological Society. Vintage books publisher, 1964.

European Commission (2009), Assessment of the options to improve the management of bio-waste in the European Union ANNEX E: Approach To Estimating Costs, 2009, European Commission Directorate-General Environment.

European Commission (2013) Commission Recommendation of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations (2013/179/EU). Official Journal of the European Union, Volume 56, 4 May 2013.

European Commission (2015a) Closing the Loop - an EU Action Plan for the Circular Economy – COM (2015) 614 Final. Brussels

European Commission (2015b) The European Economic and Social Committee and the Committee of the Regions — Closing the loop — An EU action plan for the Circular Economy (COM(2015) 614/2 of 2 December 2015), European Commission, Brussels, Belgium.

European Commission, 2016. EU Reference Scenario - Energy, transport and GHG emissions Trends to 2050. 10.2833/9127. Available at:https://ccacoalition.org/en/resources/eu-reference-scenario-2016-energy-transport-ghg-emissions-and-trends-2050 (accessed March 2020).

European Commission (2018) Heat Roadmap Europe 2050. Aalborg University, Halmstad University, Euroheat.

European Commission (2018b), EU Construction and Demolition Waste Protocol and Guidelines, https://ec.europa.eu/growth/content/eu-construction-and-demolition-waste-protocol-0_en

European Commission (2021), Better Regulation. Available at: https://ec.europa.eu/info/law/law-making-process/planning-and-proposing-law/better-regulation-why-and-how/better-regulation-guidelines-and-toolbox_en (February 2021).

Faraca, G., Tonini, D., Astrup, T. F. (2019), 'Dynamic accounting of greenhouse gas emissions from cascading utilisation of wood waste'. Science of the Total Environment, 651(part 2), 2689-2700.

Freie und Hansestadt Hamburg: Behörde für Umwelt und Energie, 2018. Abfallwirtschaftsplan Siedlungsabfälle 2017. Freie und Hansestadt Hamburg: Behörde für Umwelt und Energie.

Gálvez-Martos, J.-L., Styles, D., Schoenberger, H., Zeschmar-Lahl, B. (2018), 'Construction and demolition waste best management practice in Europe', *Resources, Conservation and Recycling*, 136, pp. 166–178.

GfK SE, 2017. Systematische Erfassung von Lebensmittelabfällen der Privaten Haushalte in Deutschland, final report. Nürnberg: Bundesministerium für Ernährung und Landwirtschaft. Available at: https://www.bmel.de/SharedDocs/Downloads/DE/_Ernaehrung/Lebensmittelverschwendung/Studie_GfK.pdf?__blob=publicationFile&v=3

Hamelin, L., Naroznova, I. and Wenzel, H. (2014) 'Environmental consequences of different carbon alternatives for increased manure-based biogas', *Applied Energy*, 114, pp. 774–782. doi: http://dx.doi.org/10.1016/j.apenergy.2013.09.033.

Harding, K.g., Dennis, J.S., von Blottnitz, H., Harrison, S.T.L. (2007) Environmental analysis of plastic production processes: Comparing petroleum-based polypropylene and polyethylene with biologically-based poly--hydroxybutyric acid using life cycle analysis. *Journal of Biotechnology* 130, 57–66.

Helander, H., Petit-Boix, A., Leipold, S., Bringezu, S., 2019. How to monitor environmental pressures of a circular economy: An assessment of indicators. *Journal of Industrial Ecology* 23, (5), 1278-1291.

Huysveld, S., Hubo, S., Ragaert, K., Dewulf, J. (2019) Advancing circular economy benefit indicators and application on open-loop recycling of mixed and contaminated plastic waste fractions. *Journal of cleaner production*, 211, 1-13

Inagro. (2019). Personal Communication.

ISPRA (2019), Rapporto Rifiuti Speciali. Rapporto n. 309/2019.

ISPRA (2020), Rapporto Rifiuti Speciali. Rapporto n. 321/2020.

Joly, G., & Nikiema, J. (2019). Global experiences on waste processing with black soldier fly (Hermetia illucens): from technology to business. (Resource Recovery and Reuse Series 16). International Water Management Institute.

Kalogo, Y., Habibi, S., Maclean, H., Joshi, S. (2007) Environmental Implications of Municipal Solid Waste-Derived Ethanol. *Environmental Science and technology*, 41 (1), 36 -42.

Komilis, D. et al., 2012. Revisiting the elemental composition and the calorific value of the organic fraction of municipal solid wastes. *Waste Management*, 32(3), pp.372–381.

Lavagna, M., Baldassarri, C., Campioli, A., Giorgi, S., Dalla Valle, A., Castellani, V., Sala, S. (2018), 'Benchmarks for environmental impact of housing in Europe: Definition of archetypes and LCA of the residential building stock'. *Building and Environment*, 145, 260-275.

Martinez-Sanchez, V., Kromann, M. A. and Astrup, T. F. (2015) 'Life cycle costing of waste management systems: Overview, calculation principles and case studies', *Waste Management*. Elsevier Ltd, 36, pp. 343–355. doi: 10.1016/j.wasman.2014.10.033.

Metabolic (2020), Mapping the country's construction sector with the goal to become 100% circular by 2050, https://www.metabolic.nl/projects/assessing-materials-consumed-for-building-in-the-netherlands

Moraga, G., Huysveld, S., Mathieux, F., Blengini, G.A., Alaerts, L., Van Acker, K., de Meester, S., Dewulf, J., (2019) Circular economy indicators: What do they measure? *Resources, Conservation and Recycling*, 146, 452-461.

Munafò, M. (a cura di), 2019. Consumo di suolo, dinamiche territoriali e servizi ecosistemici. Edizione 2019. Report SNPA 08/19.

Nemecek, T. & Kägi, T., 2007. Swiss Centre for Life Cycle Inventories Life Cycle Inventories of Agricultural Production Systems.

Niero, M., Olsen, S.I., 2016. Circular economy: To be or not to be in a closed product loop? A Life Cycle Assessment of aluminium cans with inclusion of alloying elements. *Resources, Conservation and Recycling*, 114, 18-31

OVAM, 2014. Sorteeranalyse-onderzoek huisvuil 2013-2014.

Obersteg, A., Arlati, A. and Lopes, A., 2020. D5.7 Eco-innovative solutions Hamburg.

Pagans, E. et al., 2006. Ammonia emissions from the composting of different organic wastes. Dependency on process temperature. Chemosphere, 62(9), pp.1534–1542.

Pantini, S., Rigamonti, L. (2020), 'Is selective demolition always a sustainable choice?' *Waste Management*, 103, 169-176.

Penteado, C. S. G., Rosado, L.P. (2015), 'Life Cycle Assessment of Construction and Demolition Wastes from Small Generators', Fifteenth International Waste Management and Landfill Symposium, Sardinia 2015. Cagliari, Italy, October 4-9, 2015.

Perez, O. (2013). Courage, regulatory responsibility, and the challenge of higher-order reflexivity. *Regulation and Governance.*

Pleissner, D., & Smetana, S. (2020). Estimation of the economy of heterotrophic microalgae-and insect-based food waste utilization processes. *Waste Management*, 102, 198–203.

Rigamonti, L., Taelman, S.E., Huysveld, S., Sfez, S., Ragaert, K., Dewulf, J. (2020) A step forward in quantifying the substitutability of secondary materials in waste management life cycle assessment studies. *Waste Management*, 114, 331-340.

Rodríguez Escobar, M. (2020) Holistic sustainability assessment of an improved organic waste collection system and its valorization through insects. Eco-innovative solutions for Ghent enad Destelbergen. A dissertation submitted to Ghent University in partial fulfilment of the requirements for the degree of Master Bioengineering, environmental technology.

Salomone, R., Saija, G., Mondello, G., Giannetto, A., Fasulo, S., & Savastano, D. (2017). Environmental impact of food waste bioconversion by insects: application of life cycle assessment to process using Hermetia illucens. *Journal of Cleaner Production*, 140, 890–905.

Sanjuan-Delmás, D. Taelman, S.E., Arlati, A., Obersteg, A., Vér, C., Óvári, A., Tonini, D., Dewulf, J., (*submitted*). Sustainability Assessment of Organic Waste Management in three EU Cities: Analysing Stakeholder-Based Solutions. Submitted to Waste Management journal on 30/11/2020.

Scheirlinckx, A. (2018) Transitioning towards a more circular economy: stimulating the use of waste as a resource in an urban environment. Searching for improvements in the life cycle impact of VFG waste generation in Ghent and Destelbergen and the respective processing. A dissertation submitted to Ghent University in partial fulfilment of the requirements for the degree of Master Bioengineering, environmental technology.

Searchinger, T. D.; Heimlich, R.; Houghton, R. A.; Dong, F.; Elobeid, A.; Fabiosa, J.; Tokgoz, S.; Hayes, D.; Yu, T. H. (2008). Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change, *Science* , 319, 1238– 1240.

Searchinger, T. D. (2010). Biofuels and the need for additional carbon, *Environ. Res. Lett.* 5, 024007– 024007.

Smetana, S., Schmitt, E., & Mathys, A. (2019). Sustainable use of Hermetia illucens insect biomass for feed and food: Attributional and consequential life cycle assessment. *Resources, Conservation and Recycling*, 144, 285–296.

Stadtreinigung Hamburg (SRH), 2013. Natürliche Kreisläufe als Vorbild: Biogas- und Kompostwerk Bützberg. Freie und Hansestadt Hamburg: Stadtreinigung Hamburg Biogas- und Kompostwerk Bützberg.

Stadtreinigung Hamburg (SRH), 2019a. Müllverwertung Borsigstraße: Verwertung auf höchstem Niveau. Freie und Hansestadt Hamburg: Müllverwertung Borsigstraße GmBH.

Stadtreinigung Hamburg (SRH), 2019b. Sortieranalyse von PPK, Biomüll, Wertstoffen und Restmüll an ausgewählten Standplätzen, Jahr 2018. Berlin: Oetjen - Dehne & Partner Umwelt - und Energie - Consult GmbH.

Statistikamt Nord, 2019. Hamburger Stadtteil-Profile Berichtsjahr 2018. Freie und Hansestadt Hamburg: Statistisches Amt für Hamburg und Schleswig-Holstein Anstalt des öffentlichen Rechts.

Styles, D. et al. (2018) 'Life Cycle Assessment of Biofertilizer Production and Use Compared with Conventional Liquid Digestate Management', *Environmental Science and Technology*, 52(13), pp. 7468–7476. doi: 10.1021/acs.est.8b01619.

Taelman, S.E., Sanjuan-Delmás, D., Tonini, D., Wandl, A. and Dewulf, J., 2018. D4.4 Definitive framework for sustainability assessment. REPAiR project.

Taelman, S., Sanjuan-Delmás, D., Tonini, D., & Dewulf, J. (2020). An operational framework for sustainability assessment including local to global impacts: Focus on waste management systems. *Resources, Conservation & Recycling*, 162, 1-11.

Tonini, D., Albizzati, P.F., Astrup, T.F., 2018. Learnings and challenges from a case study on UK, Waste Management, 76, 744-766. DOI:doi.org/10.1016/j.wasman.2018.03.032.

Tonini, D., Wandl, A., Meister, K., Munceta, P., Taleman, S.E. and Sanjuan-Delmás, D., 2019. D4.8 Sustainability assessment for the pilot case studies – Eco-innovative solutions. REPAiR project.

Tonini, D., Wandl, A., Meister, K., Unceta, P. M., Taelman, S. E., Sanjuan-Delmás, D., Dewulf, J., & Huygens, D. (2020). Quantitative sustainability assessment of household food waste management in the Amsterdam Metropolitan Area. *Resources, Conservation and Recycling*, 160, 104854.

Vadenbo, C., Hellweg, S. Astrup, T.F. (2016). Let's Be Clear(er) about Substitution: A Reporting Framework to Account for Product Displacement in Life Cycle Assessment. *Journal of Industrial Ecology*, 21, 1078 -1089.

Van der Heyden, C., Demeyer, P. & Volcke, E.I.P., 2015. Mitigating emissions from pig and poultry housing facilities through air scrubbers and biofilters: State-of-the-art and perspectives. *Biosystems Engineering*, 134, pp.74–93.

Wahlström, M., Bergmans, J., Teittinen, T., Bachér, J., Smeets, A., Paduart A. (2020), Construction and Demolition Waste: challenges and opportunities in a circular economy. Eionet Report - ETC/WMGE 2020/1.

WallStreetMojo, 2020. Coupon Bond Formula. [online] Available at: https://www.wallstreetmojo.com/coupon-bond-formula/ [Last accessed: 28th June 2020].

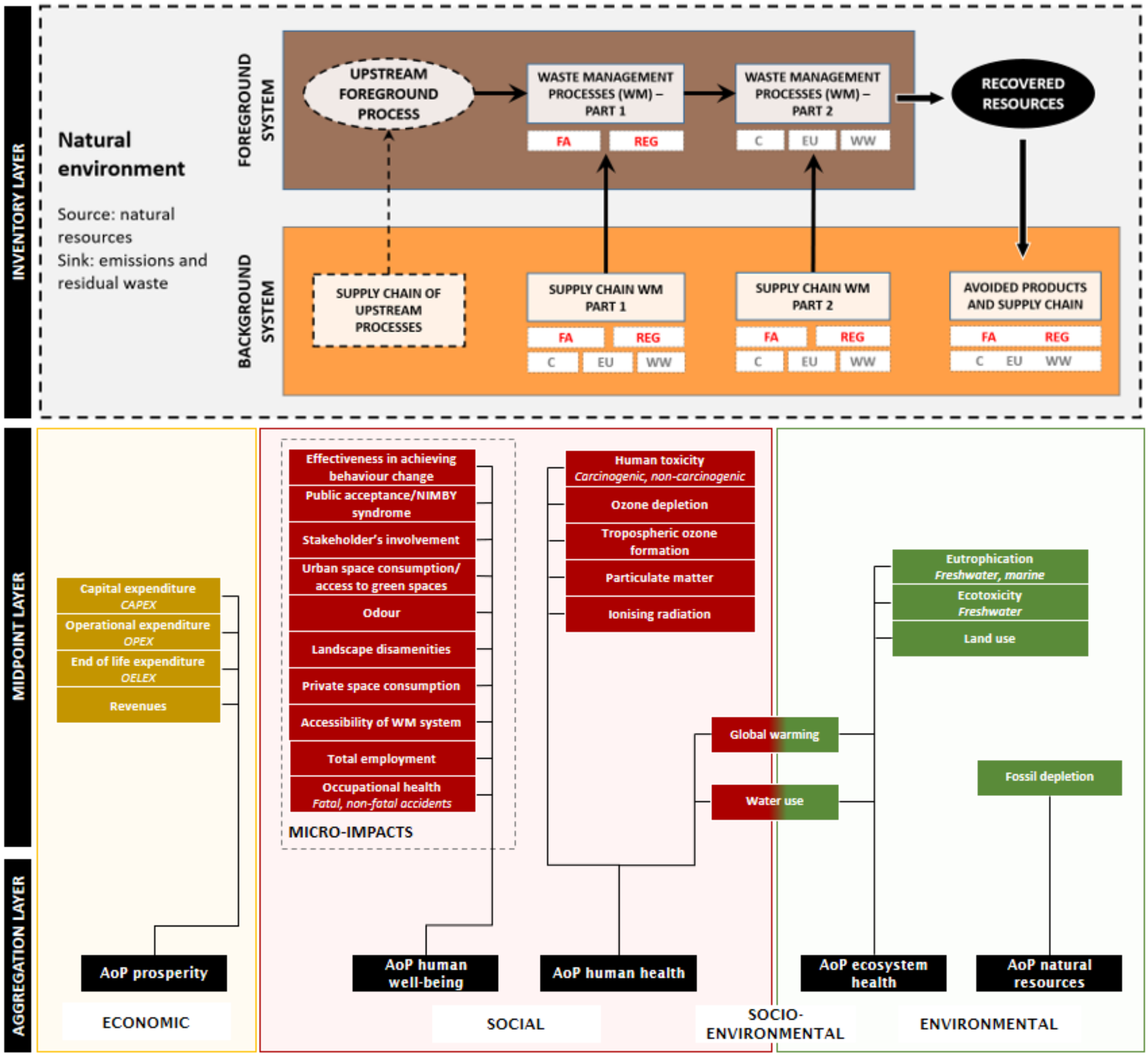
Wang, Y.-S., & Shelomi, M. (2017). Review of black soldier fly (Hermetia illucens) as animal feed and human food. Foods, 6(10), 91.

Weidema, B. (2003) Market information in life cycle assessment. Copenhagen, Denmark: Ministry of the Environment, Danish Environmental Protection Agency; Environmental project 863.

Weidema, B., Ekvall, T. and Heijungs, R. (2009) Guidelines for application of deepened and broadened LCA. ENEA. Available at: http://www.leidenuniv.nl/cml/ssp/publications/calcas_report_d18.pdf.

Annexes

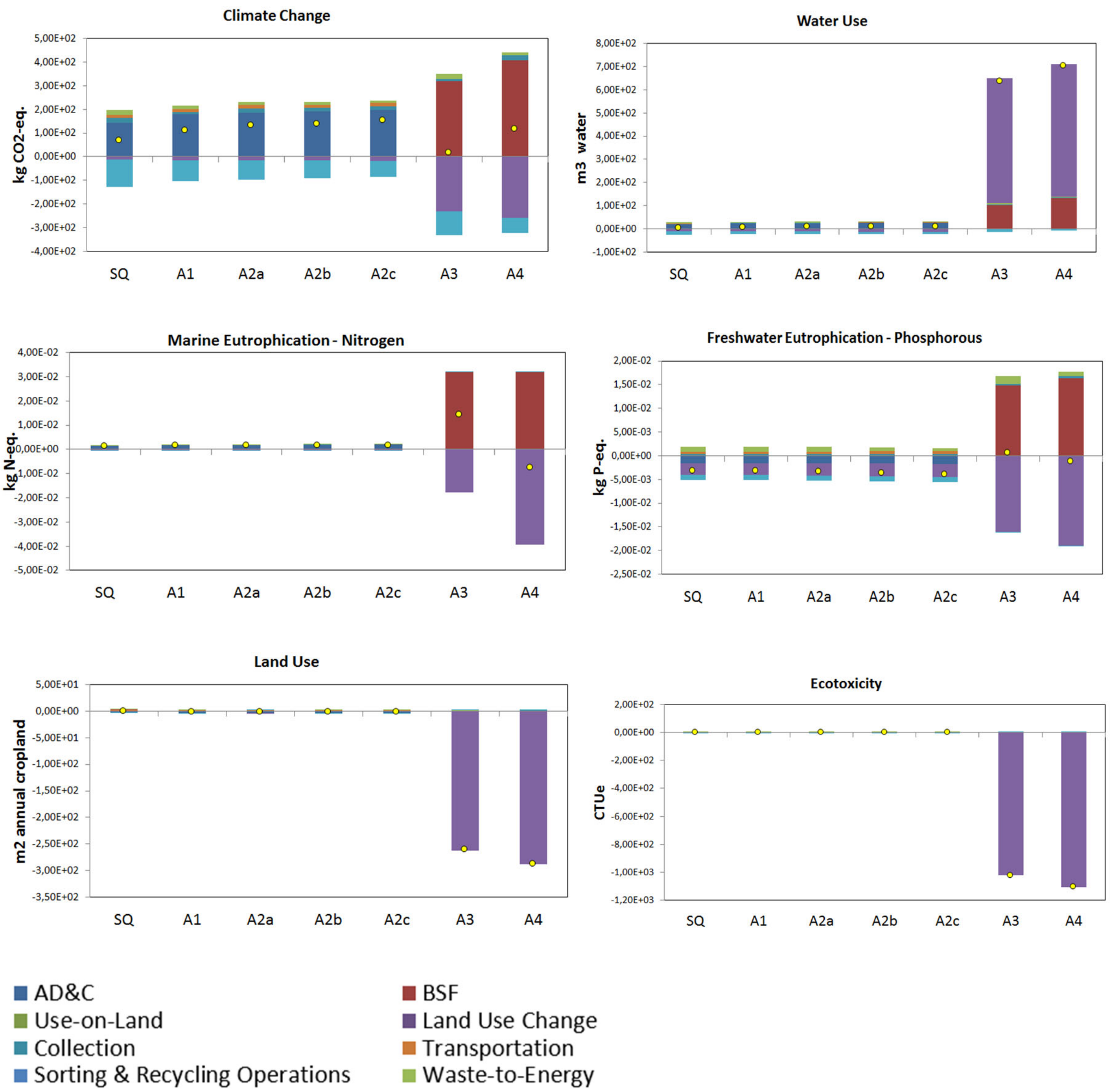
Annex A - Sustainability framework



Taken from Taelman *et al.* (2020).

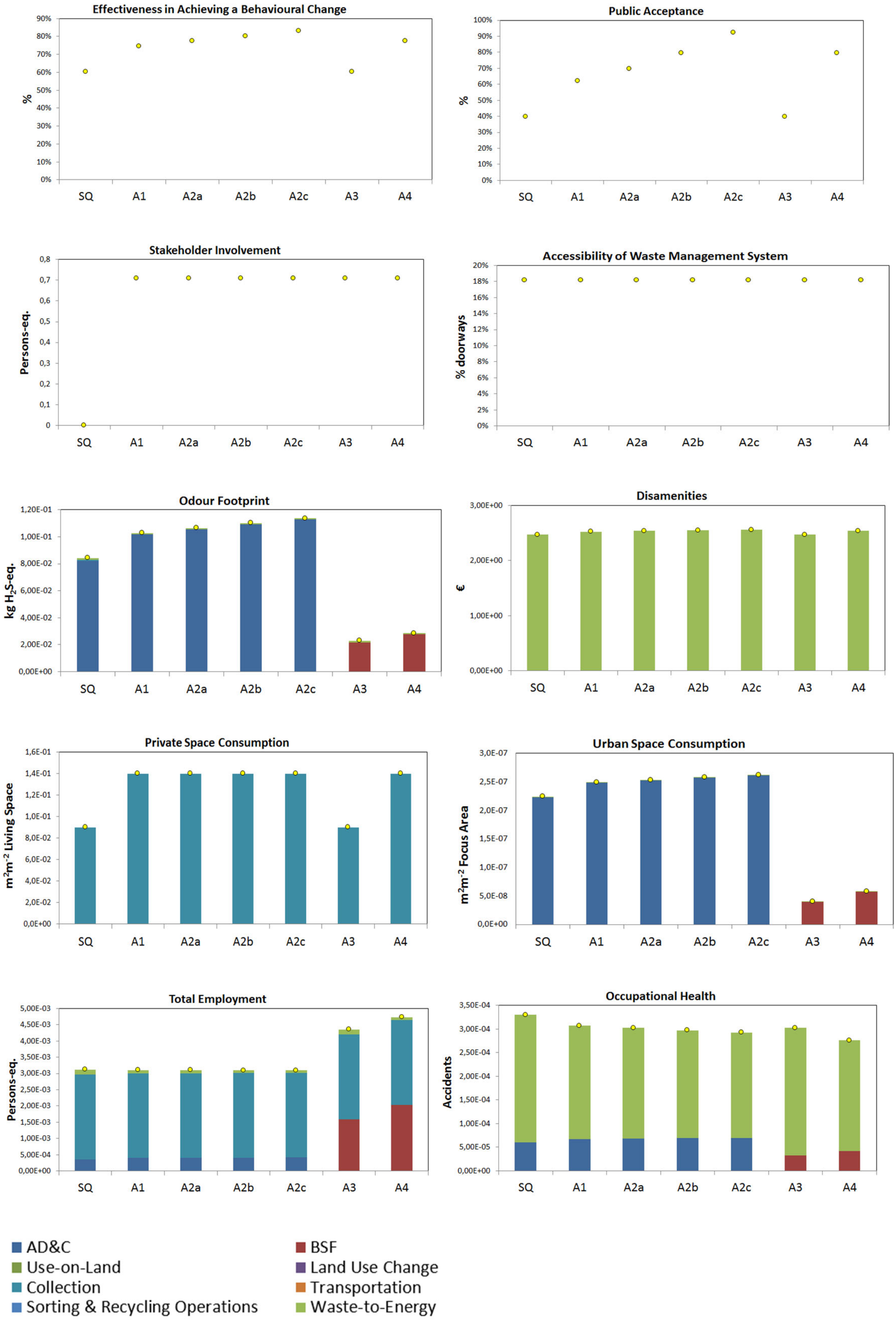
Annex B - Ghent midpoint results

AoP Ecosystem Health

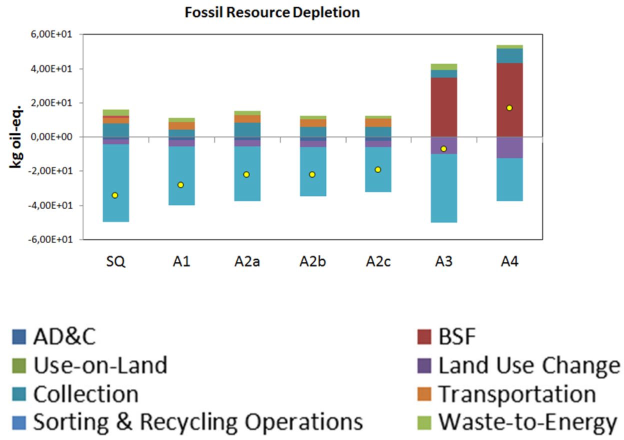


AoP Human Health

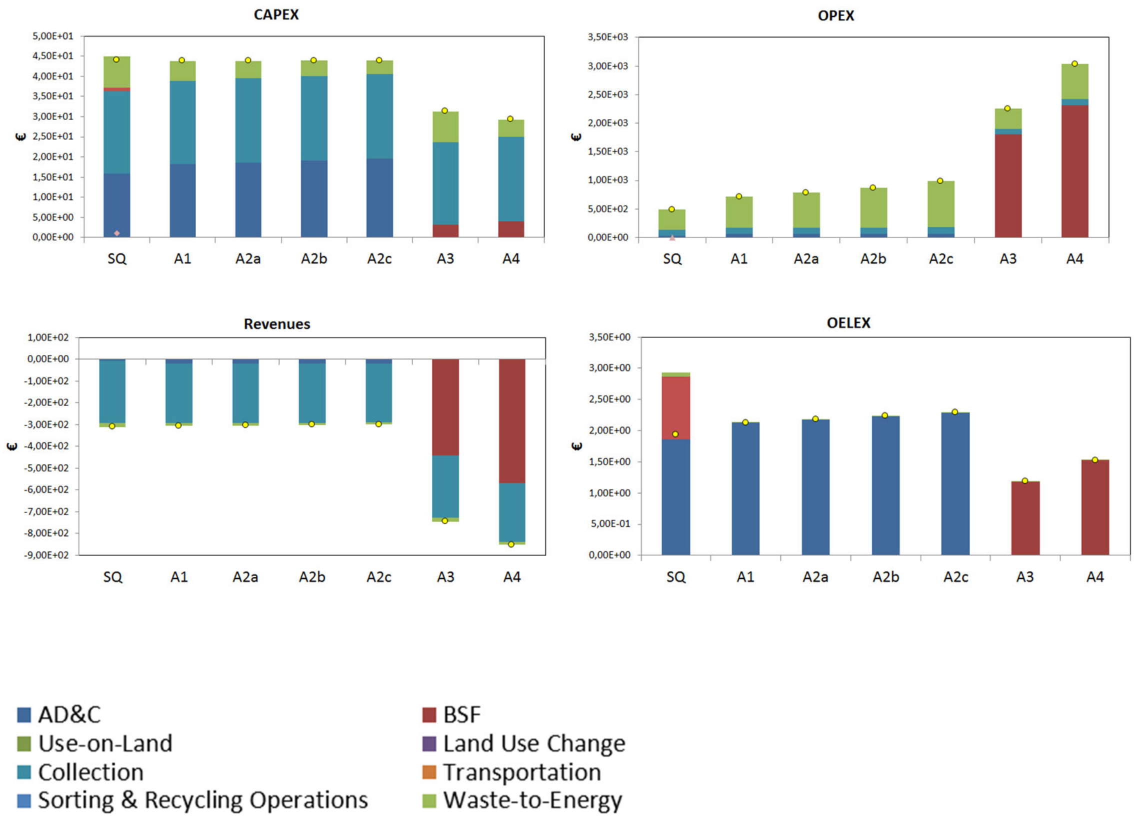
AoP Human Well-being



AoP Natural resources



AoP prosperity



Total annual impact (selected indicators)

	Climate Change Mkg CO_2-eq.	Cost (Sum) M€	Total Employment Jobs-eq.
SQ	*1,08*	*8.38*	*49.04*
S1	1,76	11.90	48.81
S2A	2,09	13.01	48.75
S2B	2,20	14.41	48.68
S2C	2,39	16.23	48,61
S3	0,25	35.93	68.41
S4	1,85	48.20	74.38

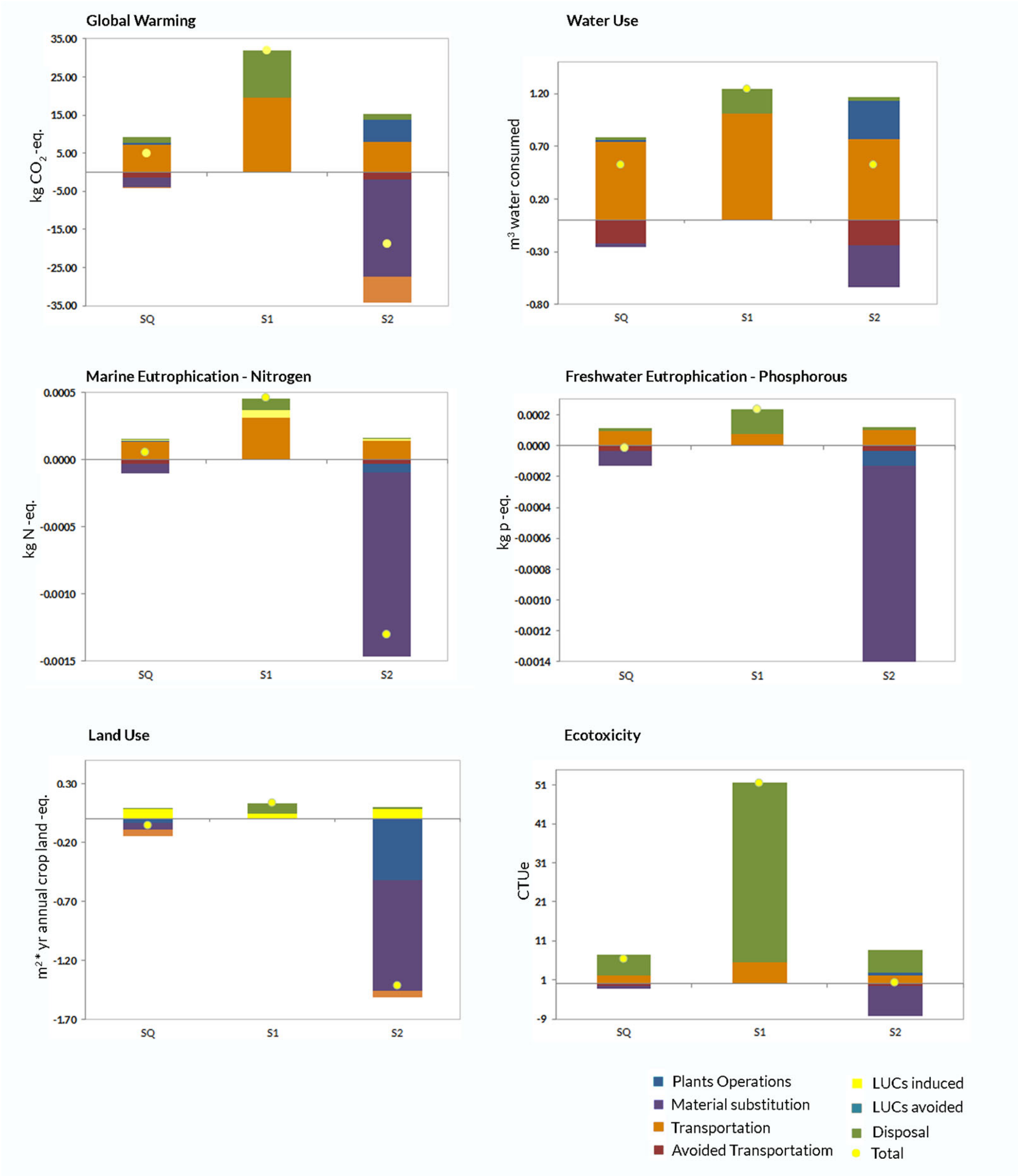
Net annual impact change relative to the *Status Quo* SQ (selected indicators)

	Climate Change Mkg CO_2-eq.	Cost (Sum) M€	Total Employment Jobs-eq.
SQ	*0 (reference)*	*0 (reference)*	*0 (reference)*
S1	0,68	3.53	-0.23
S2A	1,01	4.64	-0.29
S2B	1,12	6.03	-0.36
S2C	1,31	7.85	-0.43
S3	-0,83	27.56	19.37
S4	0,77	39.82	25.34

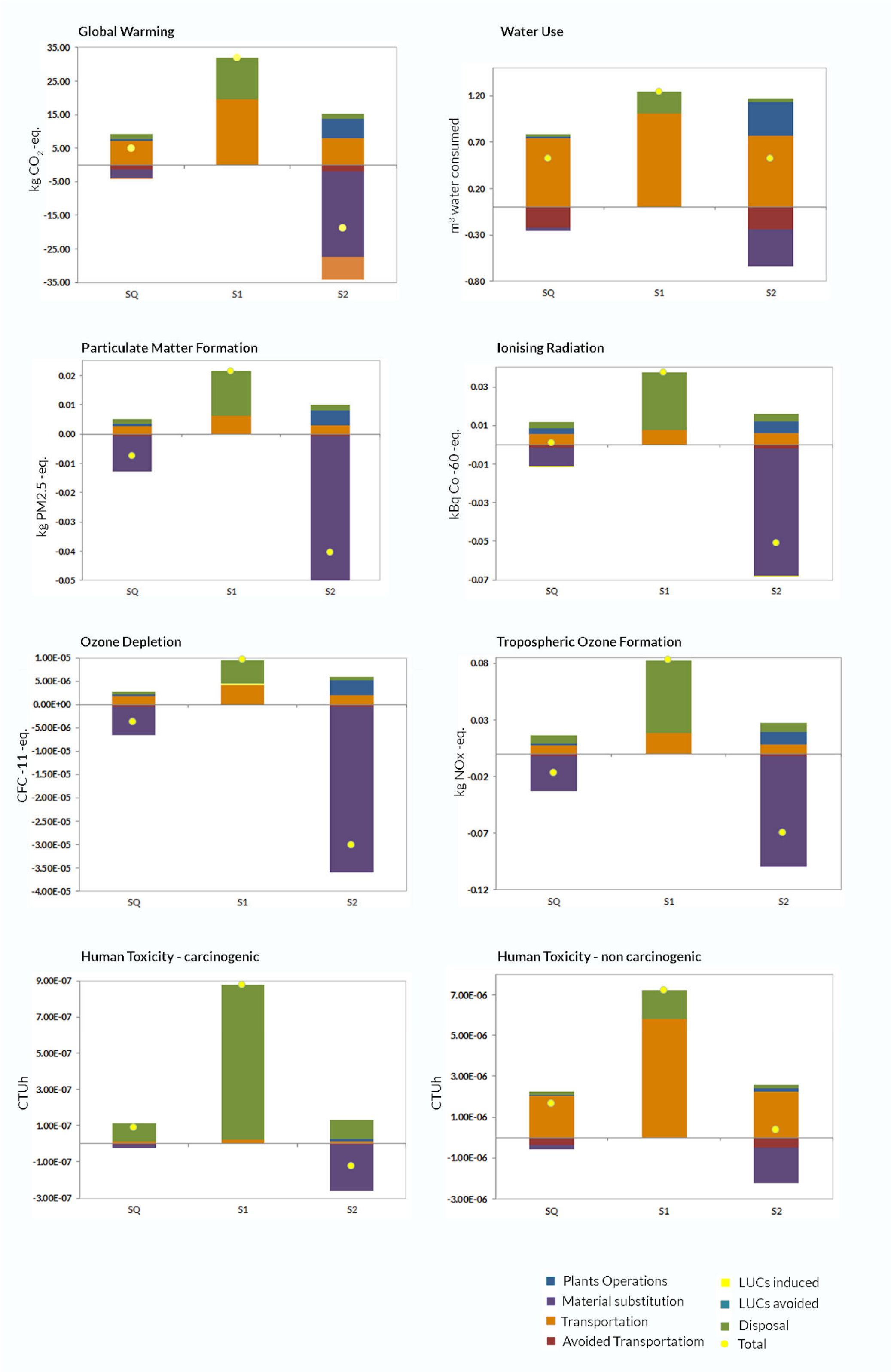
Annex C - Naples midpoint results

1) Construction and Demolition waste

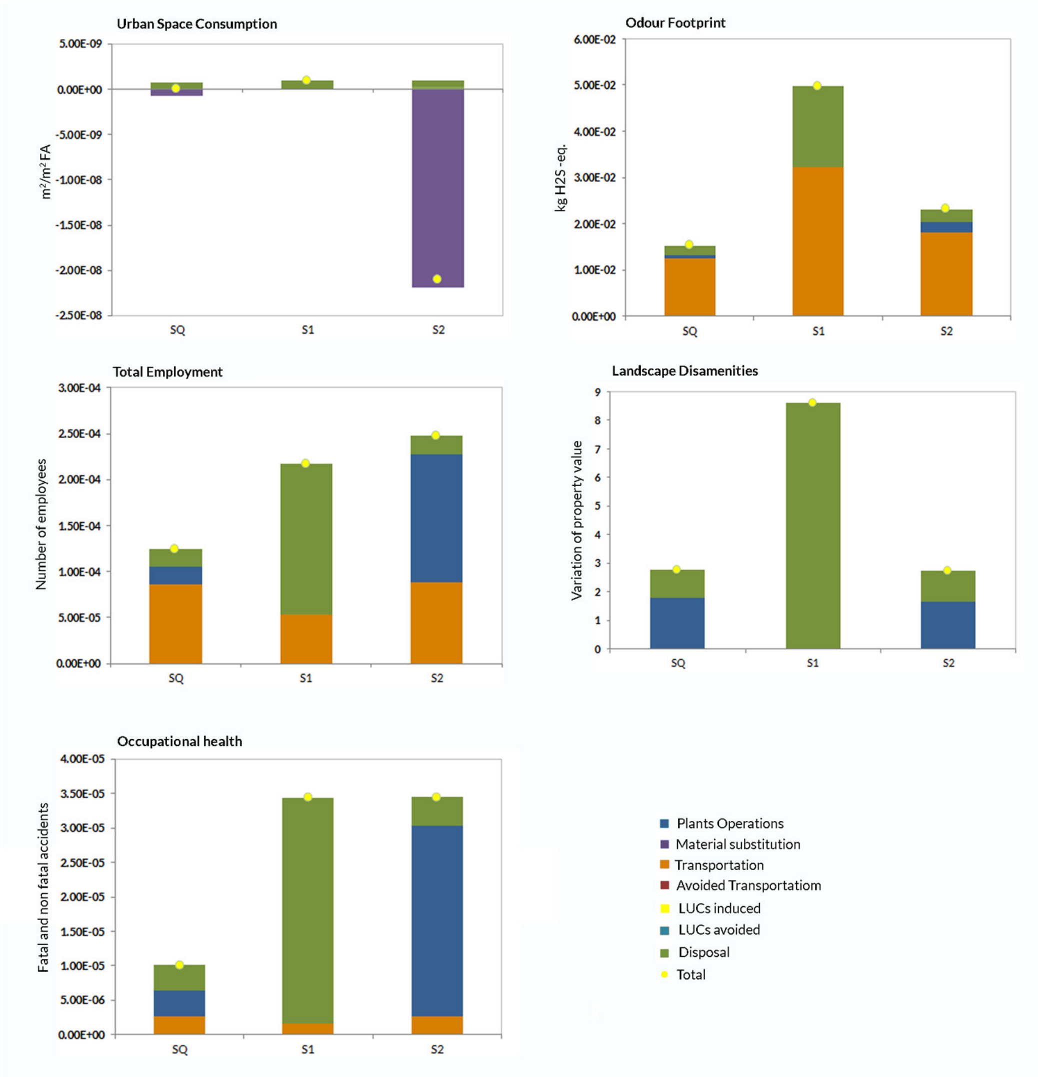
AoP Ecosystem Health



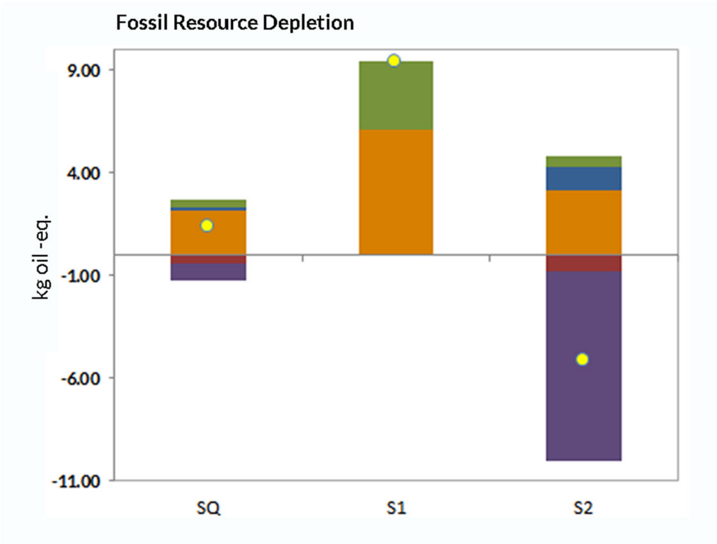
AoP Human Health



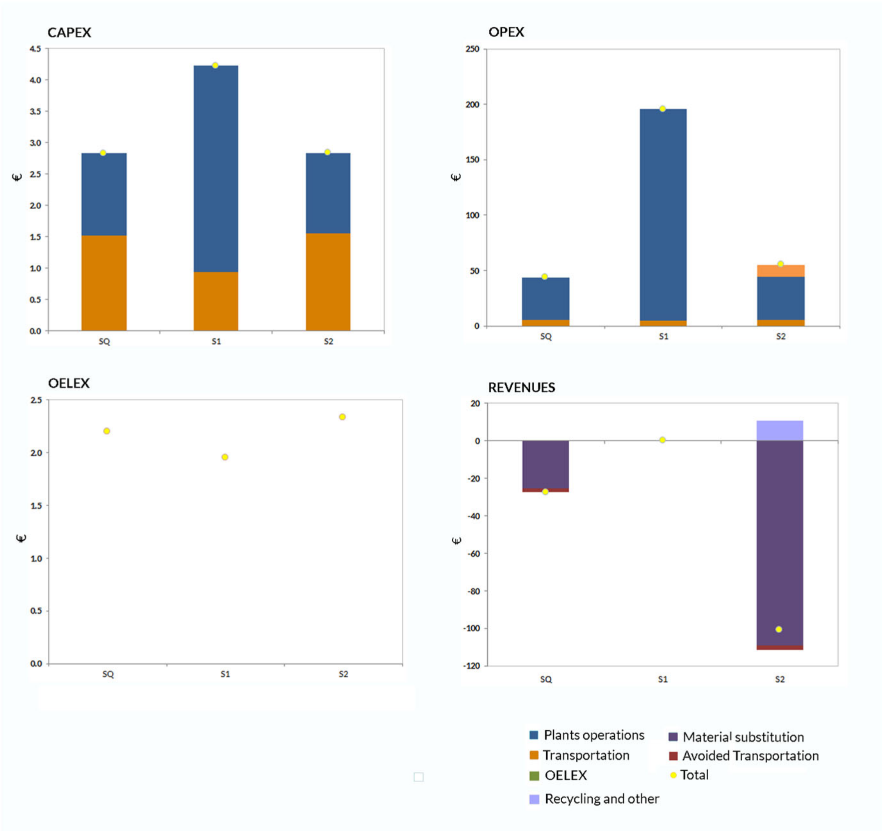
AoP Human Well-being



AoP Natural resources



AoP Prosperity



Total annual impact (selected indicators)

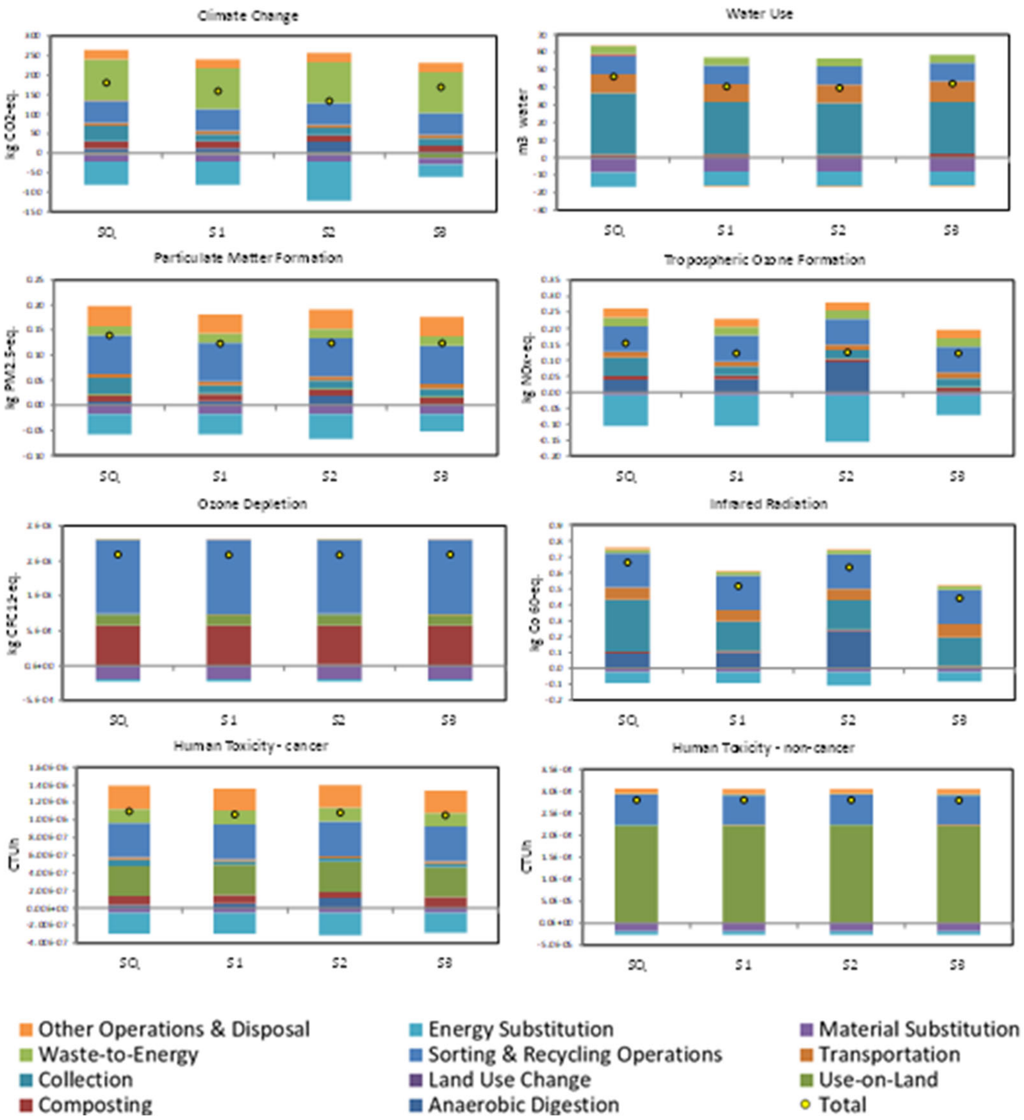
Strategy	Climate Change Mkg CO_2-eq.	Cost (Sum) M€	Total Employment Jobs-eq.
SQ	*3.86*	*16.8*	*96*
S1	24.6	156.4	168
S2	-14.5	-39.8	192

Net annual impact change relative to the *Status Quo* SQ (selected indicators)

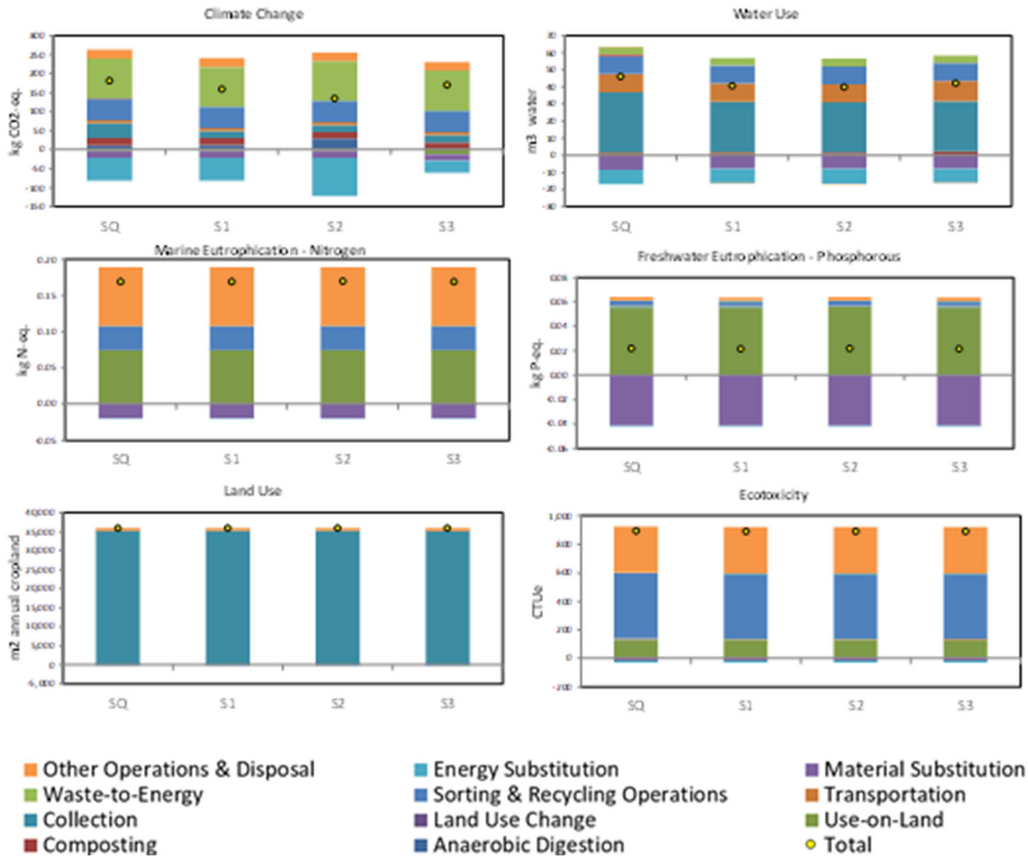
Strategy	Climate Change Mkg CO_2-eq.	Cost (Sum) M€	Total Employment Jobs-eq.
SQ	*0 (reference)*	*0 (reference)*	*0 (reference)*
S1	+20.74	+139.6	+72
S2	-18.36	-56.6	+96

2) Food Waste

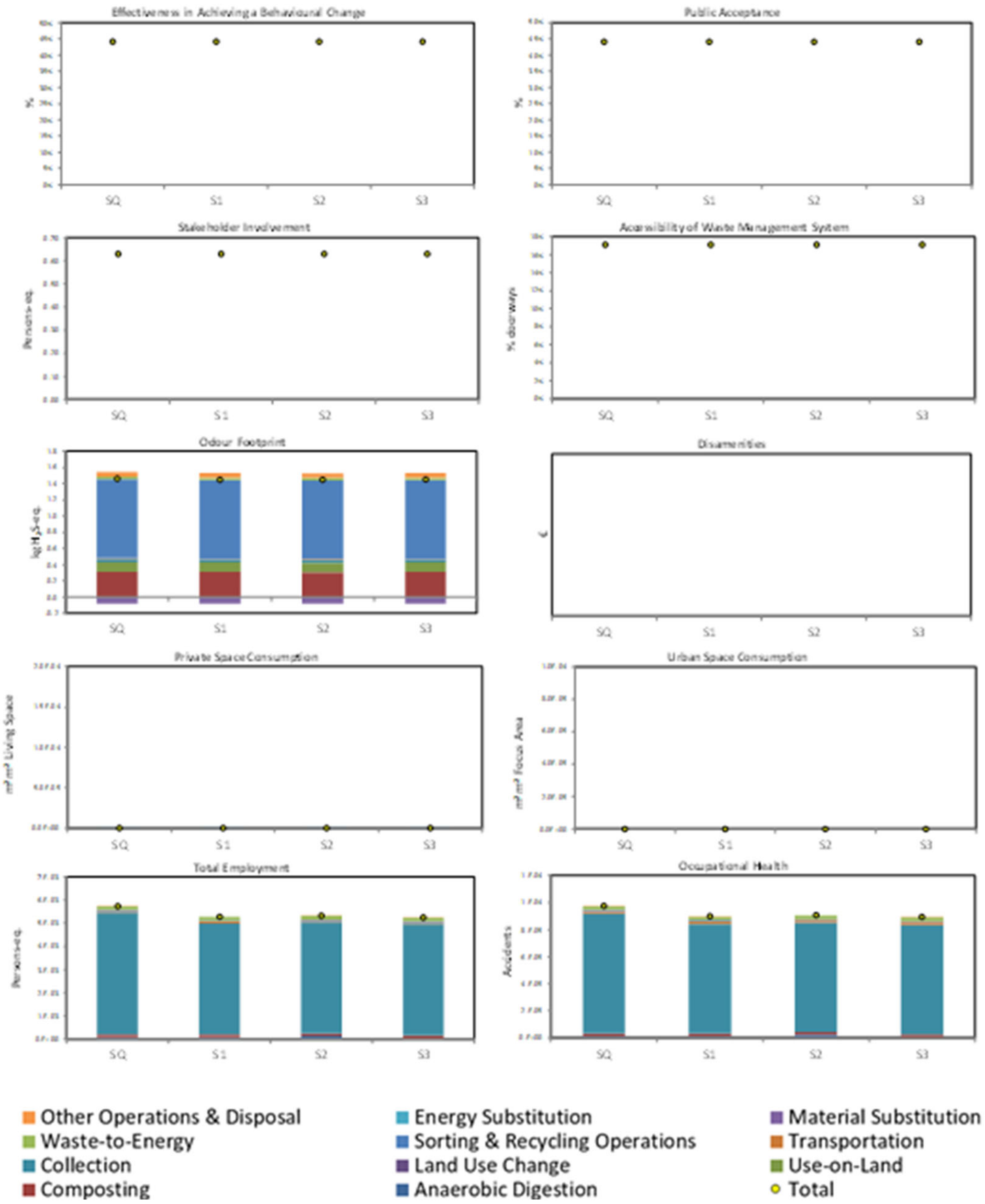
AoP Human health



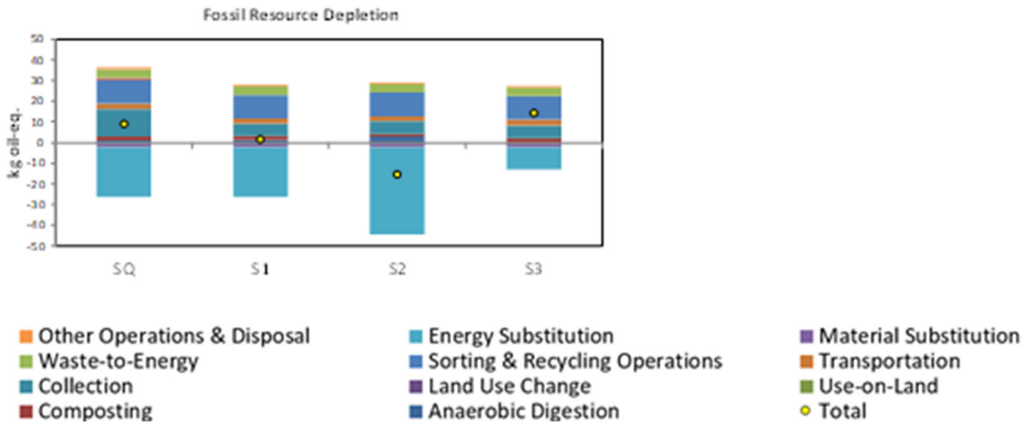
AoP Ecosystem health



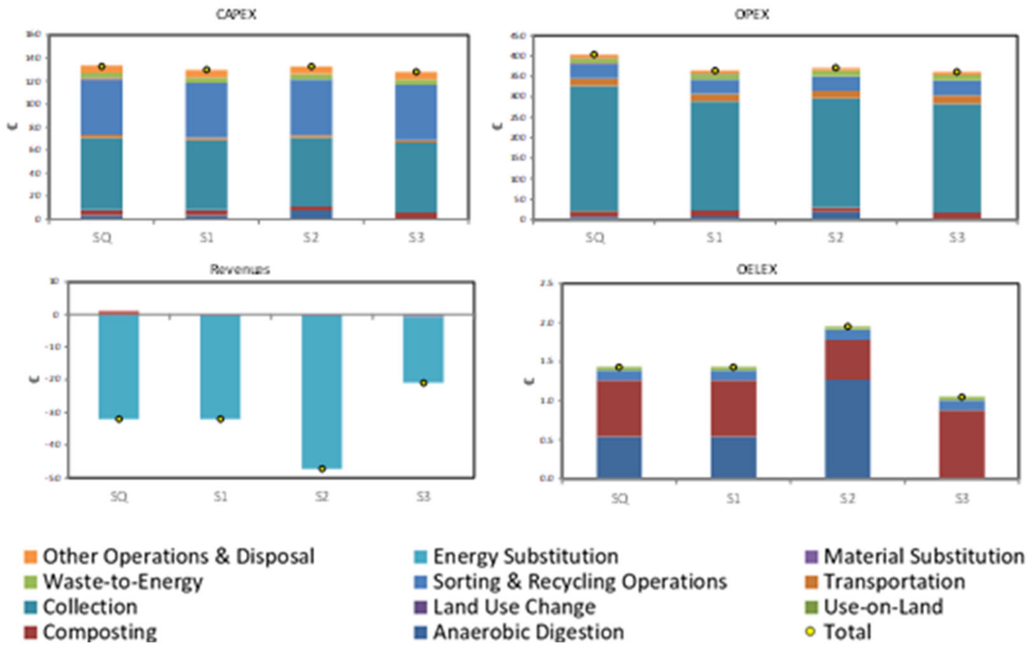
AoP Human well-being



AoP Natural resources



AoP Prosperity



Total annual impact (selected indicators)

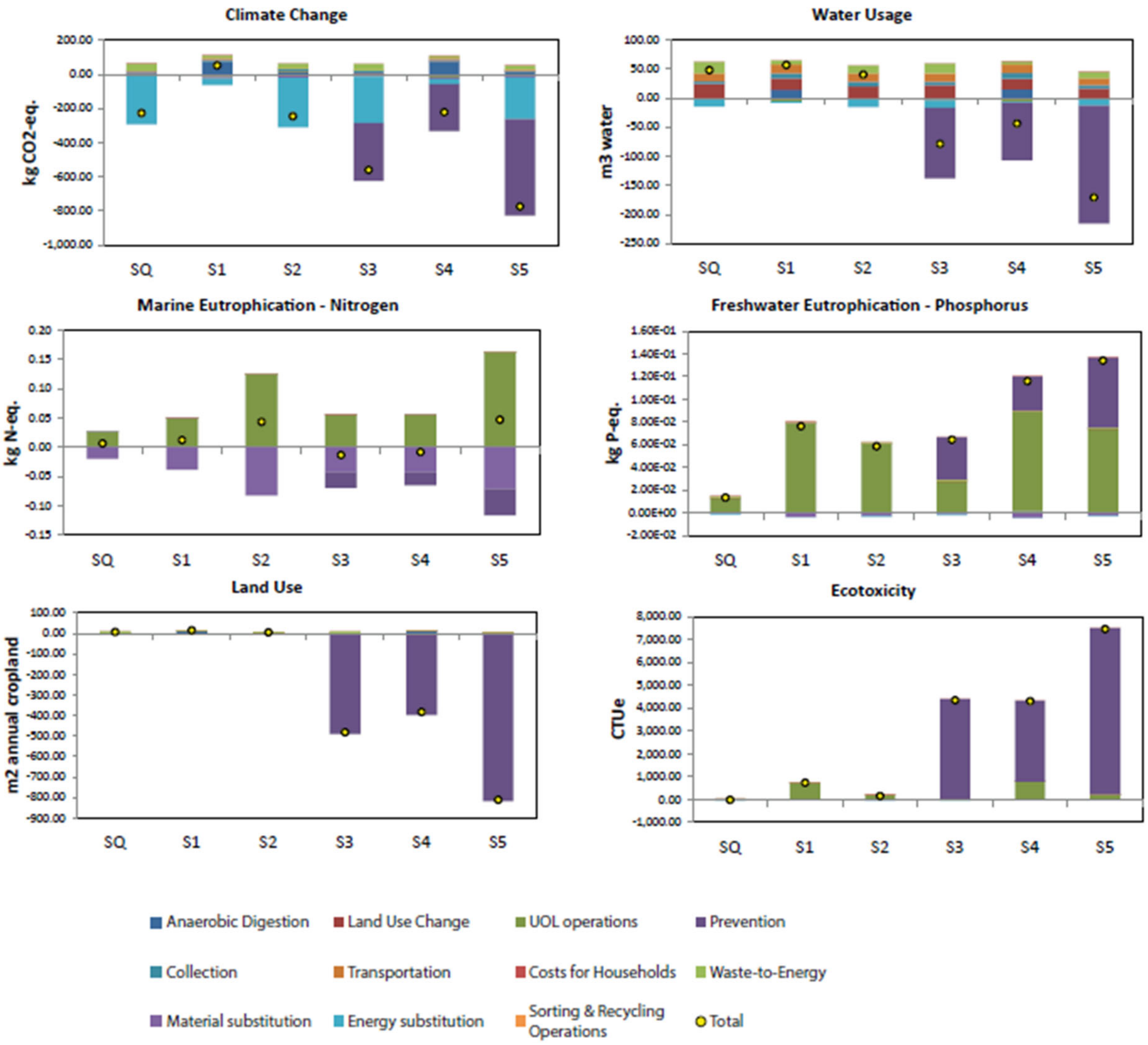
	Climate Change Mkg CO_2-eq.	Cost (Sum) M€	Total Employment Jobs-eq.
SQ	*36.5*	*102*	*1160*
S1	32.1	93.6	1066
S2	27.1	92.6	1077
S3	34.2	94.8	1060

Net annual impact change relative to the *Status Quo* SQ (selected indicators)

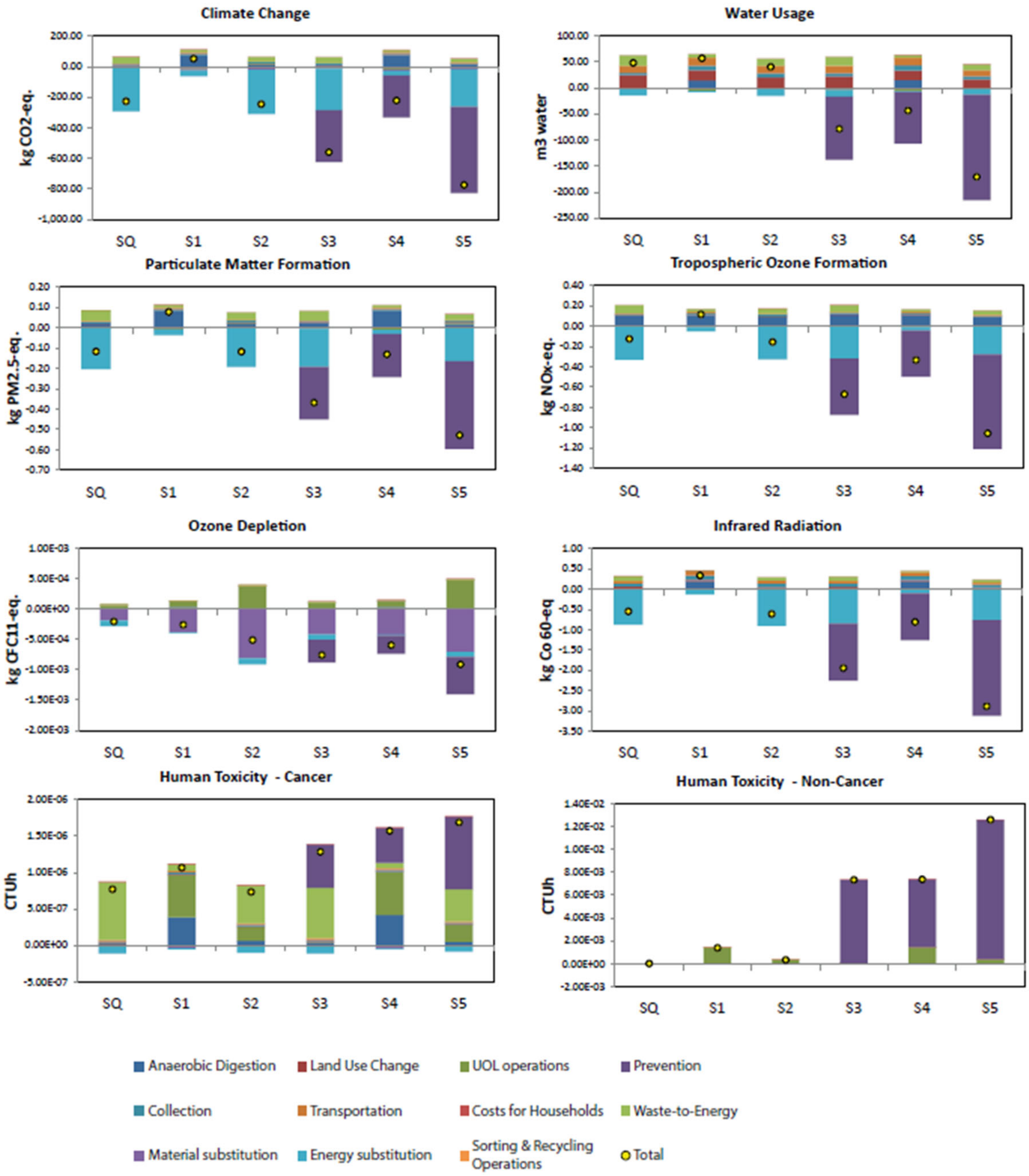
	Climate Change Mkg CO_2-eq.	Cost (Sum) M€	Total Employment Jobs-eq.
SQ	*0 (reference)*	*0 (reference)*	*0 (reference)*
S1	-4.4	-8.4	-94
S2	-9.4	-9.4	-84
S3	-2.3	-7.2	-100

Annex D - Hamburg midpoint results

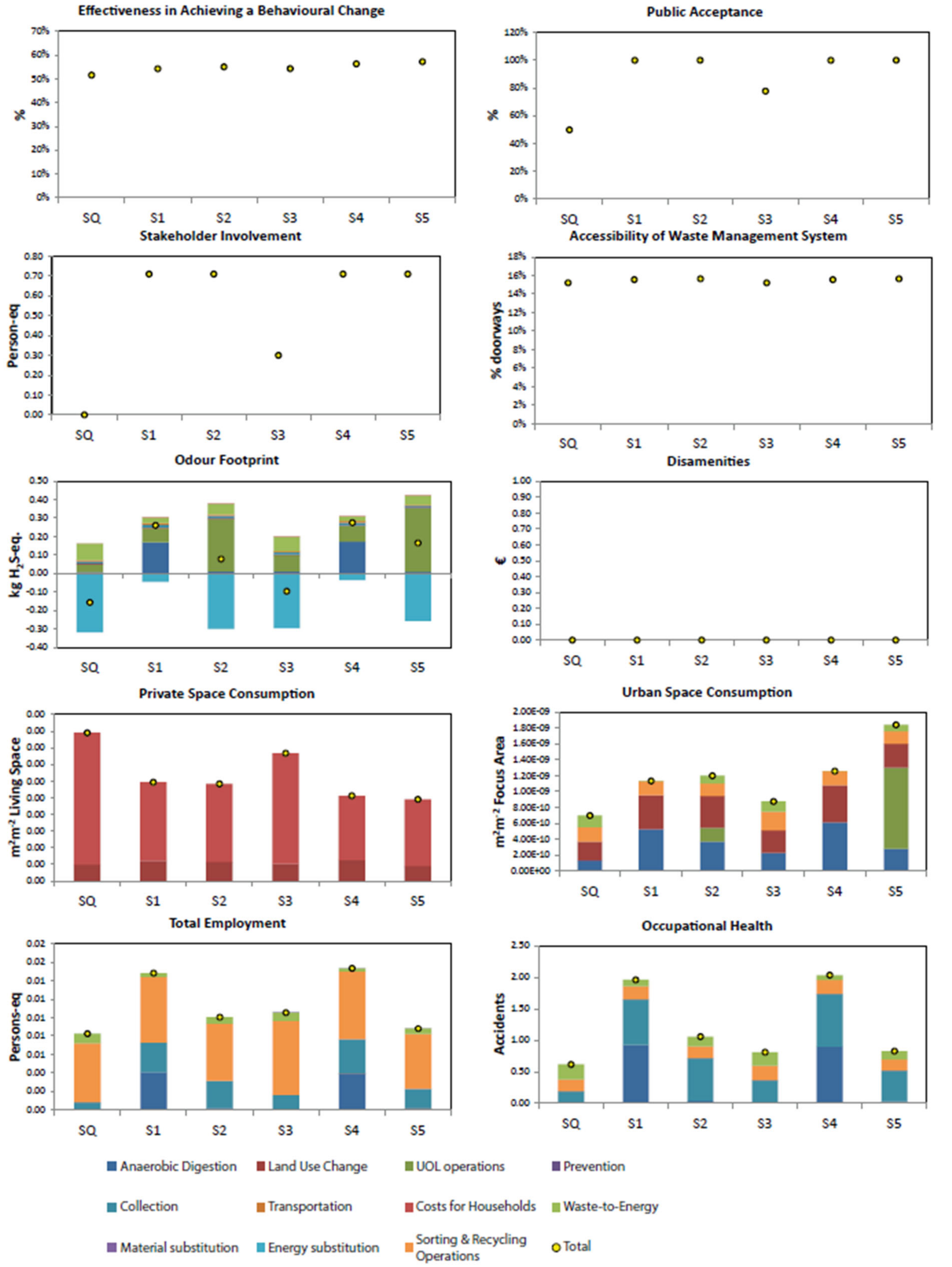
AoP Ecosystem Health



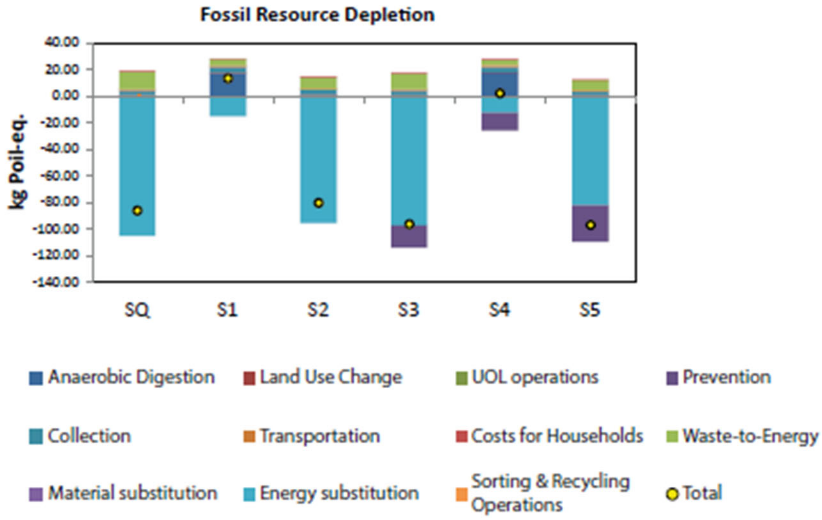
AoP Human Health



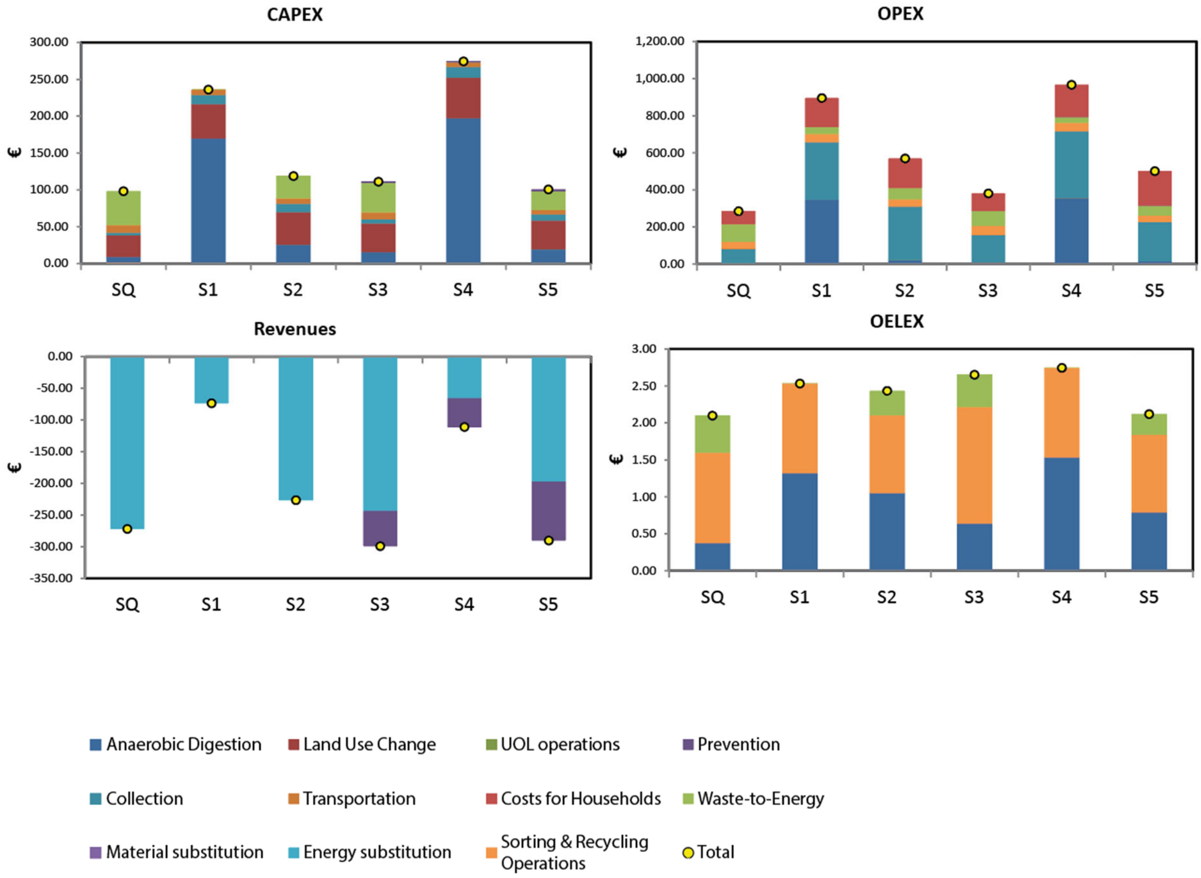
AoP Human Well-being



AoP Natural Resources



AoP Prosperity



Total annual impact (selected indicators)

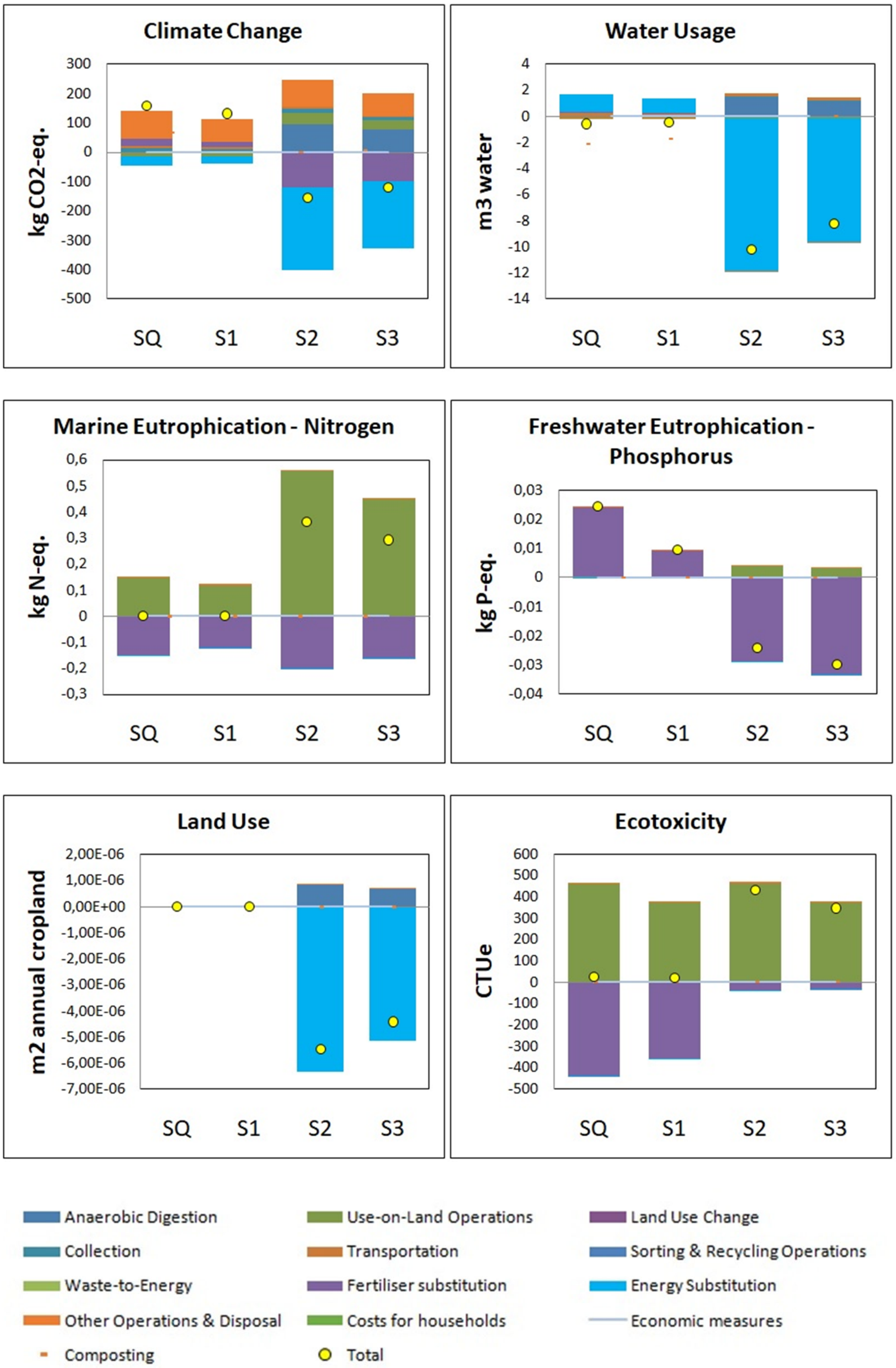
	Climate Change Mkg CO_2-eq.	Cost (Sum) M€	Total Employment Jobs-eq.
SQ	-8.4	4.2	304
S1	2.0	39.1	548
S2	-9.0	17.1	372
S3	-20.7	-47.8	390
S4	-8.1	-3.0	567
S5	-28.6	-80.4	325

Net annual impact change relative to the *Status Quo* SQ (selected indicators)

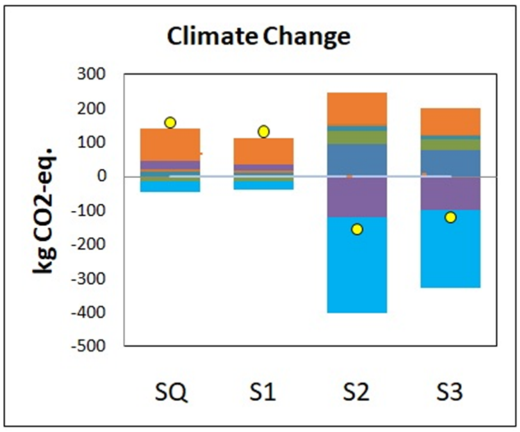
	Climate Change Mkg CO_2-eq.	Cost (Sum) M€	Total Employment Jobs-eq.
SQ	*0 (reference)*	*0 (reference)*	*0 (reference)*
S1	10.3	35.0	243.9
S2	-0.7	12.9	67.5
S3	-12.3	-52.0	85.8
S4	0.2	-7.2	263.1
S5	-20.2	-84.6	20.6

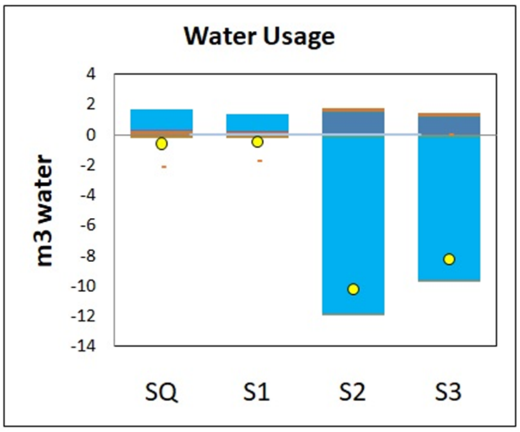
Annex E - Łódź midpoint results

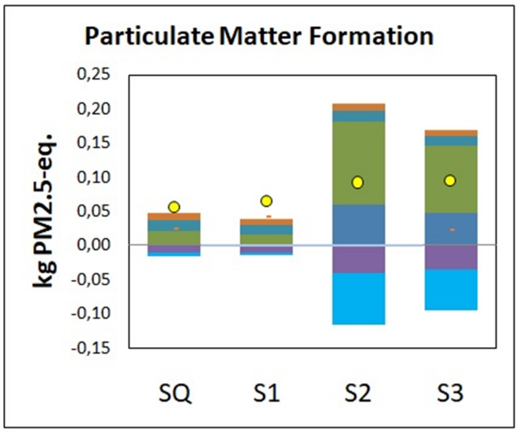
AoP Ecosystem Health

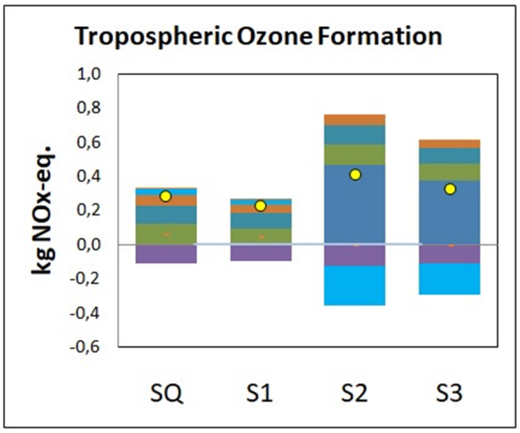


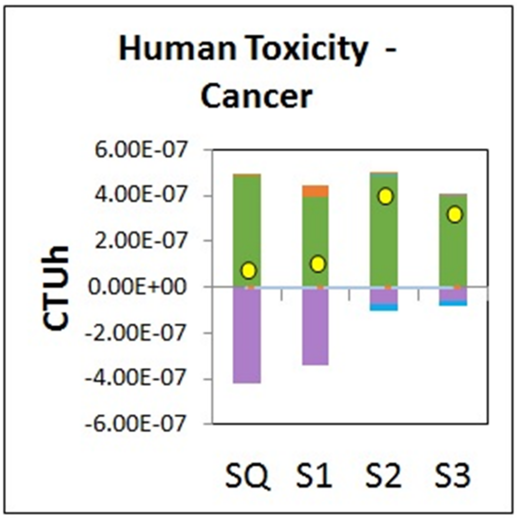
AoP Human health

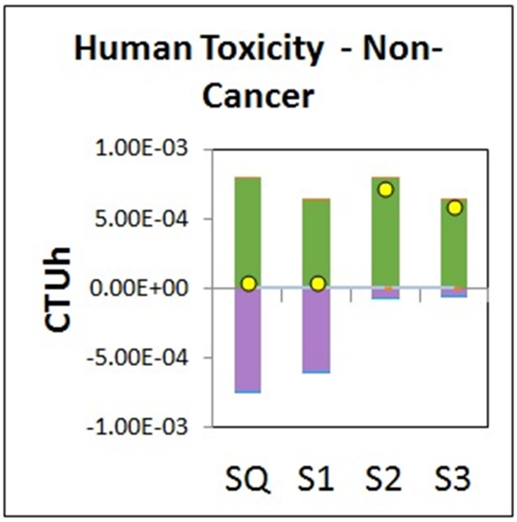


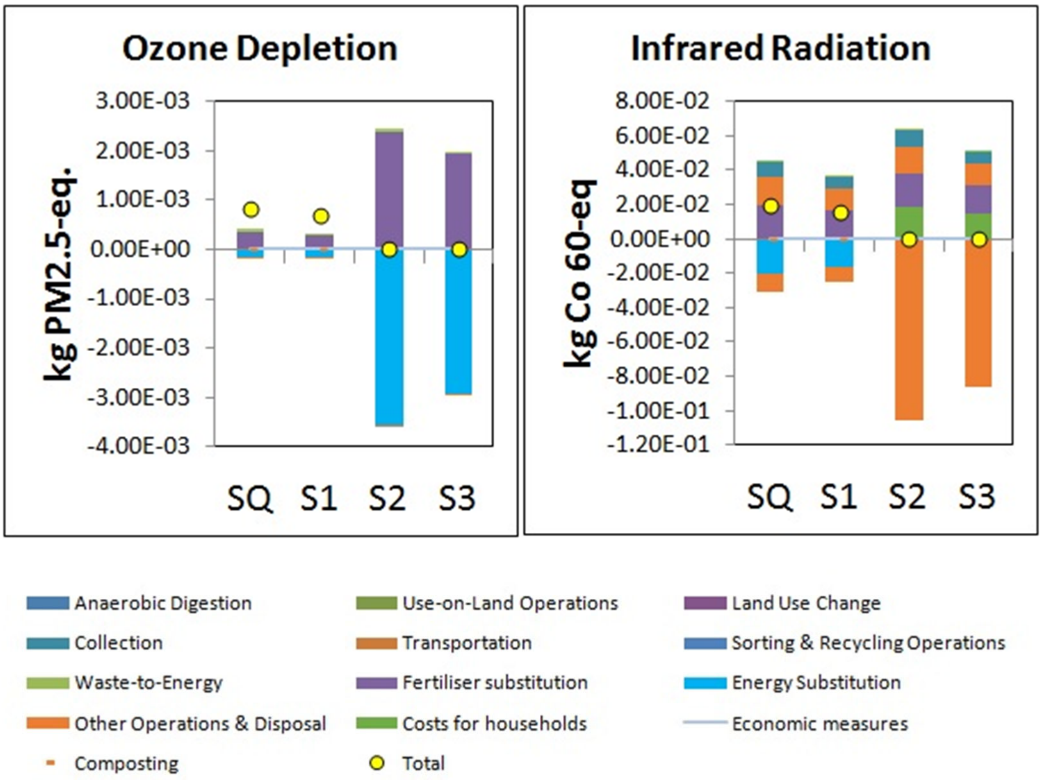




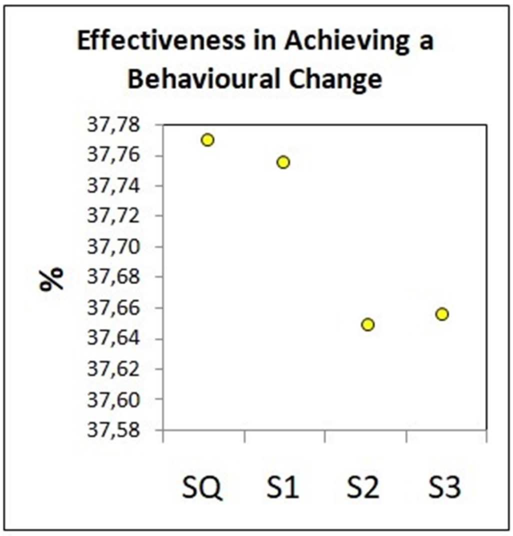


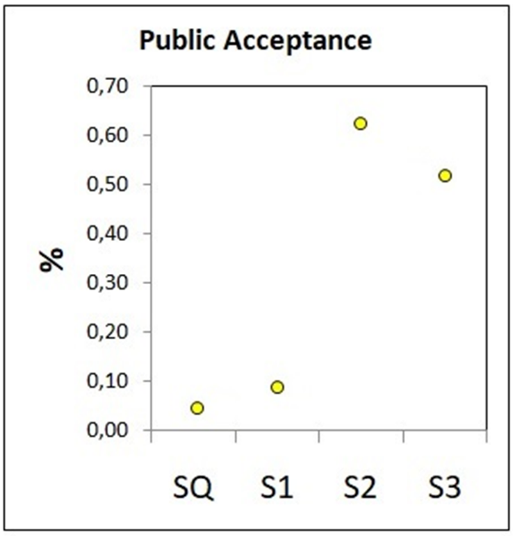


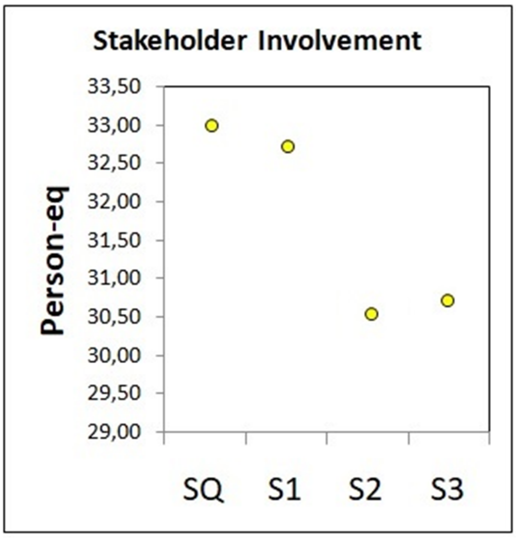


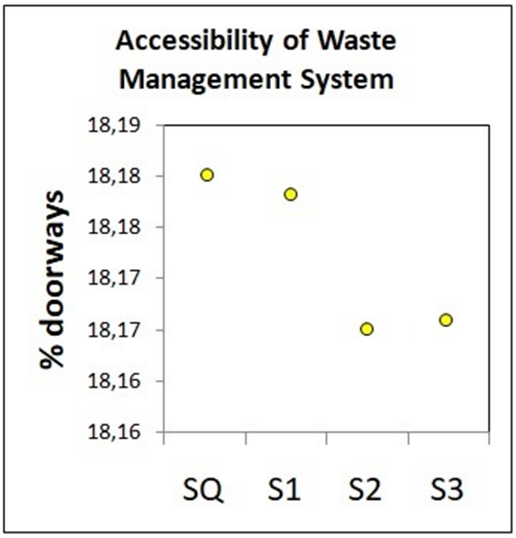

Ozone Depletion
kg PM2.5-eq.
3.00E-03
2.00E-03
1.00E-03
0.00E+00
-1.00E-03
-2.00E-03
-3.00E-03
-4.00E-03
SQ S1 S2 S3
Infrared Radiation
kg Co 60-eq
8.00E-02
6.00E-02
4.00E-02
2.00E-02
0.00E+00
-2.00E-02
-4.00E-02
-6.00E-02
-8.00E-02
-1.00E-01
-1.20E-01
SQ S1 S2 S3
Anaerobic Digestion
Use-on-Land Operations
Land Use Change
Collection
Transportation
Sorting & Recycling Operations
Waste-to-Energy
Fertiliser substitution
Energy Substitution
Other Operations & Disposal
Costs for households
Economic measures
Composting
Total

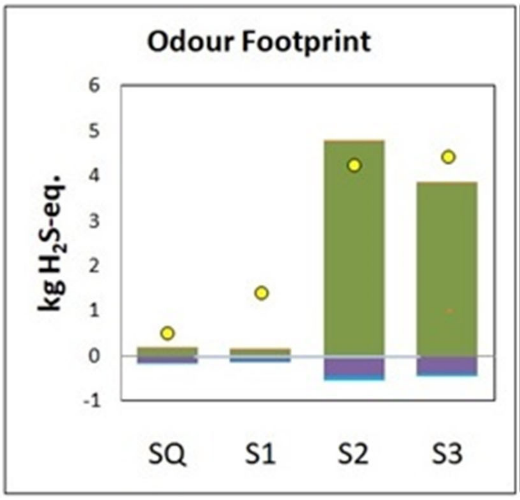
AoP Human well-being

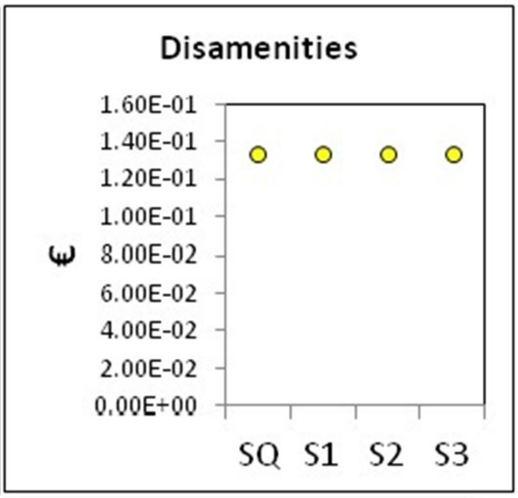


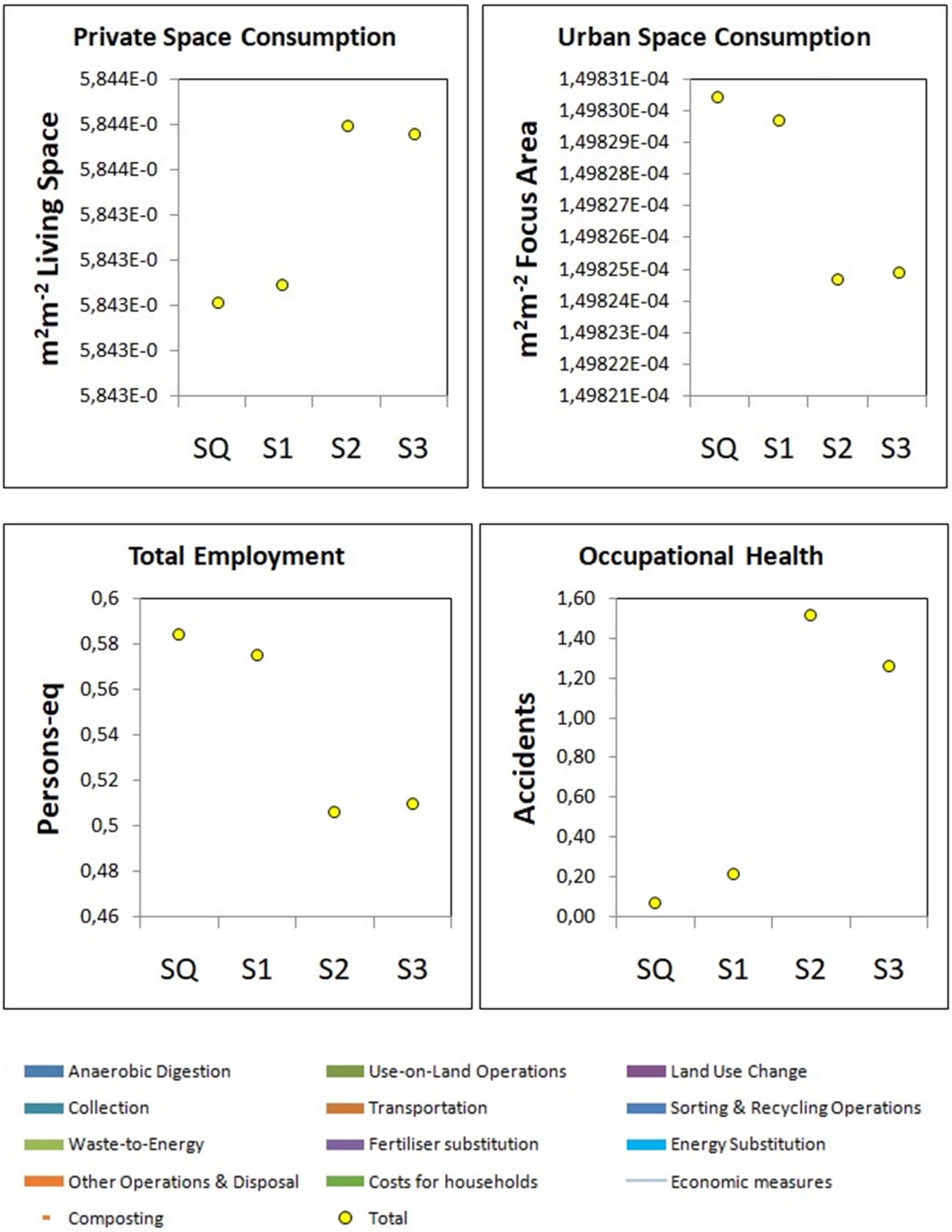




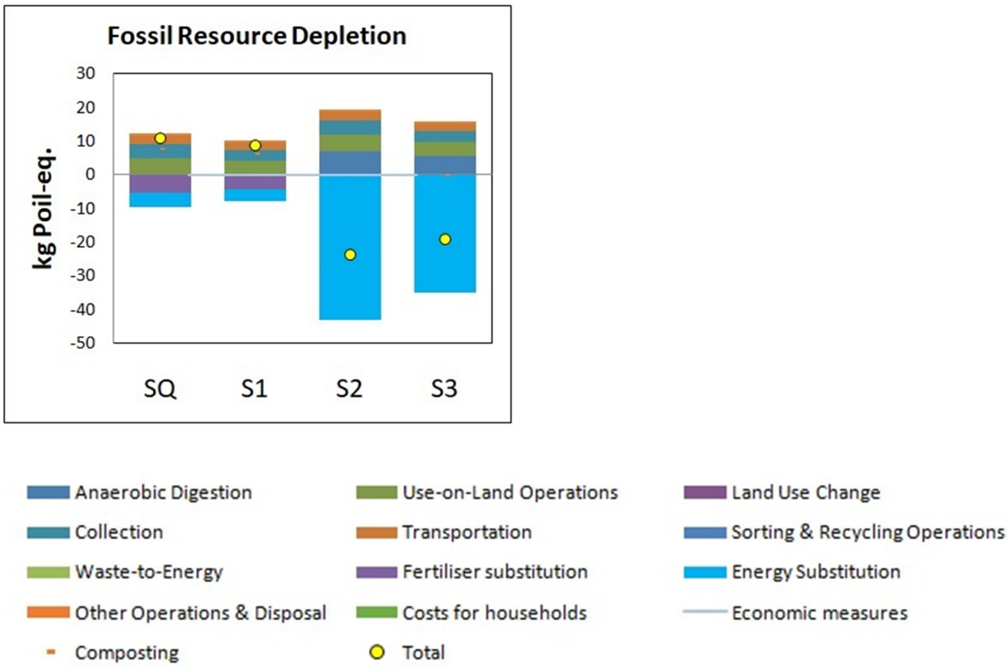




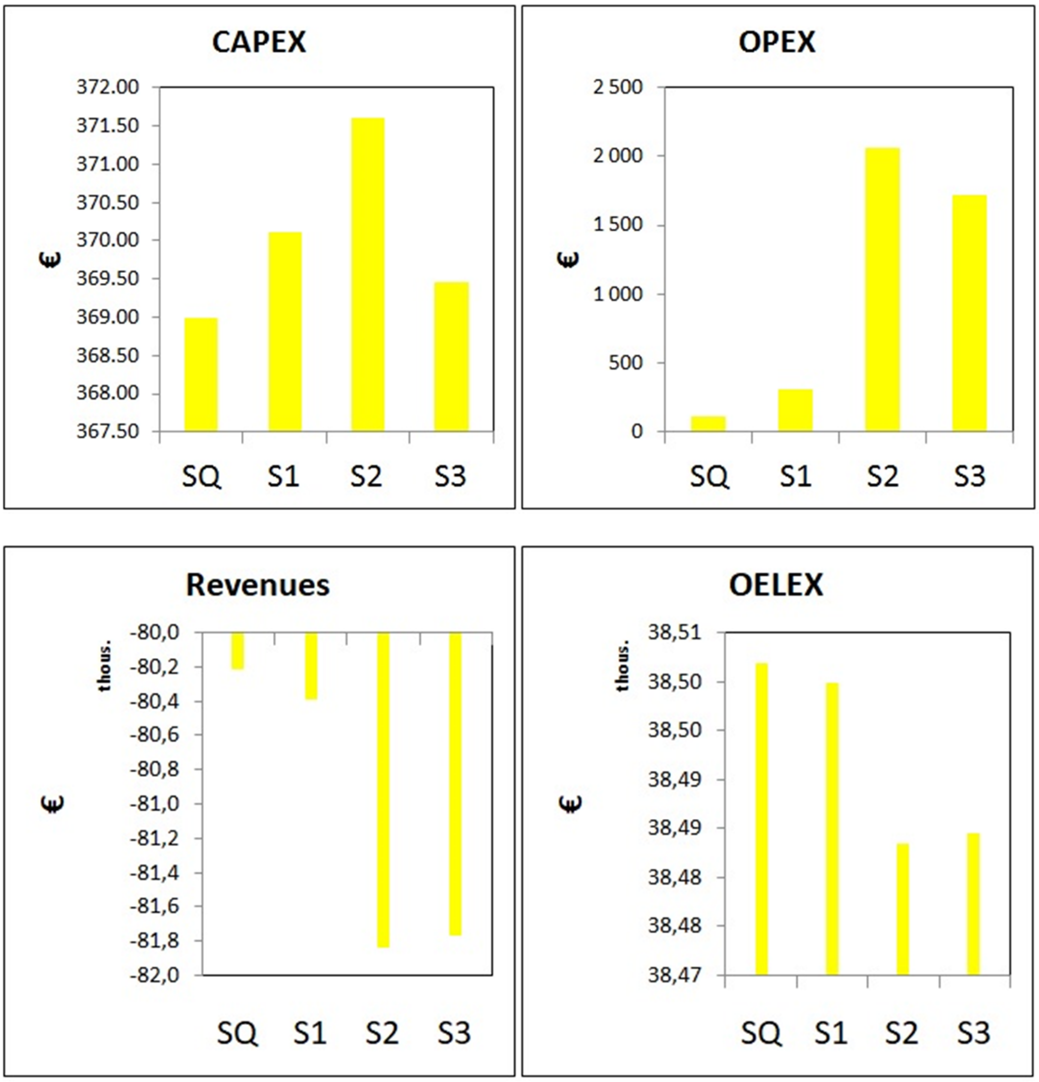



Private Space Consumption
m2m-2 Living Space
5,844E-0
5,844E-0
5,844E-0
5,843E-0
5,843E-0
5,843E-0
5,843E-0
5,843E-0
SQ S1 S2 S3
Urban Space Consumption
m2m-2 Focus Area
1,49831E-04
1,49830E-04
1,49829E-04
1,49828E-04
1,49827E-04
1,49826E-04
1,49825E-04
1,49824E-04
1,49823E-04
1,49822E-04
1,49821E-04
SQ S1 S2 S3
Total Employment
Persons-eq
0,6
0,58
0,56
0,54
0,52
0,5
0,48
0,46
SQ S1 S2 S3
Occupational Health
Accidents
1,60
1,40
1,20
1,00
0,80
0,60
0,40
0,20
0,00
SQ S1 S2 S3
Anaerobic Digestion
Use-on-Land Operations
Land Use Change
Collection
Transportation
Sorting & Recycling Operations
Waste-to-Energy
Fertiliser substitution
Energy Substitution
Other Operations & Disposal
Costs for households
Economic measures
Composting
Total

AoP Natural resources



AoP Prosperity



Total annual impact (selected indicators)

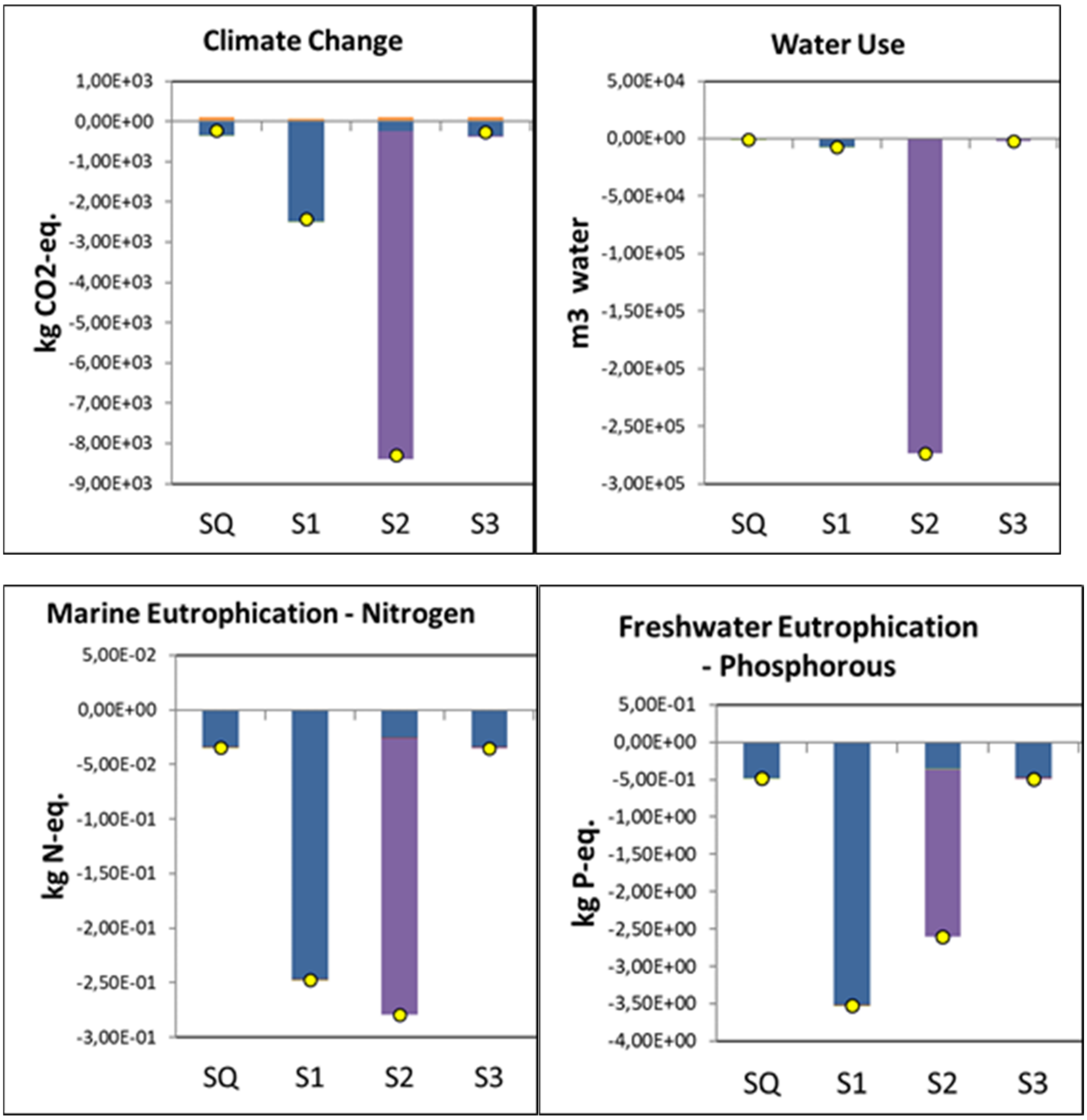
	Climate Change Mkg CO_2-eq.	Cost (Sum) M€	Total Employment Jobs-eq.
SQ	*0.356*	*87,0*	*1306*
S1	0.298	87,1	751
S2	-0.344	88,1	661
S3	-0.268	87,9	666

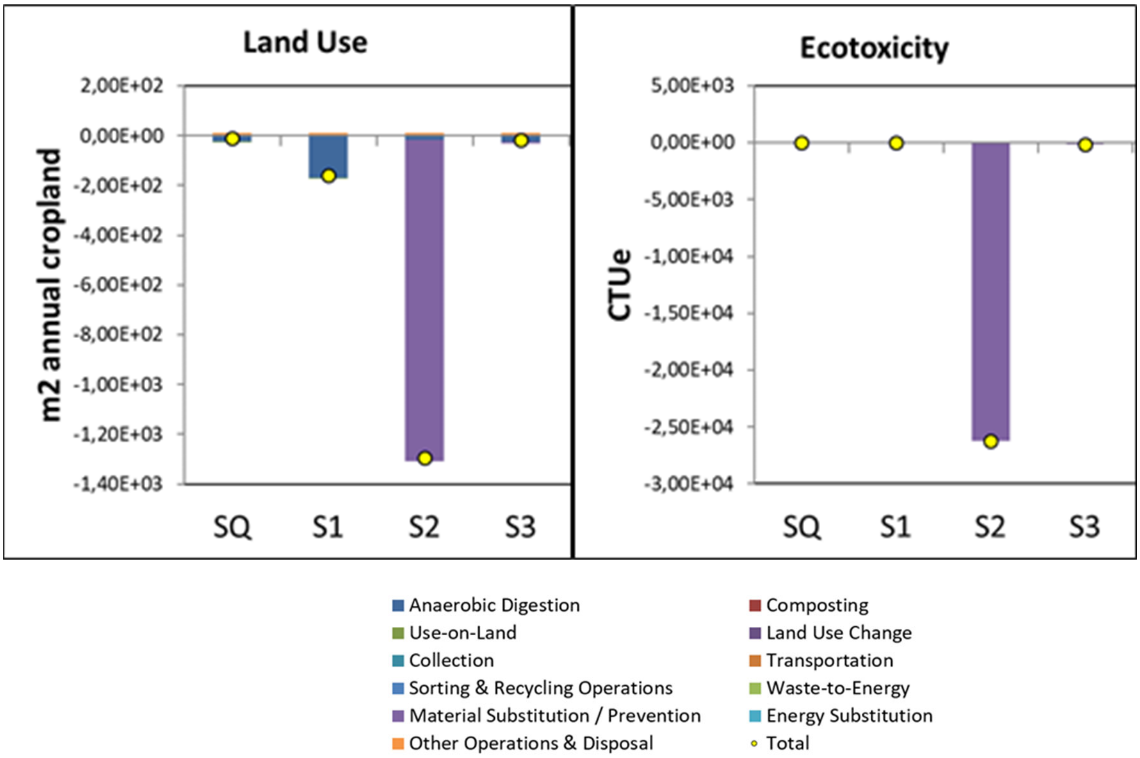
Net annual impact change to the *Status Quo* (selected indicators)

	Climate Change Mkg CO_2-eq.	Cost (Sum) M€	Total Employment Jobs-eq.
SQ	*0 (reference)*	*0 (reference)*	*0 (reference)*
S1	-0.058	0,1	-555
S2	-0.700	1,1	-645
S3	-0.624	0,9	-640

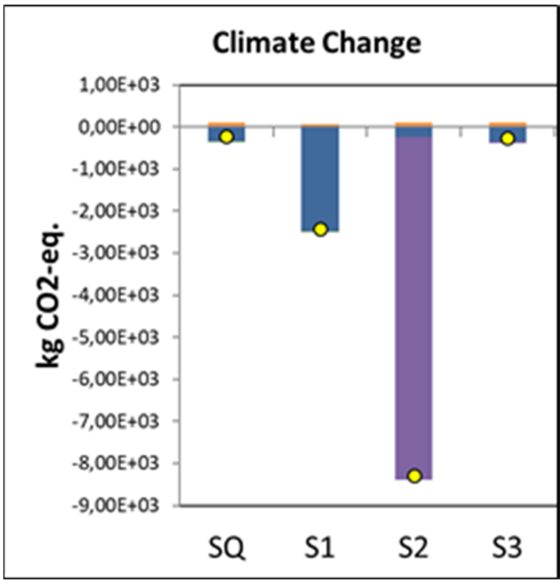
Annex F - Pécs midpoint results

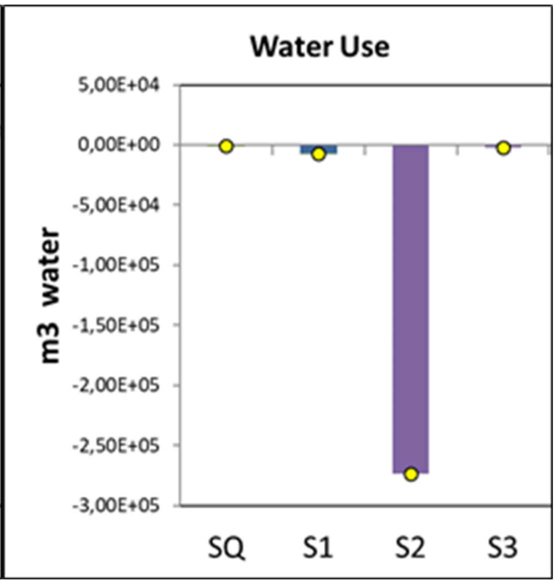
AoP Ecosystem Health

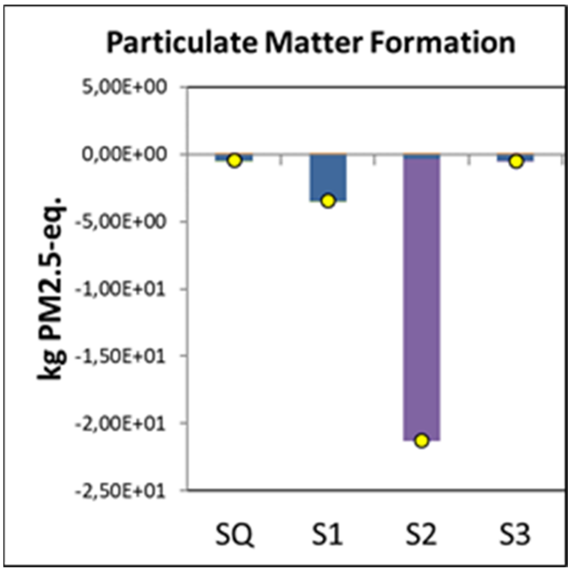


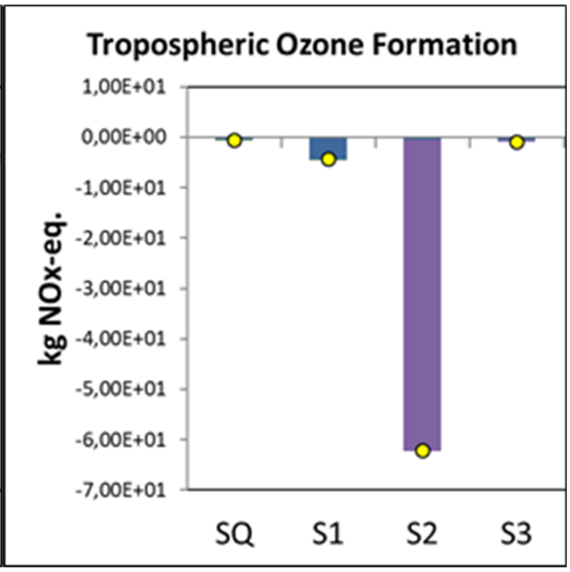

Land Use
m2 annual cropland
2,00E+02
0,00E+00
-2,00E+02
-4,00E+02
-6,00E+02
-8,00E+02
-1,00E+03
-1,20E+03
-1,40E+03
SQ
S1
S2
S3
Ecotoxicity
CTUe
5,00E+03
0,00E+00
-5,00E+03
-1,00E+04
-1,50E+04
-2,00E+04
-2,50E+04
-3,00E+04
SQ
S1
S2
S3
Anaerobic Digestion
Composting
Use-on-Land
Land Use Change
Collection
Transportation
Sorting & Recycling Operations
Waste-to-Energy
Material Substitution / Prevention
Energy Substitution
Other Operations & Disposal
Total

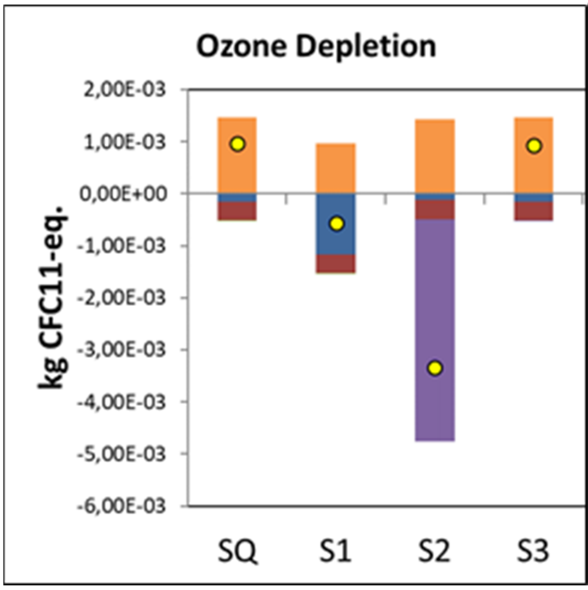
AoP Human Health

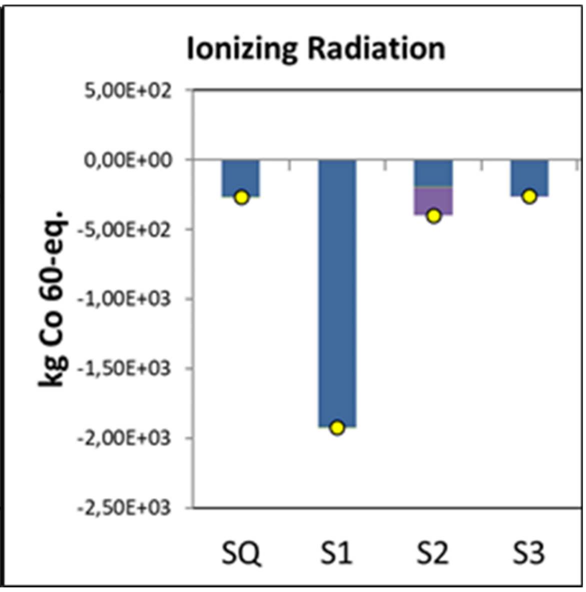


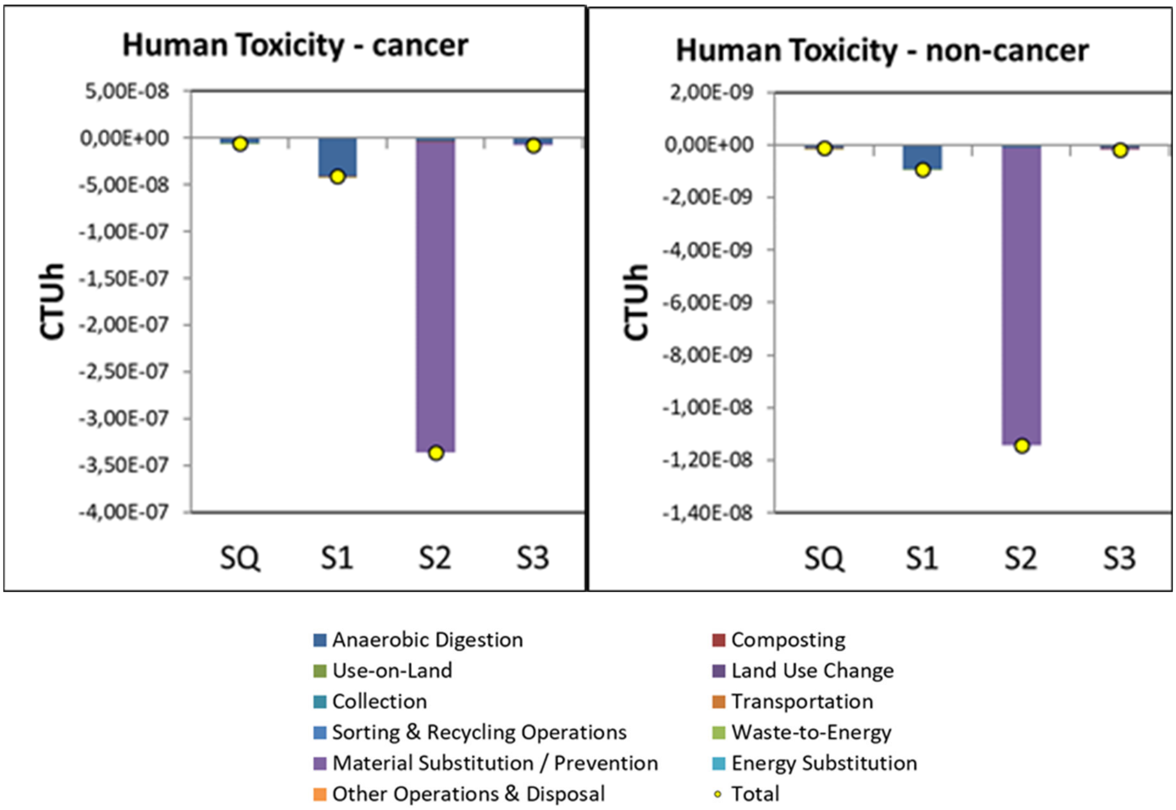




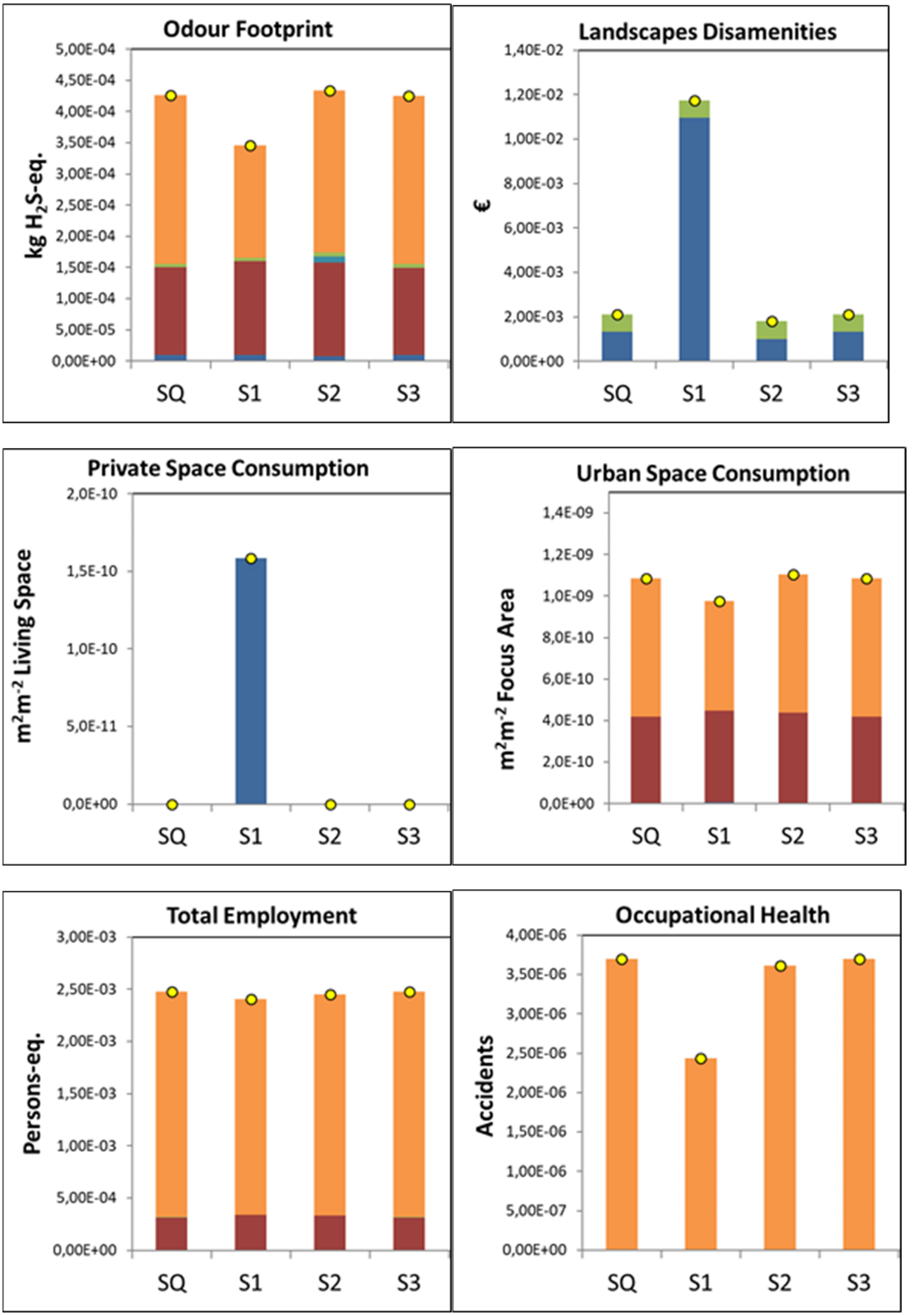


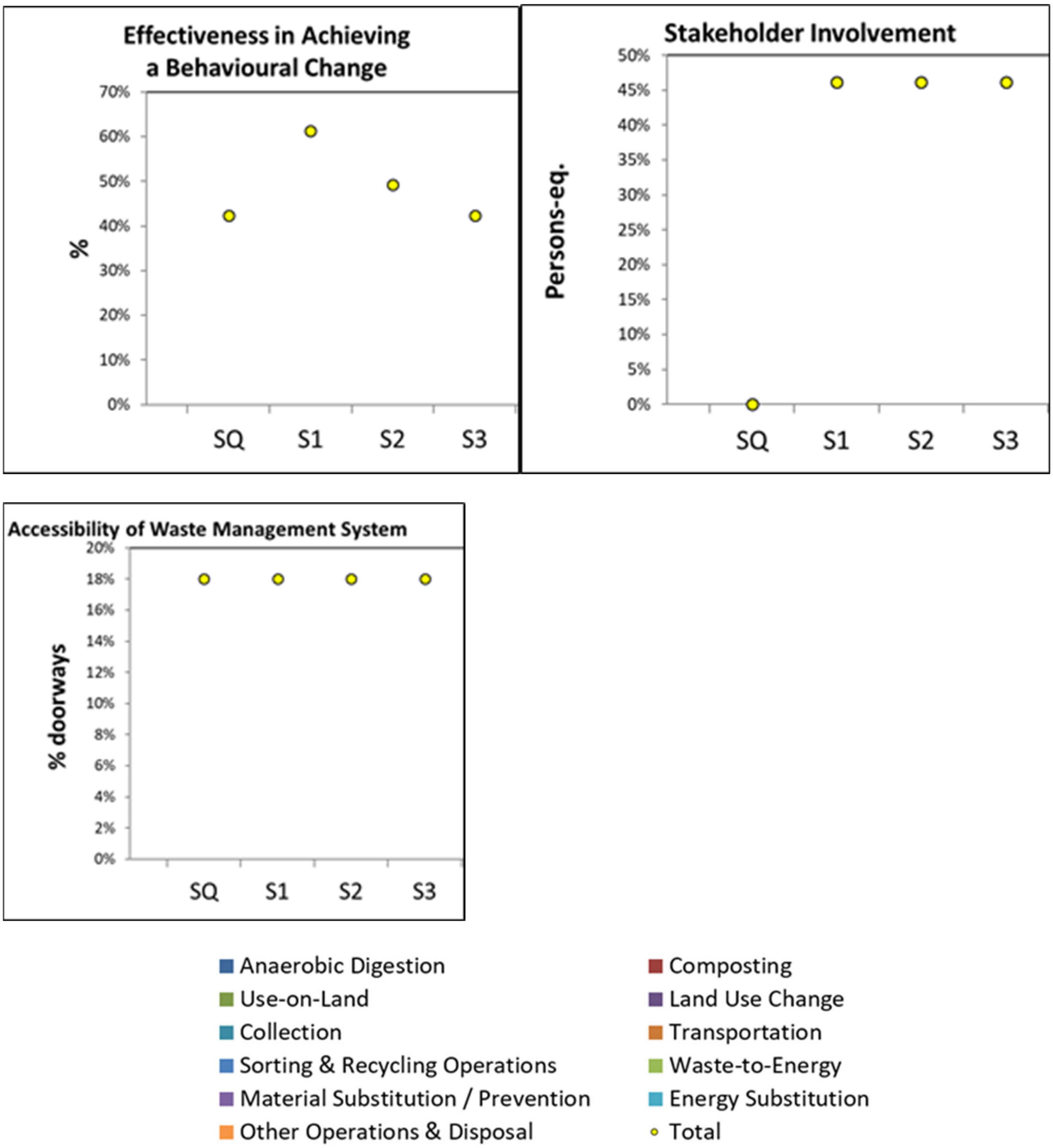




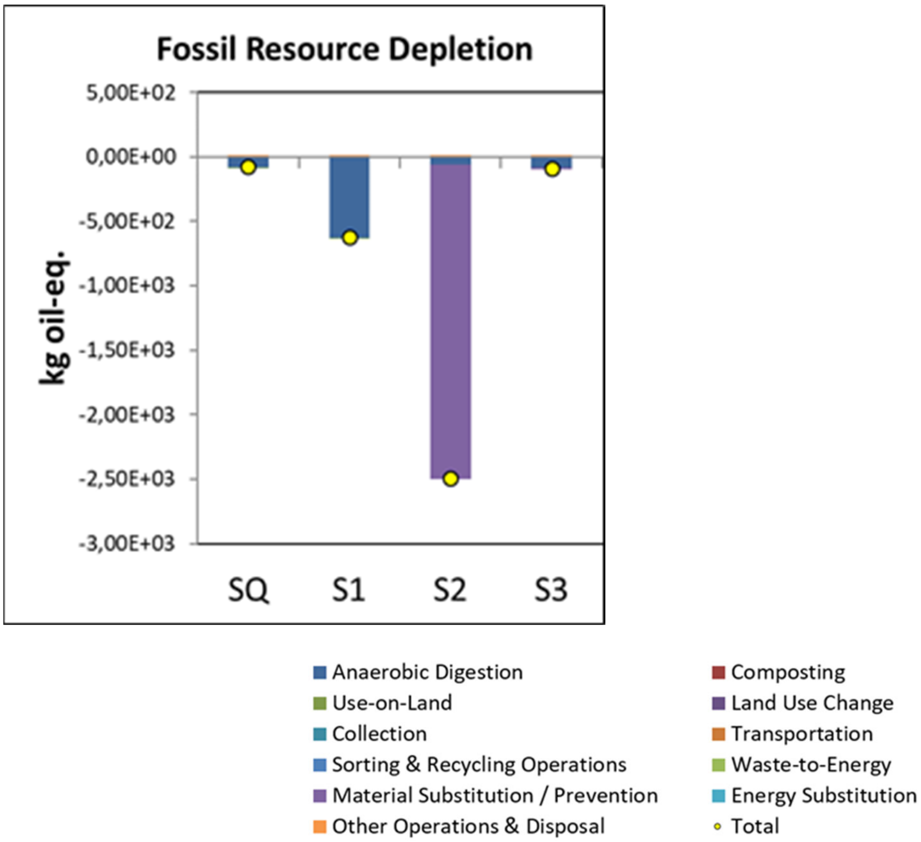

Human Toxicity - cancer
5,00E-08
0,00E+00
-5,00E-08
-1,00E-07
-1,50E-07
-2,00E-07
-2,50E-07
-3,00E-07
-3,50E-07
-4,00E-07
CTUh
SQ
S1
S2
S3
Human Toxicity - non-cancer
2,00E-09
0,00E+00
-2,00E-09
-4,00E-09
-6,00E-09
-8,00E-09
-1,00E-08
-1,20E-08
-1,40E-08
CTUh
SQ
S1
S2
S3
Anaerobic Digestion
Composting
Use-on-Land
Land Use Change
Collection
Transportation
Sorting & Recycling Operations
Waste-to-Energy
Material Substitution / Prevention
Energy Substitution
Other Operations & Disposal
Total

AoP Human Well-being

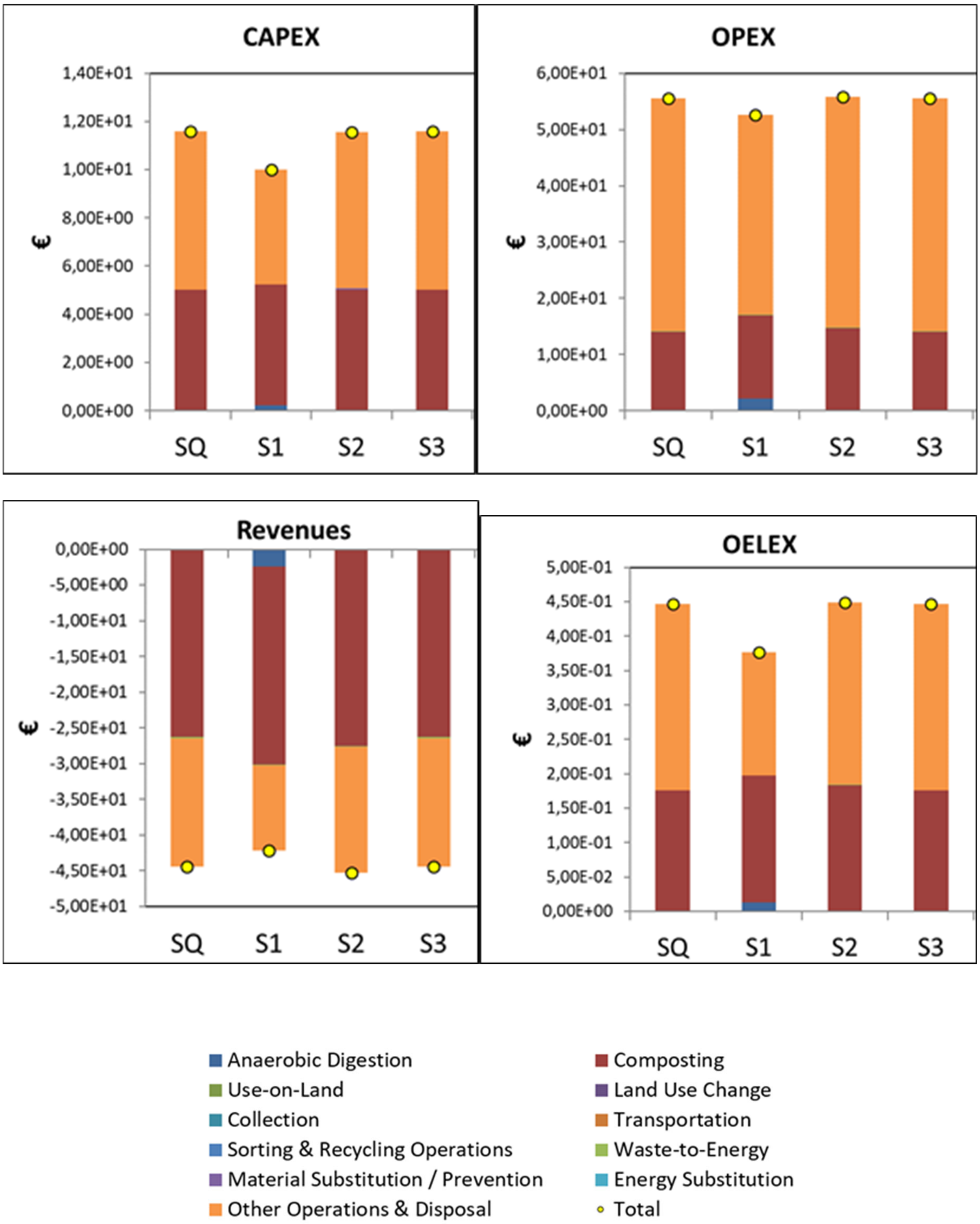



Effectiveness in Achieving a Behavioural Change
%
70%
60%
50%
40%
30%
20%
10%
0%
SQ
S1
S2
S3
Stakeholder Involvement
Persons-eq.
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
SQ
S1
S2
S3
Accessibility of Waste Management System
% doorways
20%
18%
16%
14%
12%
10%
8%
6%
4%
2%
0%
SQ
S1
S2
S3
Anaerobic Digestion
Composting
Use-on-Land
Land Use Change
Collection
Transportation
Sorting & Recycling Operations
Waste-to-Energy
Material Substitution / Prevention
Energy Substitution
Other Operations & Disposal
Total

AoP Natural Resources



AoP Prosperity



Total annual impact (selected indicators)

	Climate Change Mkg CO_2-eq.	Cost (Sum) M€	Total Employment Jobs-eq.
SQ	*-5.07*	*1.49*	*55*
S1	-53.4	1.39	53
S2	-174	1.43	52
S3	-5.98	1.49	55

Net annual impact change relative to the *Status Quo SQ* (selected indicators)

	Climate Change Mkg CO_2-eq.	Cost (Sum) M€	Total Employment Jobs-eq.
SQ	*0 (reference)*	*0 (reference)*	*0 (reference)*
S1	-48.33	-0.1	-2
S2	-168.93	-0.06	-3
S3	-0.91	0	0