Life cycle assessment of food waste management: A conceptual plan analysis

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Abstract

Life cycle analysis (LCA) is used to assess the environmental impacts of two options in an urban solid waste management policy. The approach is based on the assessment of an "incremental" system, whereby only the processes that are affected by the policy – the processes that are different accross policy alternatives – are included in the analysis. The approach allows for simpler modeling, better defined system boundaries and less demand for data than a classical separate comparison of two alternatives. Furthermore, the incremental approach is relevant when the goal is to assess the environmental impacts of constructing supplementary facilities. This methodology is applied to assess life cycle environmental impacts of anaerobic digestion and electricity generation from biogas in the organic solid waste management scheme for San Francisco as a replacement of the currently used composting facilities. The analysis shows a net beneficial impact of the proposed project with the majority of the benefits from energy recovery. However, this process may result in detrimental impacts on climate change although these impacts are partially an artifact of LCA and they warrant further study.

1 Goal and scope of the project

1.1 Project context

The goal of the project to determine potential environmental impacts of developing an alternative for organic solid waste management that includes anaerobic digestion and biogas utilization while reducing the need for composting. The City of San Francisco generates approximately 200 wet tons per day of source-separated organic solid waste. After initial sorting and processing the remaining organic waste is transported to composting facilities in the Central Valley. However, the City of San Francisco has established strong political incentives to reach a 100% landfill diversion by year 2020 through increasing organic waste recycling. The resulting policy will include provision of an additional bin for household wet organic waste collection. This waste stream will be added to the commercial food waste to yield up to 400 wet tons (160 dry tons) per day that exceeds the capacity of the composting facilities that is limited by regulations on volatile organic compounds (VOC) emissions. As an alternative, construction and operation of an additional anaerobic digester and biogas utilization facility in San Francisco is considered. Currently, the proposed solid waste management expansion is in the stage of conceptual planning.

1.2 Life cycle assessment methodology

To analyze potential impacts and benefits of the proposed expansion Life Cycle Assessment (LCA) methodology was used. According to the International Organization for Standardization (ISO) 14040 standard [1], the definition of LCA is given as follows [2]: *"LCA is a technique for assessing the environmental aspects and potential impacts associated with a product, by:*
- compiling an inventory of relevant inputs and outputs of a system,
- evaluating the potential impacts associated with those inputs and outputs,
- interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study."
LCA describes environmental aspects and potential impacts throughout the life of a product or process from raw materials through production, use and disposal. After having decided on scope and purpose of the LCA, the first step is to define the functional unit of the study, i.e., the description of the service provided or the product considered. In this work, the functional unit of processing 1 dry ton of

organic solid waste was chosen. We assumed the life span of the infrastructure and operation as 20 years.

The next step is complete the Life Cycle Inventory (LCI) for a selected functional unit listing all materials, processes, services and energy needed in construction, operation and decommission (disposal) of the functional unit. At the conceptual planning stage little detailed information is available on many LCI elements. Thus, the values used often represent best estimates from preliminary studies, engineering practice or adopted from other locations. The LCI elements are then translated into environmental emissions associated with each material or process. Inputs to the analyzed system come from two compartments: "natural resources" and "technosphere". This latter term encompasses all human activities such as energy generation, manufacturing, transport related to the analysis. Next, the emissions associated with the studied functional unit are used to assess environmental impacts. The choice of impact varies depending on the specific methodology used but typically includes greenhouse gas emissions, acidification, natural resource depletion, ecotoxicity or others. These impacts are assessed using various ecological or epidemiological models adopted for each specific LCA method. The set of impact categories is often called LCA mid-points and provides detailed information about the effects of the studied process on various environmental aspects. In some methodologies, mid-point assessment is the final outcome of LCA. However, it is possible to group comparable mid-points and aggregate them into few categories called endpoints. Typical endpoints include human health, ecosystem quality, and natural resources. The last step in this chain of analytical step may involve final merging of three endpoints (health, ecosystem, and resources) into a single score (points). This ultimate aggregation is based on assumed or selected preferences (hierarchies) that reflect normative values attributed to the endpoints. The weighing factors representing these preferences were developed by different panels of citizens, scientists, medical doctors, and other stakeholders.

The LCA process, in its sequence, attempts to reduce the number of indicators and to make these indicators more meaningful. A typical LCI may contain many elements (materials or processes) that result in multiple emissions which are then translated to perhaps a dozen of midpoints that, in turn, are aggregated into three endpoints and perhaps even in a single score. In this process, one hopes to simplify the complexity of the environmental impacts and make them more "tangible" and easier to understand by target audiences. The drawback of this procedure is the increasing uncertainty of the results as they are obtained from a succession of often highly stylized or simplified models of a process in a generic

ecosystem and social conditions. These models may produce a certain degree of uniformity of analysis but with each aggregation step they become more dependant on assumptions and less related to specific site conditions [3]. The final aggregation into a single score depends completely on assumed social values and thus may not reflect either individual preferences or community choices.

2   Incremental system description

We define a baseline system as the current "status quo" situation whereby the organic solid waste is continued to be processed ending up in the composting facilities. Any increase of the waste amount would be satisfied by increasing the capacity of the existing composting facilities outside of San Francisco. Under this scenario, 400 tons of organic waste collected daily is sorted within the city before being transported to Central Valley and composted. The structure, boundaries, inputs and outputs of the baseline system are presented in Fig 1a. The principal processes are identified as "sorting", which includes the waste collection and transport to a sorting facility within the city; and "composting", which includes the transport of the sorted waste to the composting facility, and the following windrow composting process.

In the proposed "modified" system the increase is satisfied by anaerobic digestion within the city, which decreases the mass of waste to be transported and composted. The structure, boundaries, inputs and outputs of the modified system are presented in Fig. 1b. In addition to the "sorting" and "composting" processes that are present in the baseline system, the "modified" system also includes a "digestion" process composed of pulping, anaerobic digestion, biogas treatment, electricity generation and solids dewatering processes. The choice to combine all these unit processes and operations in one single "digestion" process model is justified since they all occur in the same facility whose environmental impacts are here aggregated.

In principle, having defined the baseline system and its alternative, two LCA procedures could have been performed and the resulting environmental impact estimates compared. However, the goal of the present study is not to compare two new solutions for waste management that would be built and implemented de novo. Rather, we want to compare a new not-yet-existing alternative with the currently used infrastructure and treatment processes. The existing installations and processes associated with current practices of waste management have been

already built or operated and their environmental impacts have materialized in the past. The past impacts should be discounted and only the future impacts considered. It is sufficient for our purpose to analyze only incremental changes to the existing process. We define an "incremental" system as a group of infrastructure and processes that are required to upgrade from the baseline to the alternative system. In the present case, such a group involves the processes and infrastructure linked to the anaerobic digestion, biogas production and electricity generation, but also includes the downstream effects of these processes on the composting yields, transportation effort and emissions. Input to the incremental system is the difference between the corresponding inputs to the alternative and baseline systems. The structure, boundaries, input and output of the incremental system are presented in Fig. 1c. The principal processes considered in the incremental system are "digestion" and "composting". Furthermore, the inputs and outputs that are identical in the baseline and alternative systems are by definition zero in the incremental system. As a result, the need for data required for this assessment is greatly reduced and simplified, and the corresponding uncertainties linked to data collection are diminished. In principle, the impacts of the "incremental" systems can be both detrimental (due to depletion of natural resources or environmental emissions) or beneficial due to avoided consumption of energy or other resources. When the goal of the analysis is to evaluate the effects of a policy change consequential LCA can be used. Finnveden and co-workers [4] summarized the on-going discussion on the applicability of consequential LCA and its specific methodology. We believe that our "incremental" approach is conceptually different from consequential LCA which is applied mostly to marginal changes driven by demand and supply.

3   LCA results

The analysis of the incremental system was carried out with the help of SimaPro7 software (version 7.1.0, Pre Consultants, Netherlands). Life cycle inventory (LCI) was developed for the "incremental" system including both inputs from the natural resources compartment and from the technosphere (including avoided inputs) using data from preliminary studies and engineering analysis. These data were augmented by impact data primarily from the Swiss Ecoinvent database (version 1.3) with some data from the Swiss ETH-ESU 96 System and Unit Processes database. Electricity generation mix was adjusted for average US [5] and California conditions [6] but only California results are reported here. The main results of the LCI are shown in Table 1.
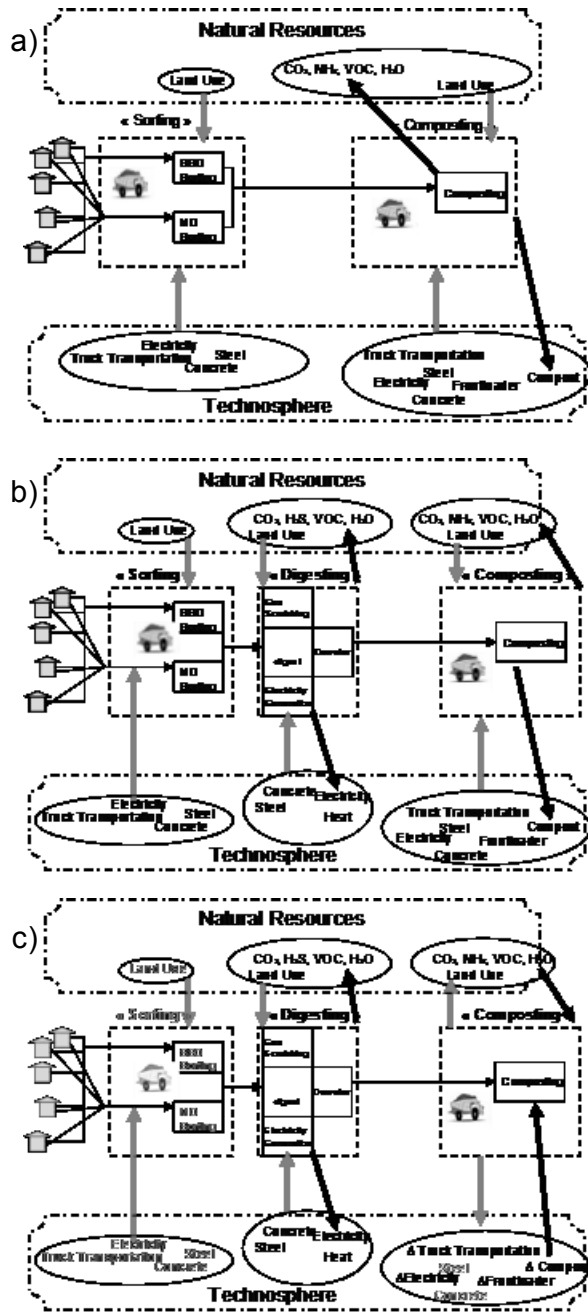
Fig 1. **(a) Existing "baseline" waste management system, (b) proposed waste management system, (c) "incremental" system for LCA as a difference between (a) and (b)**

Tab.1: Inputs to LCA - per dry ton of waste

System Elements	Value	Unit	Status
Assembly - Construction			
Concrete for Digester	0.046	t	Used
Steel for Digester	0.017	t	Used
Land Use for Digester	0.081	m^2	Used
Δ(Land Use for Composting)	-0.122	m^2	Avoided
Digester (Incremental Use)			
Δ(Electricity for Digestion)	-0.185	MWh	Avoided
Δ(Heat for Digestion)	-837720	BTU	Avoided
Digester CO2 Out	78.785	kg	Emitted
Digester CH4 Out (CO2eq)	118	kg	Emitted
Digester H2O vapor Out	96.7	kg	Emitted
Digester H2S Out	0.15	kg	
Digester VOC Out	0.21	kg	Emitted
Composting (Incremental Use)			
Δ(Compost Out)	-0.082	t	Used
Δ(Truck Transport)	-64.8	t.km	Avoided
Δ(Electricity for Composting)	0.000	kWh	
Δ(Displaced Volume)	-14.5	m^3	Avoided
Δ(VOC Out)	-0.081	kg	Avoided
Δ(Gases Out)	-0.55	kg	Avoided
Δ(H2O vapor Out)	-0.25	kg	Avoided
Δ(CO2 Out)	-0.28	kg	Avoided
Δ(NH3 Out)	-0.026	kg	Avoided

The LCA framework allows the choice of different midpoints and endpoints. In this analysis, Ecoindicator 99 methodology was used with 10 midpoint categories of impacts: carcinogens, respirable organics, respirable inorganics, climate change, radiation, ozone layer impact, ecotoxicity, acidification and eutrophication, land use, minerals, and fossil fuels. Impacts of different parts of the system on each midpoint category are first characterized in terms of percent contributions. Total impact (positive or negative) in each category is taken as 100% and the contributions of system components are allocated as percent of the total impact. In our analysis, the following three components of the incremental system were considered and their impacts evaluated: (i) waste digestion plant: construction, (ii) waste digestion: operation, and (iii) composting: operation. After characterization, impacts in related categories are aggregated into three endpoint classes: (a) human health, (b) ecosystem quality, and (c) natural resources. Human

health impact is expressed in DALY (Disability Adjusted Life Years). Ecosystem quality is reported in PDF.m^{-2}.yr^{-1} (Potentially Disappeared Fraction of plant species). The last endpoint, resources is characterized in terms of energy required to extract materials from depleted ores. Further, the impacts are normalized by the average damage attributed to one inhabitant of Europe per year and converted to eco-points (Pt). The average total environmental burden from one person is defined as 1000 Pt/yr. It is also possible to add the resulting eco-points from the three endpoints to achieve a single score, presumably describing the total impact of the system under the analysis.

3.1 Single score results

Single score results are shown in Fig. 2 with only elements contributing more than 0.5% to the total score for clarity. While single score aggregation hides important details of individual process contributions to various environmental impacts it is useful to present a simple overall picture of impact "flows". The overall system is represented by the top box "Food Waste Program Incremental." The single score value for each component is shown in the lower left-hand corner of the respective box with negative values denoting avoided (thus beneficial) impacts. The boxes are linked with each other showing the aggregate flow of single-score impacts. The thickness of the link represents relative contributions. The overall single score for the incremental system of food waste digestion is negative (-13.7 ecopoints-Pt) indicating the combined environmental and human benefit of the proposed process compared with the existing alternative. The negative impacts are associated with construction of the digesting facility and the benefits are linked to composting avoidance and operation of digesters. Better understanding of various impacts can be obtained from a more detailed analysis of midpoint characterization.

3.2 Midpoint characterization

The results of this analysis are shown in Fig. 3. The majority of beneficial (negative) impacts are attributed to composting avoidance except for carcinogens, respirable organics and inorganics, and fossil fuels. For these four categories digester operation is the most important beneficial activity. Although the single-score assessment described in the previous section indicated that the project has net environmental benefits some midpoint categories are adversely impacted. Identification of such impact shows the usefulness of midpoint analysis. In our
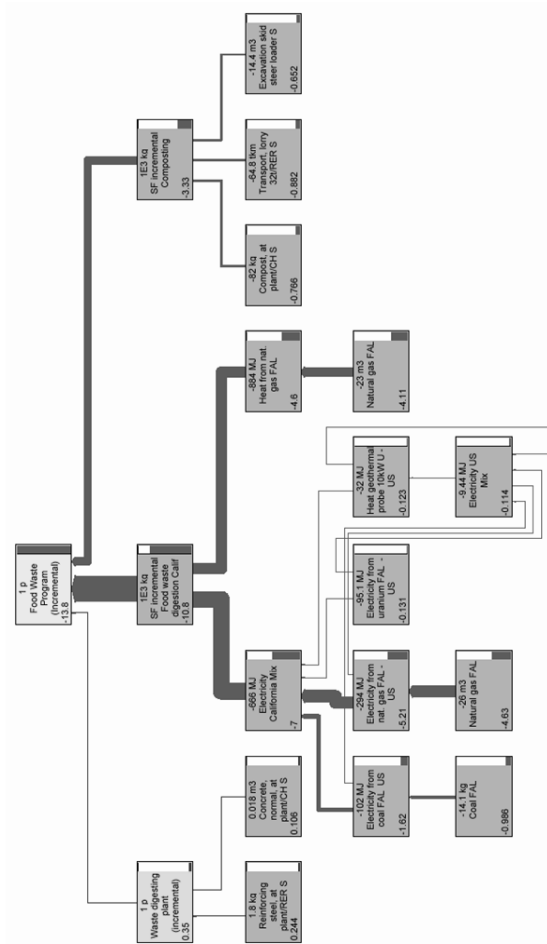
Fig. 2. Single-score impact tree for the "incremental" system

manufacturing, transportation and building activities. However, in all categories (except minerals depletion) the other two parts of the system (digester operation and composting) provide larger beneficial impacts over the project lifetime. Only for minerals depletion the overall impact is detrimental but even then mostly offset by composting avoidance. However, one midpoint characteristic needs to be addressed with more detail. The analysis indicates that digester operation can have a significant detrimental impact on climate change. To analyze this category in
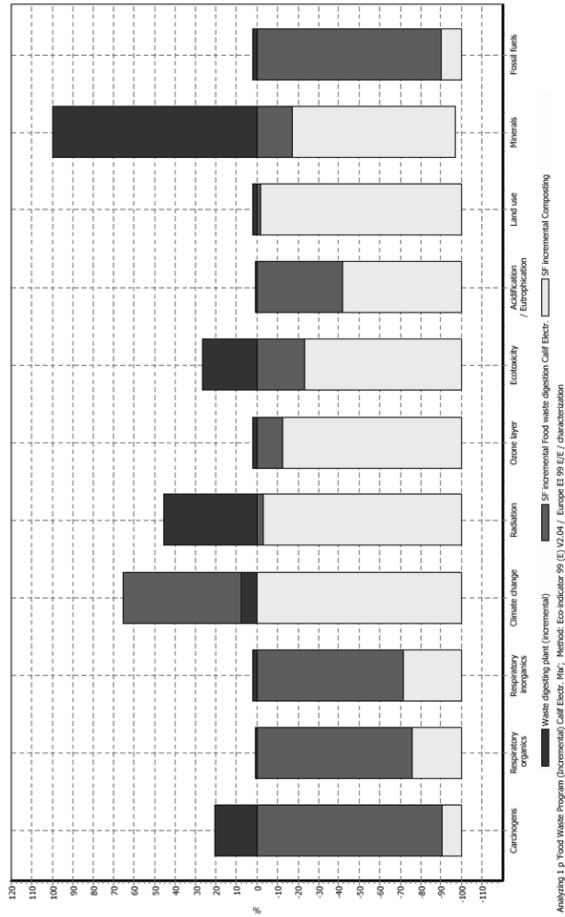
Fig 3. Midpoint characterization of environmental impacts

detail, an impact tree was constructed for the climate change category, similar in form to the single-score impact tree but specifically addressing the contributions to climate change (Fig. 4). Climate change benefits are due to avoided electricity generation and operation of the composting plant. Avoided transportation of solid waste from San Francisco to the composting facility has a minor impact. While the overall project impact on climate change is beneficial (negative scores), the operation of waste digester actually has a detrimental impact on climate change (positive score in the middle box). This detrimental impact is caused by generation and combustion of digester gas. During the combustion process (to make heat and electricity) methane is converted to carbon dioxide and water. Together with these

combustion products are released to the atmosphere and accounted by LCA as contributing factors to climate change. In essence, food waste is treated as a fuel converted to digester gas and ultimately to electricity, heat and greenhouse gases emissions. These emissions are only partially offset by avoided electricity and heat generation since the energy generation efficiency in the digestion process is lower than in power facilities. These results are due to particular boundary conditions in our LCA. We treated food waste as an input to the system and we did not consider
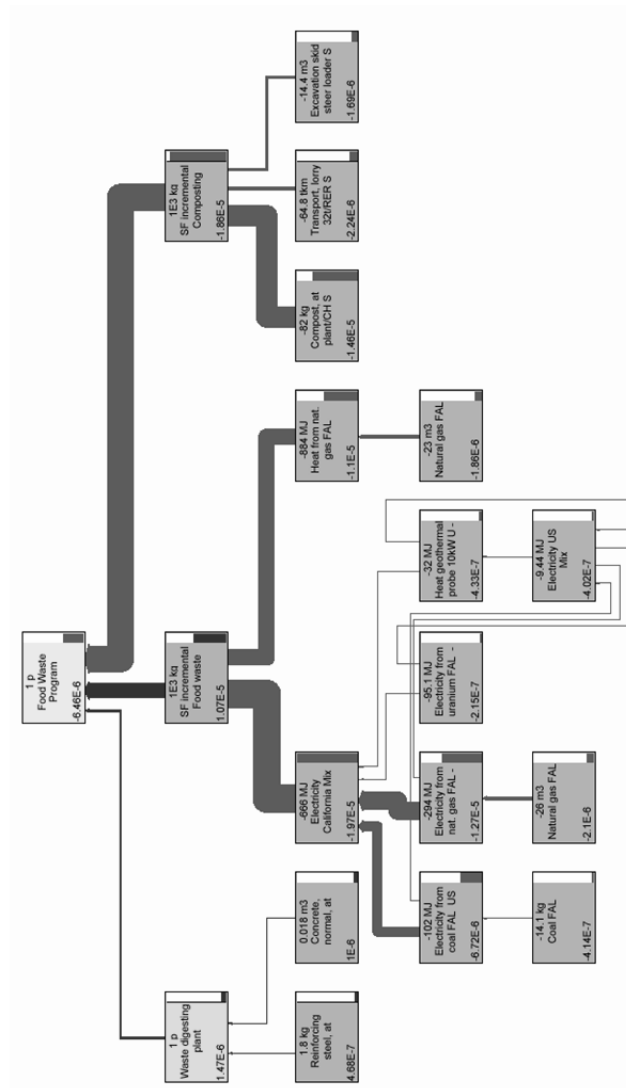
Fig. 4. Impact tree for global climate change

any impacts of food production, processing and consumption. Since food is produced directly or indirectly from plants it contains carbon dioxide sequestered from the atmosphere. During the digestion and combustion processes this carbon dioxide is released back to the atmosphere.

4   Conclusions

An incremental approach to the life cycle analysis technique has been suggested to assess the environmental impact of anaerobic digestion and biogas utilization facilities in the organic solid waste management scheme for San Francisco. The approach allows for simpler modeling, better defined system boundaries and less demanding for data than a classical separate comparison of two alternatives. Furthermore, the incremental approach is relevant when the goal is to assess the environmental soundness of constructing supplementary facilities. The analysis shows a net beneficial impact of the proposed project with the majority of the benefits from energy recovery. However, this process may result in detrimental impacts on climate change although these impacts are partially an artifact of LCA and they warrant further study.

5   References

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