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Life Cycle Assessment of prospective MSW management based on integrated management planning in Campo Grande, Brazil

Priscila De Morais Lima [a,b,*], Fernanda Olivo [c], Paula Loureiro Paulo [d], Valdir Schalch [a], Ciprian Cimpan [b,*]

[a] Department of Hydraulics Engineering and Sanitation (SHS), University of São Paulo, Av. Trabalhador São Carlense, 400 São Carlos, SP CEP 13566-590, Brazil
[b] SDU Life Cycle Engineering, University of Southern Denmark, Campusvej 55, 5230 Odense M, Denmark
[c] Deméter Engenharia (DMTR), Rua Cláudia, 239 Campo Grande, MS CEP 79022-070, Brazil
[d] Faculty of Engineering, Architecture and Urbanism and Geography, Federal University of Mato Grosso do Sul, Campo Grande, MS 79070-900, Brazil

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ABSTRACT

A crucial first step in transforming problematic waste management into sustainable integrated systems is comprehensive planning and analysis of environmental and socio-economic effects. The work presented here is a Life Cycle Assessment (LCA) that addressed the environmental performance of prospective development pathways for the municipal solid waste (MSW) management system in a large urban area, i.e. Campo Grande, Brazil. The research built on data and expanded the main development pathway proposed in the municipalities integrated waste management plan, which covers a period of 20 years (2017–2037). The system progression was assessed for milestone years (5-year intervals) considering projections of future population and waste generation growth, as well as addressing the development of surrounding systems, such as energy production. Results reveal that the rather conservative planned development pathway, which is largely based on gradual increase in selective collection, could successfully counter negative environmental externalities that would otherwise materialize due to increasing waste generation. A second, more ambitious, pathway with additionally scheduled actions to treat mixed MSW and upgrade certain treatment technologies (e.g. from composting to anaerobic digestion of collected organics), was used to illustrate a potential range for significantly higher impact reduction and even positive externalities, given a zero burden approach before waste generation.

1. Introduction

Brazil is the world's fifth most populated and fifth largest country by land area. As a country still in the course of joining advanced industrialized economies, Brazil faces substantial challenges with regard to current and future solid waste management (Alfaia et al., 2017). In 2016, Brazil generated 78.3 million tonnes of MSW (ABRELPE, 2017). Collection coverage still hovers around 90%, while 40% of collected MSW is disposed of in unsanitary conditions (ABRELPE, 2017). Recycling and biological treatment make up together less than 5% of MSW management. These national figures indicate environmental, social and economic missed opportunities and come into contrast with the fact that Brazil has both a comprehensive national solid waste management policy and a national climate policy.

The National Solid Waste Policy (PNRS – Federal law no. 12305) adopted in 2010, established general principles and objectives for Brazil, such as elimination of open dumps, the increase of selective collection and reverse logistics coverage and the inclusion of waste pickers in strategic planning (with incentives to formalize the activity through cooperatives) (Brasil, 2010). Although ambitious, the PNRS lacks comprehensive quantitative goals (targets) and transfers the responsibility for achieving objectives to municipal authorities. This aspect combined with a general difficulty in Brazil to integrate politically and administratively the different levels of government, especially the national and local level, has been identified by some authors as a main reason for the failure of the PNRS implementation to date (Maiello et al., 2018). One of the main requirements of the PNRS is the elaboration, by all municipalities, of integrated Municipal Solid Waste (MSW) management plans that include system planning, future management actions and targets for reduction, reuse and recycling of waste. Brazil has also a National Policy on Climate Change (PNMC) and is part of the Paris agreement, with a pledge to reduce Greenhouse Gas (GHG) emissions by 37% compared to 2005 levels (Brasil, 2008; Lin, 2017).

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* Corresponding authors at: Campusvej 55, 5230 Odense M, Denmark.
E-mail addresses: pri.lima.91@gmail.com (P. De Morais Lima), cic@kbm.sdu.dk (C. Cimpan).

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Waste is estimated responsible for 4% of the total GHG emissions accounted in the national inventory (Observatório do Clima, 2018). However, recent development in GHG emissions shows that the country is moving further away from the targets (Climate Analytics et al., 2018; Observatório do Clima, 2018).

Campo Grande, the state capital of Mato Grosso do Sul, located in west central Brazil, first adopted an integrated waste management plan in 2008, which was updated with a comprehensive implementation plan published in 2017 (PMCG and DMTR, 2017). Campo Grande is an urban centre with a total population of 874,000 inhabitants and an average waste generation of about 270,000 t year^{-1} (IBGE, 2017). MSW management here has been undergoing significant changes in the last few years. In 2012, both a new sanitary landfill was opened and the city formally implemented selective collection of dry recyclable materials. Informal waste pickers have self-organized in seven cooperatives, four of which operate a sorting unit for the selective collection since 2015. By formal agreement with the municipal authorities, they are responsible for sorting, selling and packing all the recyclables received at the sorting unit.

The work presented herein reports an environmental assessment of the current and prospective development pathways for MSW management in Campo Grande. The research expanded the main development pathway presented in the municipalities' updated waste plan, which covers a period of 20 years, between 2017 and 2037. Comprehensive environmental assessment studies addressing complete waste management systems in Brazil are still few, although increasing in number following the adoption of the PNRS. Data availability remains a barrier to Life Cycle Assessment (LCA) studies, e.g. lack of access to or missing data on waste management, as well as a lack of geographically-relevant Life Cycle Inventories (LCI) in mainstream (LCA) databases and assessment tools (Ibáñez-Forés et al., 2017).

Previous LCAs have addressed different treatment possibilities for specific MSW streams in Brazil, such as mixed waste (Leme et al., 2014; Lima et al., 2018; Mendes et al., 2004; Soares, 2017), as well as biodegradable and recyclable streams (e.g. Bernstad Saraiva et al., 2017; Lima et al., 2018). These studies show that the prevalent current practice of landfilling of mixed waste has high environmental impact compared to waste incineration and Mechanical Biological Treatment (MBT). However, waste incineration with recovery of electricity does not perform much better than sanitary landfilling with gas valorization, due to the low impact of avoided electricity production, which in the case of Brazil is largely from renewable sources. A growing number of studies address partial (e.g. Liikanen et al., 2018) or full management systems that compare largely theoretical system scenarios (Goulart Coelho and Lange, 2018; Mersoni and Reichert, 2017; Reichert and Mendes, 2014) to the current management in different municipalities. Many of these case studies refer geographically to the populous southeast Brazil (e.g. São Paulo). Most studies agree, finding that selective collection, recycling and biological treatment of organic waste should be prioritized, while MBT with production of refuse-derived fuel (RDF) is indicated as advantageous for the treatment of remaining mixed waste. The recent publication by Ibáñez-Forés et al. (2017), is distinct because it presented the evolution of a MSW system (in João Pessoa, Brazil) and its environmental performance, retrospectively between 2005 and 2015.

The objective of the present study was to evaluate the environmental performance of planned development in the municipality, and also to explore more broadly potential effects of additional ambitious actions towards sustainable waste management. The assessment work is unique for Brazil because: (1) it builds on extensive primary data and analyses undertaken for elaboration of the integrated management plan in Campo Grande, and (2) it assesses prospective system development in a large urban area, including both projections of future population and waste generation growth, as well as addressing the development of surrounding systems, such as energy production.

2. Materials and methods

2.1. Study area and reference data

In 2017 the municipal authorities of Campo Grande published the Plan of Selective Collection (PCS – Plano de Coleta Seletiva in portuguese), a detailed implementation plan for the integrated waste management plan adopted several years previous. The PCS was prepared over a period of two years and addressed all major waste streams generated in the municipality: MSW (household and similar commercial/institutional), construction and demolition waste, bulky waste and waste with mandatory reverse logistics (i.e. electronics, tires, batteries, lighting equipment and chemicals). The PCS consists of four comprehensive reports (volumes 1–4) containing (PMCG and DMTR, 2017): (1) a background analysis of the current waste management situation and relevant socioeconomic and environmental aspects; (2) projections for population and waste generation, and scenarios regarding separate collection; (3) detailed goals, projects and actions for the next 20 years; and (4) operationalization of the new systems, including detailed planning of infrastructure and costs of implementation. The PCS was additionally supported by a comprehensive physical characterization study for the MSW streams.

The present environmental assessment was elaborated based on data produced for the PCS. However, the study focused solely on the MSW streams, mainly due to the large level of detail in the PCS and the availability of physical characterization data. Nevertheless, here a number of updates were made to the original PCS projections, as well as a further specification of different MSW streams in the municipality, as it will be described in the following sections. This involved processing additional data provided by SOLURB (the company in charge of the operation of the current waste management system) and from Deméter Engenharia (DMTR - the consultancy that was responsible to elaborating the PCS).

In the PCS, the urban perimeter of Campo Grande was divided into four socio-economic sectors, which were used for the subsequent characterization of waste and planning. The division considered different factors, namely population density, monthly income, literacy rate and total population size. All urban areas of the city obtained weighted scores between 0 and 10 and were classified into the four sectors with a high spatial resolution (see Fig. 1). The sector "until 2.5" represented the lowest scores, therefore the least developed areas in the city, the sectors "from 2.51 to 5" and "from 5.1 to 7.5" represented the intermediate sectors, while the "from 7.51 to 10" denoted the most developed and affluent areas, located mostly in the city centre.

2.1.1. Gravimetric compositions and waste generation rates

In Campo Grande, MSW is collected in three ways: (1) mixed waste collection covering the entire municipality (termed regular collection), (2) door-to-door selective collection for mixed recyclables, and (3) a number of voluntary drop-off points (termed ecopoints). The physical characterization study performed by DMTR, covered all three schemes. In the supplementary material (SM) file the description of the methodology can be found as well as the sector-wise gravimetric compositions (Tables S1 and S2).

However, the waste characterization study performed by DMTR did not cover some of the waste streams that were included in the present environmental assessment. We further distinguished several MSW streams in the municipality based on the quantity (per year) estimates provided by DMTR and SOLURB, namely waste

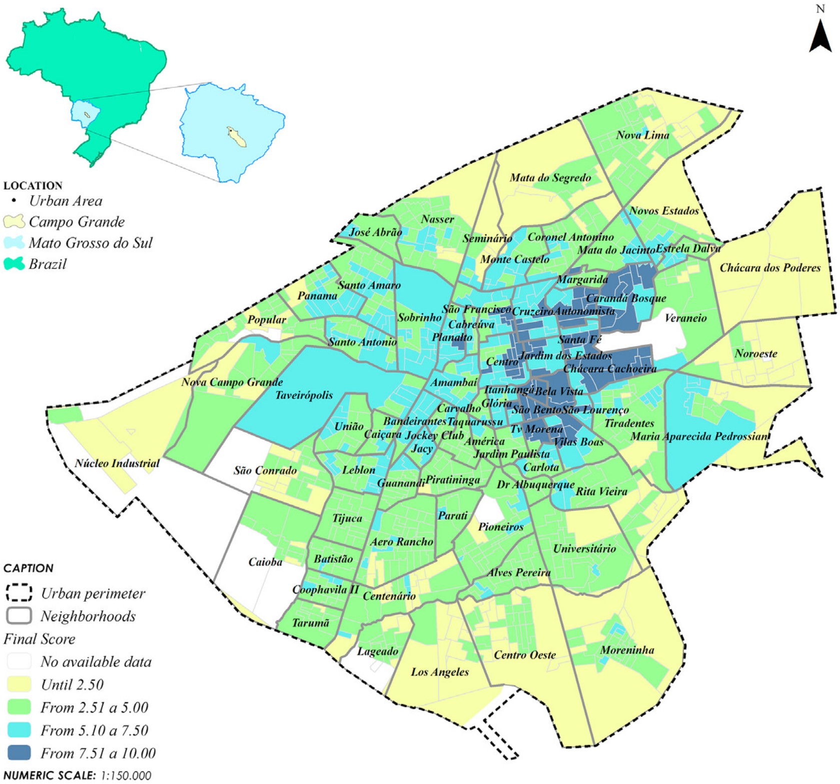

Fig. 1. Socio-economic sectors by scores in the urban perimeter of the municipality. Source: DMTR, 2018.

from street cleaning, parks and markets. These streams are currently collected with other regular mixed MSW and landfilled (PMCG and DMTR, 2017). The possible composition for biowaste, a stream that is not separately collected today, was adapted from Naroznova et al. (2016) considering a much higher rate of miss-sorting by households (i.e. 35% unwanted materials in biowaste). For waste from street cleaning, parks and markets, the gravimetric compositions were compiled, considering local conditions, from Boldrin & Christensen (2010), Das Neves & Tucci (2011), de Oliveira (2012) and Vaz et al. (2003), due to the lack of onsite data. Table 1 shows a summary of the waste stream compositions used in this work, while for the detailed waste fractions employed in the modelling the reader is directed to the Table S3 in the SM file.

Per capita household MSW generation rates in the four socio-economic sectors were elaborated for the PCS by Manzi (2017), who considered the concurrent evolution of collected waste amounts and population in representative areas in the four socio-economic sectors over a number of previous years (Manzi, 2017). Fig. 2 shows the per capita generation in each one of the sectors obtained by Manzi (2017).

2.1.2. Projections of future population, waste generation and separate collection

The PCS was framed by potential growth in waste generation in the 20 years period covered, as a result of both population and economic growth. Population increase was projected in the planning phase based on simple linear regression, using census data between 2000 and 2010, resulting in a 30% increase over the whole period (PMCG and DMTR, 2017). Projection for all MSW streams were made by applying a consistent growth rate of 0.5% per year to the per capita generation rates and combining that with the population projection over the period, which led to a 44% increase in total waste production over the period. In terms of waste

Table 1
Summary of gravimetric compositions for the waste streams included in this work; given in percentage wet weight.

Waste category	Regular mixed waste [wt.%]	Door-to-door selective [wt.%]	Ecopoints [wt.%]	Biowaste [wt. %]	Street [wt.%]	Markets [wt.%]	Parks [wt.%]
Paper	2.44	9.78	7.91	0.71	2.23	–	–
Multilayer packaging	0.99	3.72	1.84	3.51	0.30	–	–
Cardboard	9.21	18.75	41.33	2.05	6.77	–	–
Metals	0.92	4.44	2.12	0.64	0.60	–	–
Glass	2.61	16.10	21.05	0.32	1.24	–	–
Plastics	20.80	23.71	17.10	7.98	9.69	15.80	–
Organic	46.63	0.81	–	65.02	19.26	84.20	99.60
Other combustibles	11.45	1.35	–	2.55	1.50	–	–
Other non-combustibles	4.89	21.34	8.65	17.21	58.41	–	0.40
Hazardous	0.06	–	–	–	–	–	–
Total	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**

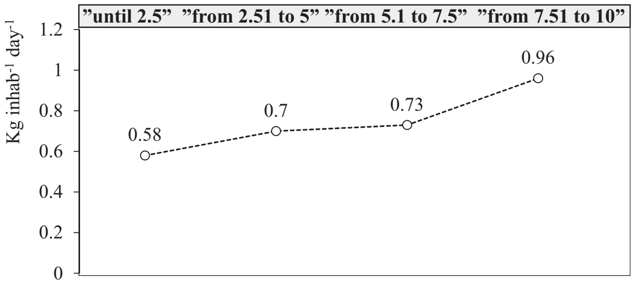

Fig. 2. Waste generation per capita for the different sectors in Campo Grande. Source: Adapted from Manzi (2017).

compositions, it was assumed that the overall composition of the waste would not change significantly over the period.

In the present study, we maintained the underlying projections in the PCS, however, we corrected the starting point with newly available data, i.e. the total MSW generated in 2017 (271,267 t). Furthermore, the baseline (or starting quantity of) MSW streams in 2017 were elaborated with the following approach. First, the mixed waste (regular collection) from households was calculated using the generation rates per capita in the four sectors and their respective population, resulting in a total of 222,671 t. Next, total MSW originating at the households was determined by adding any selective collection streams to the previous amount, resulting in 229,923 t. The remaining difference to the total MSW generated in 2017, was then assumed to account for other MSW streams. Street cleaning, parks and markets totalled 13,379 t in 2017. The remaining difference, 27,966 t, was then assigned as MSW generated by services, commerce and institutions in the municipality. Once the 2017 baseline was established, the projection of future waste generation was performed as described above, i.e. with a consistent growth rate for all streams. The baseline amounts are presented in the 2017 column of Table 2.

Regarding the future development of waste management in Campo Grande, the PCS constructed a comprehensive scenario revolving around the gradual expansion (in coverage and public participation) of separate collection. More specifically, this addressed collection of mixed recyclable materials in the door-to-door selective scheme, expansion of the drop-off collection points (ecopoints) and a new scheme called "spiral collection" which will cover the less developed urban areas. The latter will be operated as a door-to-door scheme directly by three cooperatives of waste pickers (COOPERNOVA, COOPERSOL and COOPERVIDA). Lastly, a separate biowaste (food waste) stream was planned from 2028 onwards, which would be destined for a composting plant. The amounts projected for these separate streams were calculated by maintaining the PCS goals and are summarized in Table 2 for the milestone years and detailed in Tables S6 and S7 in the SM file. Essentially, these projections account for the gradual increase of the separated streams of recyclables from 7.5% of the total potential (generated recyclable fractions in MSW) in 2017 to 32% in 2037. For biowaste, it was assumed that the separate stream would grow linearly from 1% of the potential organic fraction in MSW in 2028 up to 30% in 2037 (parks and markets not included).

2.2. LCA methodology

The **goal** of the study was to: (1) assess the environmental performance of different pathways for the development of MSW management in Campo Grande, and (2) to identify the contribution of different system components and waste treatment options to the overall impacts. As recommended by the European Commission (EC-JRC, 2011), the potential effects of prospective changes to the large-scale waste management systems addressed in this work were evaluated through the framework of consequential LCA. This implies system expansion in the case of multi-functionality (e.g. with substitution of by-products) and the use of marginal LCI data (as opposed to average data).

The **scope definition** includes the generation-based **functional unit (FU)** representing: the management of the total MSW generated in Campo Grande on a yearly basis between 2017 and 2037, with the quantities presented in Table 2 and compositions in Table 1. System models were elaborated in Easetech for milestone years: 2017, 2022, 2027, 2032 and 2037. The reference flow MSW should be understood as the total generated household waste and similar from small businesses, commerce and institutions, street sweeping, parks and markets. The **system boundaries** in this study were defined as the sum of foreground and background systems (Clift et al., 2000; EC-JRC, 2011). The foreground system comprised all waste management activities from waste generation, through treatment and recovery of materials and/or energy, while the background systems represent the surrounding economic activities (e.g. energy production, material production and related markets) that exchange flows with the waste systems. The temporal scope is 20 years, while the technological scope refers to existing waste management practices and treatment technologies. LCI process data is described in Section 2.4 and consisted of primary collected data from existing system operations in 2017 complemented with literature data where information was missing, while additional scenario-based treatment options were modelled with data elaborated in Lima et al. (2018).

The models and **impact assessment** were executed in Easetech, a software developed specifically for waste management LCA (Clavreul et al., 2014). The impact assessment was performed with the International Reference Life Cycle Data System (ILCD) recommended method (EC-JRC, 2010), considering 12 mid-point impact categories and global normalization factors shown in the SM

Table 2
Summary waste generation in tonnes per year for the milestone years, and related urban population.

	2017	2022	2027	2032	2037
Population (urban)	857,808	922,011	986,216	1,050,420	1,114,625
MSW Waste streams					
Household waste (HHW)	229,922.6	253,371.6	277,858.8	303,420.9	330,097.0
Regular collection (mixed waste)	*222,671.1*	*233,220.4*	*247,918.6*	*232,208.9*	*234,728.6*
Door to door selective	*6,692.9*	*18,417.8*	*27,445.2*	*35,289.5*	*41,073.8*
Ecopoints selective	*558.5*	*1,733.4*	*2,495.0*	*3,113.8*	*3,952.12*
Biowaste selective	–	–	–	*32,808.7*	*50,342.4*
Commercial and institutional	27,965.9	30,818.0	33,796.5	36,905.6	40,150.3
Street cleaning	5,028.7	5,541.5	6,077.1	6,636.2	7,219.6
Parks	7,754.4	8,545.2	9,371.1	10,233.2	11,132.9
Markets	595.6	656.3	719.7	785.9	855.0
Total MSW	**271,267**	**298,933**	**327,823**	**357,982**	**389,455**

Table 3
Summary of the main foreground scenarios and variations, in the different milestone years.

Series	Year	System scenario	Scenario variations
a series – Planned development	2017	- Dry separate collection sorted in an MRF and mixed waste (incl. street, parks and market waste) sanitary landfilling without gas valorization.	a(e) sanitary landfill with gas valorization
	2022 and 2027	- Dry separate collection sorted in an MRF and mixed waste (incl. street, parks and market waste) sanitary landfilling **with** gas valorization; parks and market waste **composting**.	
	2032 and 2037	- Dry separate collection sorted in an MRF and mixed waste (incl. street, parks and market waste) sanitary landfilling with gas valorization; waste from parks, markets and **biowaste is composted**.	a(-o) without selective biowaste collection
b series – Planned development + mixed waste treatment	2017	- Dry separate collection sorted in an MRF and mixed waste sanitary landfilling with gas valorization; parks and markets **composting**.	
	2022 and 2027	- Dry separate collection sorted in an MRF and **partial** (100.000 t) mixed waste in advanced anaerobic–aerobic MBT (incl. material recovery); parks and markets composting.	b(i) RDF to dedicated WtE
	2032 and 2037	- Dry separate collection sorted in an MRF and mixed waste is **extended** (200.000 t) in advanced anaerobic-aerobic MBTs (incl. material recovery); parks composting; and markets and **biowaste anaerobic digestion**.	b(u) biogas upgraded and used as vehicle fuel b(-o) without selective biowaste collection b(i) RDF to dedicated WtE

(Sala et al., 2017). In the Climate Change impact category (measured as Global Warming Potential (GWP)), CO_2 that is biogenic in origin was considered climate neutral and biogenic carbon that was not emitted within 100 years was considered stored (and accounted as an avoided impact). The **sensitivity** of the LCA results to various uncertainty sources was addressed by contribution analysis and scenario analysis (Bakas et al., 2018). A contribution analysis decomposes the results into process contributions, providing a quick overview of the important contributors. The scenario analysis was performed by considering different technology choices at different points in the systems assessed (described in Table 3).

2.3. Scenarios for future development of MSW management

2.3.1. Development of foreground systems

This study assessed two different but complementary development pathways for MSW management in Campo Grande. The first, noted as the "a series", starts from the current practices in 2017 and follows the planned development until 2037, broadly in line with the PCS (described in Section 2.1.2). The second, noted as the "b series", comprises of additional treatment alternatives to the "a series". Essentially, the b series does not change separate collection goals, but adds additional or different treatment perspectives for the collected streams. The main are MBT for mixed waste from regular collection, and Anaerobic Digestion (AD) for the separate biowaste stream and waste from markets. The chosen technologies were a selection of best performing options evaluated previously in Lima et al. (2018). Table 3 presents the two foreground series highlighting the main waste treatment developments. Both series have a main system scenario and several scenario variations, such as for the a series: a(e) denoting a variation with energy recovery from landfill gas vs. gas flaring; and for the b series: b(i) denoting a variation where RDF in incinerated in a dedicated Waste-to-Energy (WtE) plant vs. use in cement production (main scenario), and b(u) biogas upgrading vs. direct electricity production (main scenario). A variation lacking separate collection of organic waste is used in both series, denoted by a(-o).

2.3.2. Development of background systems

The main background system considered in this study was the electricity production system affecting both system consumption and substitution of waste-recovered energy. The identification of marginal electricity suppliers was based on the method developed by Schmidt et al. (2011), whereby long-term marginal technologies are defined as the technologies that display higher investment rates compared to their capital replacement rate over a given period of time. Essentially the method finds marginal electricity mixes for a given year, by a weighted average of the technologies that have increased their production from the previous reference year. The overall evolution of electricity generation in Brazil was given by the baseline projections made by International Energy Agency - IEA (2013), illustrated in Fig. 3 (left). The calculated marginal electricity mixes for 2017, 2022, 2027, 2032 and 2037 are presented in Fig. 4 (right side). The technology processes were

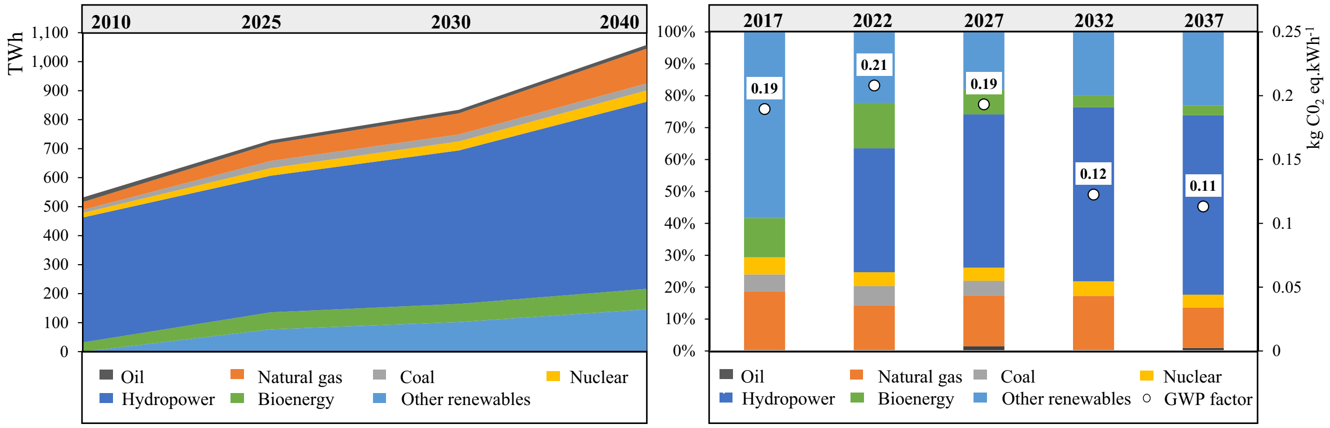

Fig. 3. Electricity generation projection for Brazil according to IEA (2013) and marginal electricity mix for each milestone year with corresponding GWP factors. Note: for the colored version of this figure, please see the online version.

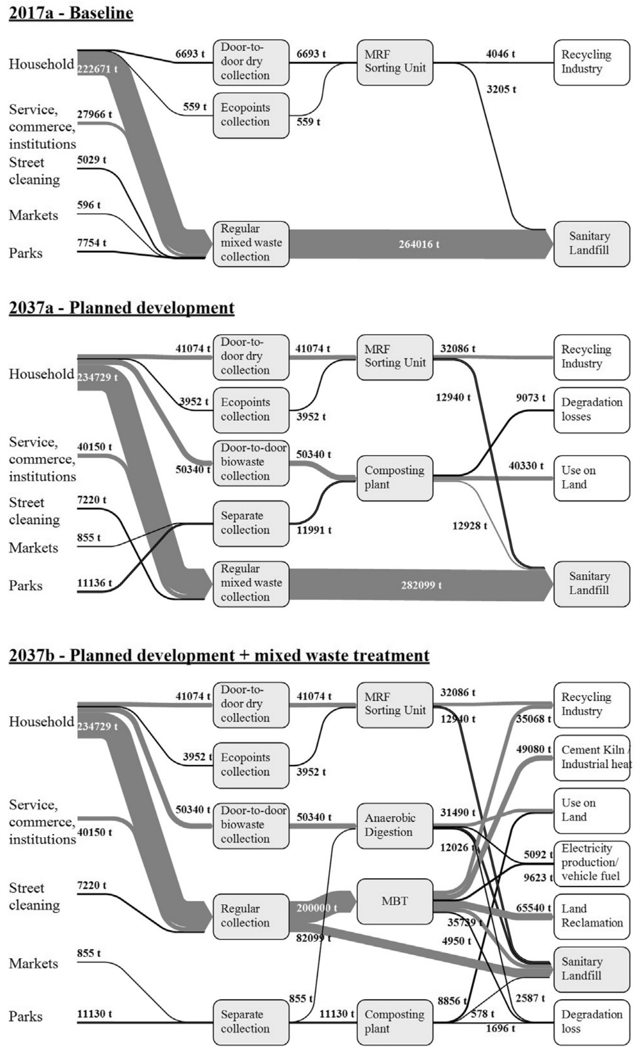

Fig. 4. Sankey diagram with the MSW flows for 2017 (current system) and 2037 (both development scenarios).

imported from the ecoinvent 3 database (Wernet et al., 2016) and described in the SM file.

Other background systems defined in the study address:

- RDF utilization in the industry: (1) cement production - RDF substitutes for use of petroleum coke, production and combustions was modelled as in Lima et al. (2018); (2) industrial heat by dedicated Waste-to-Energy (WtE) plant – RDF was assumed to substitute heat or steam from natural gas boilers. The latter assumption was based on the long-term increase of natural gas in industry, as projected by the IEA.
- Recycled materials were assumed to avoid primary production for the same material. Recycling processes were modelled based on existing literature due to the lack of LCI data of recycling systems from Brazil. However, electricity consumption was changed to the marginals developed in this work. All processes were assumed constant for the 20-year prospective period. Recycling process efficiency and substitution ratios for primary production (Rigamonti et al., 2010) are detailed in the SM file (Table S12).
- Stabilized digestate and compost from biological treatment that is applied on agricultural soils, was assumed to substitute production and use of mineral fertilizers, as detailed in Lima et al. (2018). When upgraded, biogas from AD is assumed utilized as vehicle fuel in large commercial vehicles (e.g. buses and trucks), thereby displacing diesel.

2.4. Life Cycle inventories (LCIs) of collection and treatment processes

2.4.1. Collection and transportation

Consumption of diesel during collection was provided by SOLURB, for currently running regular mixed waste (4.3 L t^{-1}) and selective waste collection (11.3 L t^{-1}). Waste collection accounted for route collection and transport to the first handling facility and was modelled with regular (rear-loading) trucks of 10 t capacity for both types of collection. Transportation from the first handling facility to a final processing was accounted for all streams sorted for recycling, as well as for residues from sorting, composting and digestion processes to the local landfill, and RDF transport to industrial facilities. Transport was modelled with long-haul trucks of 25 t capacity for streams for recycling and RDF and trucks of 10 t for residues. Diesel consumption was 0.03 L t^{-1} times the distance for long-haul and 0.06 L t^{-1} times the distance for the smaller trucks (Bassi et al., 2017). MRFs, MBTs, composting and AD sites were considered placed close to the landfill site, therefore a 5 km distance was considered for residues transport. The destinations for recycling processes were taken from the PCS and are summarized in Table 4.

2.4.2. Sanitary landfill

Two types of sanitary landfill were modelled, i.e. without and with energy recovery from captured landfill gas. On the current landfill, Dom Antonio Barbosa II, landfill gas is flared. However, considering the short remaining lifetime of 2 years, a future extension or new landfill was assumed to include landfill gas utilization.

The landfill modules in Easetech were adapted to reflect Brazilian climate settings by changing a number of parameters (e.g. annual average temperature, precipitation, decay rates). All settings were described in Lima et al. (2018). Compared to this previous work, only the depth of the landfill was modified to 5 m, as provided by SOLURB.

Table 4
Destination and transport distance for treatment outputs.

Process outputs	Municipality	State	Distance (km)
Paper/Juice cartons/PET	Itabira	Minas Gerais	1374
Cardboard/Fe-metal	Campo Grande	Mato Grosso do Sul	50
PE/PP	São José dos Campos	São Paulo	1090
LDPE	Itabira	Minas Gerais	1374
Glass	Porto Ferreira	São Paulo	855
Al-metal	São Paulo	São Paulo	1009
Compost/Digestate	Campo Grande	Mato Grosso do Sul	10
RDF to industry	–	–	400
Residues to landfill	Campo Grande	Mato Grosso do Sul	5

2.4.3. Material recovery facility (MRF)

This MRF is managed by four of the seven cooperatives of waste pickers in Campo Grande (COOPERMARA, ATMARAS, CATA-MS and Novo Horizonte). The MRF is based mainly on manual picking (around 100 workers) assisted by basic equipment such as conveyor belts and balers. The combined yield for recovered materials represents around 55% of the waste input. In the prospective scenarios, the MRF overall efficiency was increased to 58% (2022), 63% (2027), 66% (2032) and 70% (2037), as projected in the PCS. The efficiency changes account for increased recovery of specific materials as well as the addition of glass, which is not recovered in 2017. The transfer coefficients employed for each fraction and each year are presented in the SM. Consumption of electricity (15 kWh t^{-1}), diesel (0.7 L t^{-1}) and steel wire for bales (0.85 kg t^{-1}) were included in the process LCI (Cimpan et al., 2016, 2015).

2.4.4. Mechanical biological treatment (MBT)

MBT for mixed MSW was modelled with the template developed for advanced plants in Lima et al. (2018). The facilities consist of (1) a mechanical processing section which includes the splitting of the incoming mixed stream into wet and dry components, followed by sorting of recyclables from the dry portion with a combination of mechanical and manual sorting; and (2) a biological treatment section, which consists of dry AD followed by a stabilization of digestion residues by composting. The dry waste that remains after the sorting process is size reduced by shredding and designated as RDF. Two destinations were considered for the RDF, namely cement production facilities and dedicated WtE facilities attached to industries. The latter process was modelled with an adapted regular WtE process template, accounting for heat-only production with a boiler efficiency of 90%. The stabilized digestion residues were assumed to be used for land reclamation purposes, namely landfill cover, due to the amount of possible contaminants.

2.4.5. Biological treatment of selective streams

Composting of waste from markets and parks was modelled based on enclosed windrows composting. Physical contamination is separated in the process and sent to the landfill, while the compost output was assumed to be used as soil amendment. Biowaste which begins to be collected in 2028, is treated by dry AD, technologically based on gas-proof box-shaped reactors, operated in batch mode at mesophilic temperatures. Digestion residues are stabilized, refined similarly to compost and used as soil amendment. Details on both composting and digestion processes can be found in Lima et al. (2018).

3. Results

3.1. Waste flows and recycling over the study period

According to the projection adopted in the plan of selective collection of Campo Grande, in the period between 2017 and 2037, population and MSW generation are expected to increase by 30% and 44%, respectively. Fig. 4 illustrates through Sankey diagrams the MSW flows from generation to final treatment or disposal, for the current system (2017) and for the potential systems in the end milestone year (2037). The latter are determined by the two development pathways assessed in this work. Fig. 5 presents the progression of system efficiency over the 20-year period, by marking recycling rates as percentage of total generated waste. The recycling rates include both material recycling (counted by mass going to the recycling process) and biological treatment of biowaste that is separately collected (counted as mass collected).

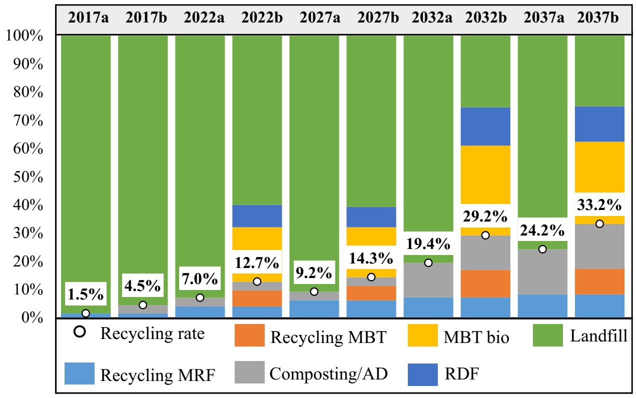

Fig. 5. Recycling rates achieved from 2017 to 2037. Note: for the colored version of this figure, please see the online version.

Both figures portray the rather dismal state of recycling today, whereby more that 98% of MSW ends up in the landfill. According to the planned development in the PCS (a series), the percentage of waste mass directly landfilled should decrease to around 73% by 2037. The inclusion of residual streams from treatment brings this percentage up to 79%. In the alternative system scenario (2037b), that includes treatment of mixed MSW from regular collection by MBT, the total amount of waste that is sent to the landfill decreases to under 40%. This includes residual streams. A further 17% would constitute low quality compost that could be used to reclaim degraded land, or as daily, temporary or permanent cover for the landfill.

3.2. Life cycle impact assessment results

Fig. 6 shows the impact assessment normalization step results in net PE (Person Equivalents) per environmental impact category. The net represents the sum of environmental burdens and benefits, and thus a positive net denotes an overall impact while a negative one a net saving within a category. The main system scenario development series (a and b series described in Table 3), are illustrated connected by lines, while scenario variations are illustrated with points. Besides the two series, a business-as-usual (BaU) scenario was added, which illustrates results if the 2017 profile of management operations is maintained throughout the period. The results values in connection to Fig. 6 are given in Table S13 in the SM.

3.2.1. Evolution of impacts over the period

At a first glance, it can be observed that both development pathways lead to a decrease in environmental impact over time, in most impact categories. There are, however, exemptions that will be analysed in the following.

Net savings in the climate change category (as GWP) were not achieved in any of the “a series” scenarios, however the impacts decrease by 87% from 2017 to 2037, even though the waste generation amount is projected to increase by 44%. The relatively conservative separate collection and recycling goals in the planned development pathway of the PCS, lead to savings due to avoided materials production, but cannot compensate the impacts related to the large amount of waste that is still landfilled. The “b series” transitions to net climate savings already by 2022 and savings increase substantially by 2037. The gap between the two development pathways is explained by high savings due to the material recovery for recycling and utilization of RDF as substitution of coke in cement production, both associated with the MBT process. The

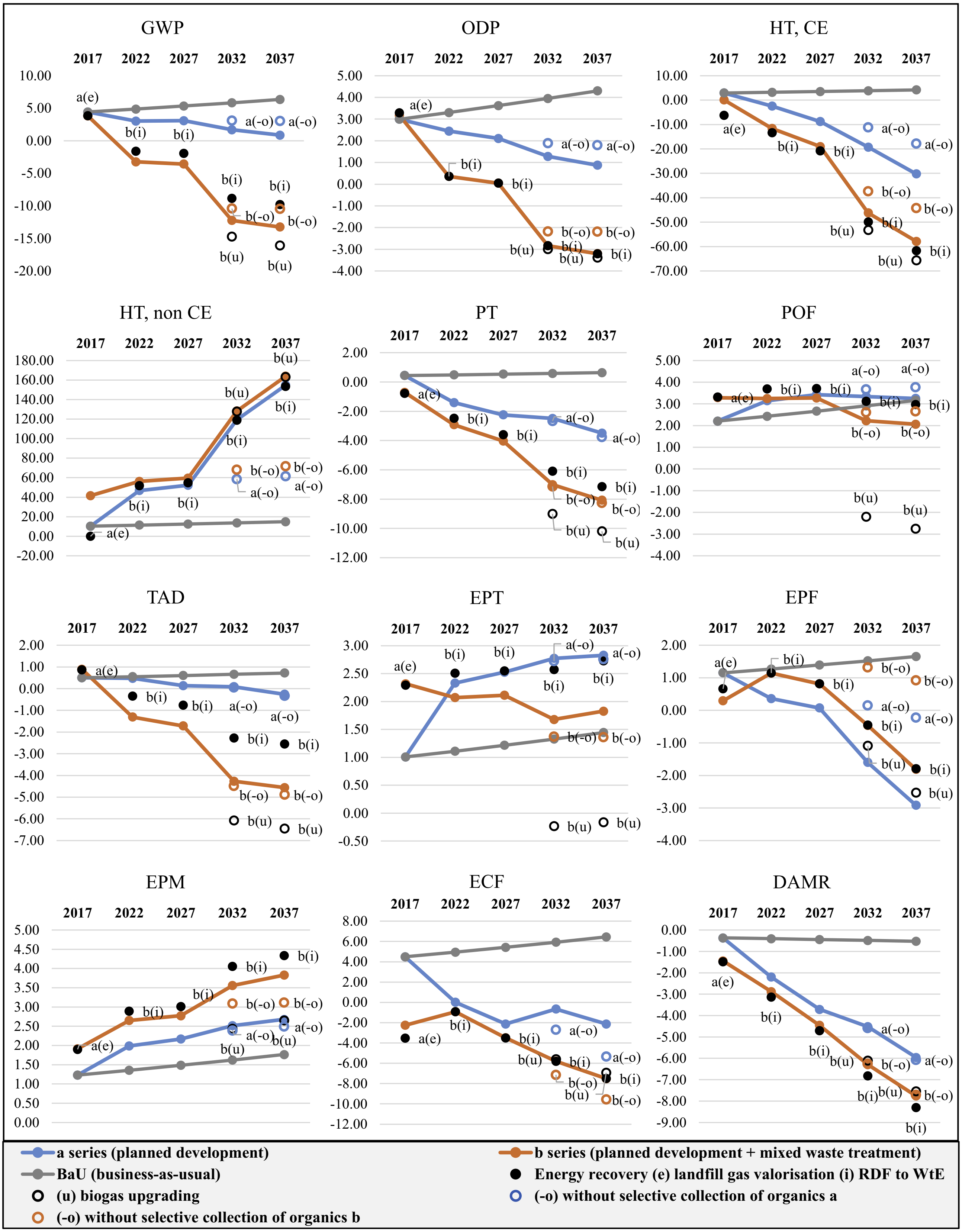

Fig. 6. Normalization step results (in 1000*PE) for: Climate Change (as GWP), Ozone Depletion (ODP), Human Toxicity, Cancer Effects (HT, CE), Human Toxicity, non Cancer Effects (HT, non CE), Particulate Matter (PT), Photochemical Ozone Formation (POF), Terrestrial Acidification (TAD), Eutrophication Terrestrial (EPT), Eutrophication Freshwater (EPF), Eutrophication Marine (EPM), Ecotoxicity Freshwater (ECF) and Depletion of Abiotic resources, Mineral fossil and Renewable (DAMR). Note: for the colored version of this figure, please see the online version.

development over the period observed for GWP, is similar for a number of other categories, namely Ozone Depletion (ODP), Human Toxicity, Cancer Effects (HT, CE), Particulate Matter (PT), Terrestrial Acidification (TAD) and Depletion of Abiotic resources, Mineral fossil and Renewable (DAMR).

In contrast, Human Toxicity, non Cancer Effects (HT, non CE) is an impact category where burdens increase substantially and similarly in both development pathways. This was tracked to the metals present in biowaste compost (such as zinc and lead), mainly originating in plastic products and other non-combustibles, but also present in fine fractions of park waste (e.g. leaves, grass). For Terrestrial Eutrophication (EPT) combustion processes (such as biogas combustion, collection and transportation) are the biggest contributors, mainly with NOx (Nitrogen oxides) emitted. The difference between the two development pathways and the better performance in the "b series" is due to reductions in the amount of waste that is directly landfilled. Burdens also increased in Marine Eutrophication (EPM) over time. This was connected largely to landfilling and waste collection processes. The impact is higher in the "b series" due to land reclamation using the compost-like output from MBT. The main contributing emissions are nitrate leaching to water and nitrogen oxides emissions from collection trucks to air. Lastly, burdens decreased in both development pathways with regard to Freshwater Eutrophication (EPF) but were consistently higher for the "b series". The processes determining this decrease were land reclamation using the compost-like output from MBT, and, rather surprisingly, recycling of LDPE plastics and cardboard. If compost-like output from MBT are applied solely as landfill cover, their potential for eutrophication is in reality expected to be minimal, due to onsite treatment of leachate and runoff from the landfill site.

3.2.2. Scenario variations

The immediate change from a sanitary landfill with gas flaring to a sanitary landfill with energy recovery, improved the performance of the existing waste management system (2017a(e)) in more than half of the assessed environmental impact categories. This included climate change (as GWP), Human Toxicity, Cancer Effects (HT, CE) and non-Cancer Effects (HT, non CE), Particulate Matter (PT), Freshwater Eutrophication (EPF), Freshwater Ecotoxicity (ECF) and Depletion of Abiotic resources, Mineral fossil and Renewable (DAMR).

The source separation of biodegradable waste, especially food waste, and it's treatment either by composting or AD, was shown to have a specific high importance for decreasing a large number of potential environmental impacts. The (-o) scenarios represent system variations where food waste from households is not separated, and therefore facilitate illustrating the significance of this system choice in Fig. 6.

The utilization of biogas from AD for electricity production did not result in significant savings due to the relative low burdens of marginal electricity production in Brazil over the period. Upgrading of biogas and utilization as vehicle fuel, showed significantly higher benefits especially in GWP, PT, Photochemical Ozone Formation (POF), Terrestrial Acidification (TAD) and Terrestrial Eutrophication (EPT). Except for GWP, benefits in the other categories are explained by large amounts of mainly NOx, SO_2 (Sulfur dioxide) and Nitrate (NO_{3-}) that are avoided.

3.3. Specific contributions to climate change

The characterization step results for all scenario variations are illustrated in Fig. 7, both in absolute scenario values and per tonne

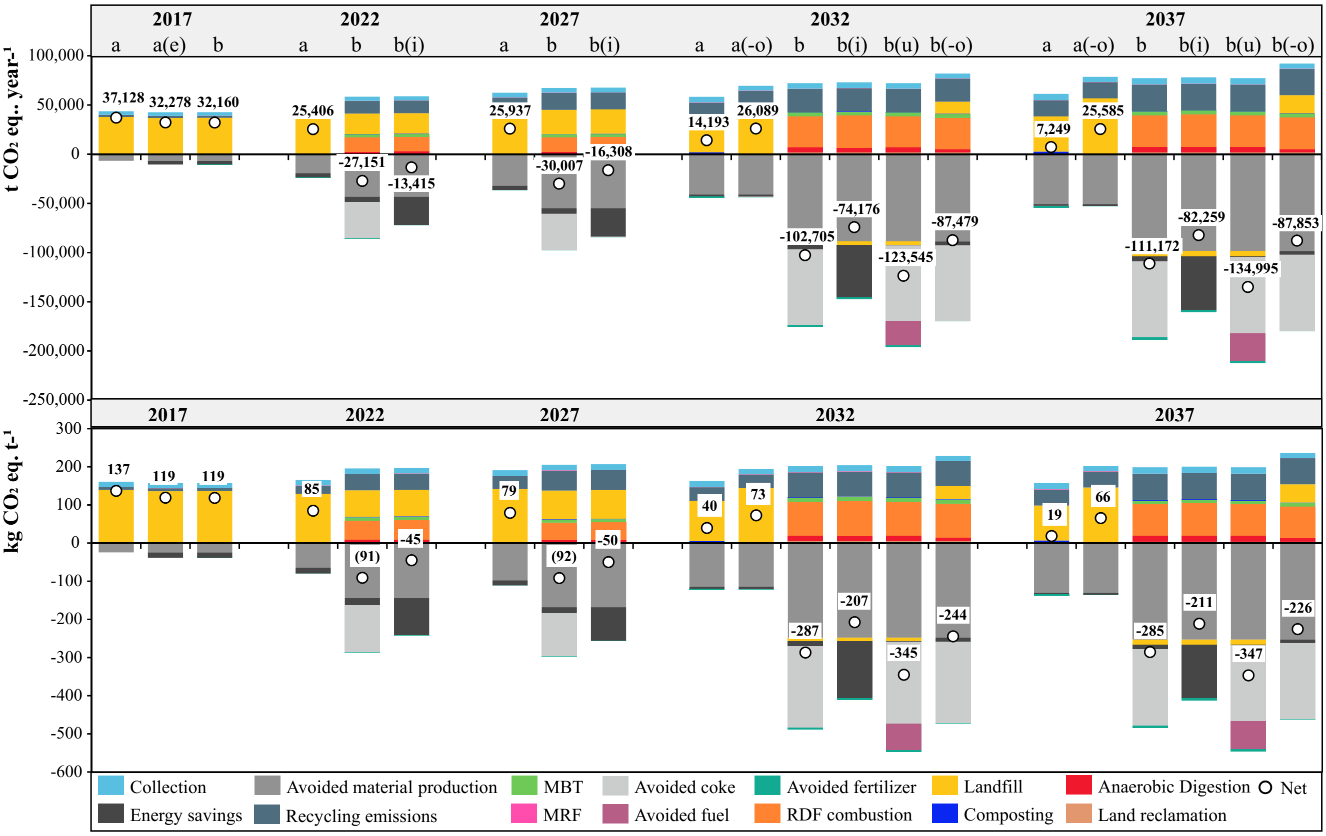

Fig. 7. Characterization step results for Climate Change (as GWP) in absolute values and per tonne of waste generated. Note: Collection represents the sum of emissions from regular and selective; Landfill represents the net of emissions minus carbon storage; Recycling represents the net of recycling emissions minus savings of primary production; Energy savings represents the sum of all energy saved in the system (e.g. from landfill gas and steam in the industry). Note 2: for the colored version of this figure, please see the online version.

of waste generated in the five milestone years. The result values can also be found in Tables S15 and S16 in the SM file.

Landfill GHG emissions remained the main contributor to climate burdens in all "a series" scenarios. In absolute terms, landfill emissions decrease only by around 5% between 2017a and 2037a. However, if biowaste would not be collected separately (2037a(-o)), there would be an overall increase in emissions by almost 50% over the same period (accounting for the increase of waste generated in the period). The results are more optimistic when accounting development of impacts per tonne of waste generated. Between 2017a and 2037a, GHG emissions decrease by 35%, while if biowaste would not be collected separately (2037a (-o)), there is only a small overall increase of 4%. A more interesting prospect is put forward by results from the "b series". With the installation of a second MBT, more than two thirds of mixed waste from regular collection are treated. When combined with the selective collection of biowaste (2032b, 2037b), this results in a drastic reduction of food waste going to the landfill, which in turn renders the overall net impact of landfilling to become negative (i.e. a saving). This is due to the presence of hardly degradable carbon in other waste than food waste, which will be stored in the landfill.

The upgrading of the current landfill (2017), from flaring of captured landfill gas to utilization for electricity production, would contribute with energy savings equivalent to 10% of the current landfill emissions. These savings are also equivalent to 50% of the climate savings brought by recycling and avoided materials production in 2017.

Collection represents in all scenarios 7–10% of the total climate burden and this remained constant over the period. However, in absolute terms the burden would almost double between 2017 and 2037. The long-distance transport of the RDF (400 km) contributes around 6% of the total climate change burden of the process (i.e. sum of transport and direct RDF combustion emissions). In the case of recycling processes, long-distance transport contributes in total between 18% and 22% of the total climate change burden of the processes. However, in categories like POF, TAD, EPT and EPM the contribution can be much higher, between 40% and 50%.

Composting of parks and markets waste, and later biowaste in the "a series", contributes with a net burden even after subtracting the savings brought by avoided mineral fertilizer. This net burden is quite small compared to emissions if this organic waste is instead landfilled. This can clearly be seen when comparing 2032a with 2032a(-o) and 2037a with 2037a(-o) in Fig. 7. Dry digestion, employed in the "b series" in both MBT and for biowaste, results in net savings, but these are relatively small (barely visible in Fig. 7) due to the low impact of background energy production in Brazil over the period. Biogas upgrading and utilization as vehicle fuel in large commercial vehicles (e.g. buses and trucks) results in much higher savings, if it avoids diesel use, as modelled in this study.

In the "a series", recycling and avoided material production accounts for the majority of climate benefits over the period, with energy savings connected to the landfill decreasing in share substantially (5% in 2037). Absolute savings due to recycling should triple between 2017a and 2022a and become seven times higher at the end of the period assessed. In the "b series" benefits connected to recycling double compared to the equivalent "a series" scenarios. Recycling emissions contributing to climate change, which account for long distance transport and actual materials reprocessing, are on average three times smaller than the benefits from avoided primary materials production. However, this does not apply across the board to other environmental impacts. For other categories, savings are smaller, only 1.2–2 times bigger than the recycling burdens (e.g. PT, POF, TAD and all eutrophication impact categories).

Direct emissions from RDF combustion in the "b series" dominate the climate burdens in 2032 and 2037. However, savings related to avoided production and utilization of coal coke in cement kilns (b scenarios), as well as avoided natural gas boilers in industry (b(i)), are higher in both cases.

4. Discussion

The present work assessed the environmental performance of two complementary pathways for the development of MSW management in Campo Grande over the next 20 years. While one pathway is based primarily on the municipality's official implementation strategy (the PCS), the second was constructed with the intention to explore the upper range of potential environmental benefits by complementing separate collection with a parallel development of mixed waste treatment infrastructure. Despite the significant range between the results for the two pathways, the b series can still be regarded as conservative, as we intended to present a scenario that can reasonably be implemented in Campo Grande. The inclusion of the BaU scenario, whereby there is no significant future change in the current waste management system, was not expressly in focus. Nevertheless, a no change scenario was tested, and revealed as expected a gradual increase in environmental burdens in line with the increase in waste generation (44% over the period). Therefore, our results suggest that even the implementation of the PCS with or without selective collection of biowaste (a(-o) in Fig. 7), would result in a significant reduction in the climate impact of MSW management. This applies across most environmental impacts.

The technological option of WtE by incineration for direct treatment of mixed MSW was not included in the "b series" as a result of previous research that determined little benefits from its application in Brazil. Firstly, WtE is an option that would require Brazilian municipalities to dispose of much higher budgets for waste management (Leme et al., 2014). Secondly, compared to Europe or Asia, WtE does not bring significant environmental savings to the system by energy production, due to the big share of renewable sources in the electricity matrix of Brazil (Goulart Coelho and Lange, 2018; Liikanen et al., 2018; Lima et al., 2018; Soares, 2017). In addition, from a social perspective, WtE does not create work places in the same way as MBT. WtE requires relatively few specialized operator positions, whereas MBT can be labour intensive and could incorporate many more low skilled workers (sorting positions), as well as specialized positions to operate the various mechanical sorting and biological treatment operations.

In the case of MBT, which dominates the results of the "b series", it is important to stress that environmental benefits are dependent on two main aspects, namely process efficiency and substitution factors in relation to process outputs when utilized further in the economy. The latter applies especially to materials that are recovered for recycling. The effect of process efficiency was tested in Lima et al. (2018), where both simple and advanced MBTs were modelled. Result revealed that except for the resource depletion category, there are minor trade-offs between basic and advanced MBTs, as long as materials that are potentially recyclable and are not sorted end up in RDF, whereby they are used for energy production instead. Sorting efficiencies (transfer coefficients, kg sorted/kg input material) for the MBT in this study included 30%/40% for paper/cardboard, 80% for ferrous metals, 60% for aluminium and 60% for plastics. These efficiencies are on the higher end of values reported in literature (e.g. Montejo et al. (2013), Cimpan et al. (2015)) but not unreasonable. In relation to substitution, we consider the cumulative effect of final processing yield (e.g. aluminium waste re-melting) and market-based substitution factors. In the case of problematic materials such as plastics, the result is 0.75 * 0.81 = 0.61, meaning that 1 kg of sorted waste plastics potentially replaces 0.61 kg of primary produced plastics. The effect of using lower substitution factors is an almost linear decrease in benefits of recycling in most impact categories, but does not change scenario ranking (within a and b series or between series).

RDF utilization in cement production has been widely implemented in Europe, but not without challenges (Cimpan et al., 2015; de Beer et al., 2017; Gallardo et al., 2014). Although Brazil has a large cement production industry, there is little to no experience with RDF streams from MSW. For this to change, and to ensure that this option of RDF utilization will not cause more environmental harm than benefits, the implementation and strict compliance with some quality standards would be necessary (Velis et al., 2010). RDF could be used instead in dedicated boilers, essentially WtE plants that are connected to other industrial production processes. In this case, quality would be less important, however environmental benefits would depend on substituting heat or steam produced by burning fossil fuels.

4.1. Further limitations and uncertainty

The present environmental assessment was built on the basis of comprehensive primary data, including most of the data that described the systems, such as waste flows, collection and some treatment processes, Remaining treatment processes were modified to be geographically representative, following an approach demonstrated by Henriksen et al. (2018) for landfilling, The combination of local data and context specific process modelling should reduce uncertainty in the results (see for example Ripa et al. (2017)). Similarly, some background systems were described by developments in Brazil for background sectors, e.g. the energy system. However, other LCIs could not be based on local primary data. Notably among these are processes for material recycling, which were based on inventories for processes mostly documented in Europe, where the authors only changed electricity inputs to that produced in Brazil. In general, there is a need to produce more LCIs that represent the technological and socio-economic characteristics of Brazil, and more broadly also for other developing countries.

Another area that needs to be addressed concerns datasets for physico-chemical properties of waste fractions. Most studies to date, including the present work, are not based on analyses of Brazilian waste. The elemental composition for all material fractions (in the Easetech library) are based on analysis of waste collected in Denmark. Variations in composition and physico-chemical properties can alter LCA results, sometimes significantly as demonstrated by Bisinella et al. (2017). Including this uncertainty is likely to change absolute values in our results but will not change ranking between scenarios. Our results showed, for example, that a significant presence of zinc in the matrix of certain garden and park waste fractions contributed significantly to burdens in human toxicity (HT, non CE) through the application of compost. As we cannot validate this result for the moment, it is a general indicator that the presence of heavy metals in compost is of concern, and should be tested and monitored on the relevant waste and compost streams.

Finally, the overall gravimetric composition of MSW generated by households was not changed over the 20 year period. This could be considered a weakness, but the reason for proceeding this way was that the baseline composition, unlike typical compositions for regions in developing countries, already displayed quite a low share of biodegradable organics (46%) and high shares of plastics (21%) and paper-cardboard (11%), which is typical of high-income countries. A further decrease in organics over time would result in lower impacts related to waste degradation in landfills, while an equivalent increase in dry waste fractions would probably benefit recycling and energy recovery through RDF.

4.2. Barriers to sustainable MSW management

Since 2012, selective collection for recyclable materials has been running in Campo Grande and it covers today more than 40% of the urban population. However, actual participation in the scheme is quite low, which explains the current amounts collected. The PCS, in its strategic planning, follows a cautious, conservative approach with regard to milestones and goals, which reflect that the municipality has been taking relatively small steps towards a more sustainable waste management system in the past few years. Even so, similar to many other municipalities of Brazil, there is a risk that the PCS will not come to fruition, at least in terms of expected performance.

Both barriers and potential solutions to an efficient development towards sustainable solid waste management in Brazil are increasingly well understood (Conke, 2018; Maiello et al., 2018). It is crucial for the local government to consider them, in order to reap the environmental benefits indicated by this work, as well as associated socio-economic benefits. The success of local policies on waste recycling implemented by local governments is dependent on households' acceptance and change in behaviour, just as much as it is on the behaviour of local representatives, and their continued commitment to modify current practices (Conke, 2018). Moreover, success is dependent also on commitment to quality of service from all actors in the management chain, including collectors, the cooperatives responsible for sorting and companies performing other waste treatment. Both participation by households and delivery of quality service by actors involved, need to be incentivized through targeted actions.

One of the main barriers found by researchers in Brazilian recycling programs is the lack of any kind of tangible return for citizens recycling behaviour. They are typically not informed of what happens to the waste they sort, and unlike other services such as energy or water consumption, for waste services there is no association between behaviour and cost to access the service. The lack of adequate waste fees affects all subsequent actors, in the form of inadequate budgets for collection, sorting and treatment infrastructure. Additionally, selective collection recyclables across Brazil display large amounts of contamination, and this has been connected to a lack of proper communication strategies concerning the materials covered by these schemes. All this is in contrast with a general public acceptance of recycling and its benefits in Brazil, and this suggests that there is great potential for success, given a proper and committed approach from everyone involved.

5. Conclusions

With a projected population increase of 30% and MSW generation increase of 44% over the next 20 years, environmental burdens related to waste management in Campo Grande, Brazil will proportionally grow given lack of changes in management practices. Based on the present evaluation of two prospective development pathways where management practices are gradually changed, we can conclude the following:

(Planned development pathway): A gradual increase in separate (selective) collection for recyclables balanced or even decreased negative environmental impacts in several impact categories over time. The addition of biodegradable organics to separate collection further decreased impacts in some categories (e.g. Global Warming Potential) but pointed to potential burdens in some toxicity categories (e.g. Freshwater Ecotoxicity) due to compost application in agriculture.

(Planned development + mixed MSW treatment): Mixed waste treatment by MBT, entailing sorting of several recyclables and production of RDF to be used in cement production, showed a high potential for positive environmental externalities, given the assumption that these process outputs can displace primary materials and fossil fuels respectively in the wider economy. Further technology changes, such as anaerobic digestion of separately collected biowaste and organic fractions sorted in MBT, have minimum positive effect if biogas is used directly for production of energy (given the low impact of electricity production in Brazil). Biogas upgrading would be preferred on the condition that it can replace fossil fuels in heavy transport.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2019.04.035.

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