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Introducing municipal solid waste streams in a CGE framework: A step in the direction of circular economy analysis

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Growing population and per capita consumption are expected to generate about 3.4 billion tons of waste by 2050. The reuse and recycling of waste reduces the need for landfill, dumping, and incineration, and the extraction of virgin inputs. Such a transition impacts climate change, virgin material providers, producers and consumers. To quantify the direct and indirect impacts of this transition on the economy and environment, we extend a CGE model by developing a method and database including municipal solid waste streams. The waste stream constitutes of five types of municipal solid waste, three types of waste collection services and four types of waste treatment sectors that produce commodities to substitute those made by virgin materials. The model also tracks emissions caused by different waste treatment alternatives. The relationship between consumption, waste generation and waste treatment makes it possible to analyze circular economy policies. A baseline application shows that worldwide waste generation and collection is expected to grow by 45% between 2020-2050. Other waste is expected to grow the most by 53%; food waste is projected to grow the least at 35%. Therefore, without waste management policies, more waste will be incinerated or landfilled, which in turn aggravates climate change.

JEL codes: C68, Q53

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1. Introduction

Around 2 billion tons of Municipal Solid Waste (MSW) have been generated globally in 2010, with more than half generated in high income countries (Wilson and Velis, 2015)[1]. The volume of MSW is projected to increase to 3.4 billion tons by 2050 (Kaza et al. 2018) and the peak in volume is expected after 2075 in the best-case scenario (Hoornweg et al., 2014). MSW accumulation poses serious health and environmental problems (WHO, 2015). In the United Nations' global sustainability strategy, MSW has emerged as a new challenge (Ngoc et al. 2009, Ayeleru et al. 2018, Madaleno, 2018). Landfilling and to a lesser extent incineration contribute significantly to global climate change (Siddiqua et al, 2022). However, MSW can be used to generate fertilizers, energy and other waste-based products. The problem of waste is therefore also an opportunity.

The European Union circular economy (EC, 2020) and biobased economy strategy (EC, 2012, 2018) are key to guide this transition in Europe. The bioeconomy is part of the circular economy that is characterized by a circular, closed flow of materials, where waste from one process becomes an input in another. Circularity is about the reduction, reuse and recycling of raw materials and energy (Ellen MacArthur Foundation, 2013, 2023). The SDGs and the COP21 Paris Agreement indicate that a systemic view is necessary and that there is a need for change, and the overall direction away from a fossil-based economy towards a circular and climate neutral economy is clear (UNFCCC, 2015).

There is therefore a need to assess the economy wide impacts of waste policies and transitions. However, linear (produce, use, discard) product life cycles are standard in established (bio)economy models. Pyka et al. (2022) argue that to increase the effectiveness of economic models in the context of the bioeconomy, the proper representation of recycling, reuse, cascading of materials, as well as waste reduction strategies is of outmost importance. Material cycles and recycling, as well as co- and by-production of products and materials are almost completely ignored in existing multi-sectoral models, with a few exceptions (e.g., Pauliuk et al., 2017; McCarthy et al., 2018).

Global Computable General Equilibrium (CGE) models are useful for analyzing circular economy policies that involve multiple agents, countries, and integrated sectors within a market environment (McCarthy et al., 2018; Winning et al., 2017, Pyka et al. 2022). CGE models can facilitate the assessment of circularity

[1] Municipal waste is defined as waste collected and treated by or for municipalities. It covers waste from households, including bulky waste, similar waste from commerce and trade, office buildings, institutions and small businesses, as well as yard and garden waste, street sweepings, the contents of litter containers, and market cleansing waste if managed as household waste. The definition excludes waste from municipal sewage networks and treatment, as well as waste from construction and demolition activities.

measures by depicting interactions among producers along global supply chains and consumer responses to changing prices and incomes, as well as analyzing endogenous economic-wide price effects and socioeconomic and environmental impacts. The implementation of waste systems in CGE models, however, is not yet a common practice. Work focusing on small fractions of the puzzle does exist - residues from agriculture and forest (Taheripour et al. 2010, van Meijl et al. 2016, Philippidis et al., 2016), food waste reduction (Rutten et al. 2013) - however exploring the possibilities of a truly circular system remains unfulfilled.

There are four multi-region CGE models which have been used to model circular economic systems. Firstly, the ENGAGE-Material (Winning et al., 2017) model has been used to model waste management, material recovery and secondary production sectors for steel. Secondly, the MAGNET CGE model (van Meijl et al., 2018) has been modified by Gatto et al. (2023) to include food loss and waste in all stages of the value chain as an ex-post indicator and to allow bio-based residues to be used for feed, bioenergy, or biobased materials. The MAGNET model has also been used by Gatto et al. (2024) to analyze policies to stimulate aspects of a circular food system with a focus on animal feed. Thirdly, the ENVISAGE model (The World Bank, 2022) has been used to studied trade implications of circularity. Fourthly the linkage model (OECD, 2022) has been used to explore circularity in the plastics sector.

None of these applications however consider the entire municipal solid waste stream from waste generation during consumption, cost of waste collection, and finally the cost of waste treatment and revenues of reusing composted and recycled materials. Doing so enables the quantification of the whole waste flow. This is necessary to explicitly model policies aimed at influencing waste generation, composition, and treatment.

Outside of global CGE models, single-region CGE models and partial equilibrium (PE) models have also been used to analyze circularity. Several single-region CGE models introduce a waste management sector in order to analyze secondary production such as Godzinski (2015), Masui (2005), Hartley et al. (2016) and Fujimori et al., 2017). In PE models, the use of residues and recycled materials is typically considered in more detail. For example, in the forestry context recycled paper and by-products (e.g., wood chips, sawdust, black liquor) are generally considered as by-products in agricultural models. Nevertheless, these models still fall short in considering recycling (e.g., post-consumer waste) or cascading of products.

One of the hurdles to implementing waste streams in a CGE model is the availability of data. Municipal solid waste originates during consumption of products by households and should be linked to consumption of goods that are wasted. In this paper we use the Global Trade Analysis Project (GTAP) version 10.1 data (Aguiar, et al, 2019) which is often used within CGE and Integrated Assessment models (IAM). The GTAP database is a global database describing bilateral trade patterns, production, consumption and intermediate use of commodities and services. However. while waste is included in the GTAP database, the GTAP database provides data on waste disposal only as a component of 'Water supply; sewerage, waste management and remediation activities' (wtr) sector.[2] Given that the consumption structure does not specifically model complementary between consumption of goods and consumption of waste treatment, no link between consumption of goods that generate waste and type of waste generated/collected/treated can be made.

To introduce such a link, we model waste collection as a domestic margin commodity. The idea is that consumer price of a commodity now includes both the price of the original commodity and the price of collecting and treating the waste generated as a result of consumption of corresponding commodity. In this way the new commodity can be seen as a composite bundle of original commodity, and waste collection services required to collect waste associated with consumption of that commodity. Technically such an approach is already available albeit in a different context. This margin commodity approach has been implemented in a CGE framework by Peterson (2006), making available a detailed description of how to introduce domestic trade margins within GTAP. We adapt the approach to model waste streams. The waste streams (generation-collection-treatment-disposal) are implemented in the Modular Applied GeNeral Equilibrium Tool (MAGNET) model (Woltjer et al., 2014)[3], which in turn is based on the Global Trade Analyses Project (GTAP) model (Hertel, 1997, Corong et al. 2017).

In this paper we provide details on the methodology and database required to implement MSW streams. Section 2 describes the methods used to implement MSW streams in a CGE model using a domestic margin approach. Firstly, the standard MAGNET model is introduced. Secondly, we introduce the core waste stream concepts: (i) five types of waste are introduced (food waste, garden waste, paper waste, glass waste and other waste), (ii) three types of waste collection services (green waste, glass and paper, grey waste), (iii) four types of waste treatment sectors (composting, landfill, waste incineration, and recycling) that produce (iv) biomass, energy, and recycled materials to be used in the other sectors of the economy. Thirdly, the implication for the consumption equations and other equations in the model are introduced. In section 2, we present the construction and gathering of the waste database which is challenging given the lack of detailed waste data and strong assumptions are required to fill data gaps and get a complete dataset. Section 3, illustrates the model by running a baseline until 2050

[2] It is important to note that while theoretically the "wtr" sector should reflect costs of the waste disposal services and treatment, individual countries may report part of these costs in different sectors within their input-output tables.

[3] https://www.magnet-model.org/

and analyses future developments regarding amount and composition of waste, waste treatment usage, and demand by different sectors of their outputs. Finally, a few concluding remarks are presented in section 4.

2. Methods

1.1 A standard MAGNET model

We use a global CGE model to quantify changes in MSW. Global CGE models encompass the whole economy including agricultural, industrial, and service sectors. Global CGE models represent a circular flow of income and expenditures: a closed global system in monetary terms, tracing money from production to income and expenditures on produced goods. CGE models describe how producers respond to technological changes and to changes in input and output prices. These price changes are partly driven by agricultural and non-agricultural sectors competing for primary factors (land, labor, capital, natural resources) and intermediate inputs (commodities produced by other sectors). Consumers adjust their demand for agricultural and non-agricultural commodities in response to changes in income (derived from sales of primary factors to producers), commodity price changes and changes in consumer preferences. A third factor affecting prices is international trade which influences import and export demand when relative prices adjust. The complete representation of primary production, international trade, intermediate and final demand by consumers allows an integrated analysis of economic adjustments and substitution effects of MSW streams and policies that influence these streams. For this study we use the global CGE model called MAGNET developed with a focus on agri-food sectors, land use and the rest of the bioeconomy (Van Meijl et al. 2006, Woltjer et al. 2014). In Van Meijl et al. (2018) biomass can be used in the biofertilizer, bioenergy, 2nd generation biofuels or biochemicals sectors. Bioeconomy related analyses focused on implications on food security (Van Meijl et al. 2020a, 2020b), greenhouse gas emissions (Perez-Dominguez, et al. 2021), and biodiversity (Leclere et al. 2020). It is an advanced recursive dynamic variant of the well-known GTAP model (Corong et al. 2017). To focus on the modelling of MSW, we use a simplified MAGNET model that covers 64 sectors and has a focus on a few key features which are likely to influence waste generation. These features are: modelling agricultural production and food demand, sector-specific production trees, endogenous agricultural land supply, nested land allocation to capture different substitution possibilities between land uses, and bioeconomy and residue production to cover the substitution between biomass from residues and biomass from composting. In terms of regions, we use 17 aggregate geographical regions representing all continents in the world. Both the sectoral and the regional aggregation are shown in Appendix 1.

1.2 Waste stream implementation

Figure 1 shows how waste streams are modelled in MAGNET. This covers the entire cycle from generation of waste to collection, treatment and disposal. Private households generate waste and demand waste collection services. In this study, consumption can generate one or more of the five kinds of waste types – food waste, garden waste, paper waste, glass waste and other (unsorted combination) waste. Other types of recyclable waste like metal and plastics are not yet taken into account and excluded from the database.

Treatment of waste depends both on the type of waste generated and the way waste is collected. Three types of waste collection services exist: collection of green waste which includes organic household and garden waste, collection of glass and paper waste, and unsorted grey waste, which is the "other" category. Figure 1 illustrates how green waste is collected by either green or grey collection services. Paper and glass waste is collected by either paper and glass collection or grey collection services. Other waste can only be collected by grey waste collection and not the other two waste collection services.

Waste collected by grey waste collectors is sent to landfill or incineration. Waste collected by green waste collectors is sends to a composting sector which produces biomass to be used as bio fertilizer or as biomass in the second generation bioeconomy sectors: bioenergy, 2nd generation biofuels or bio chemicals. Use of biomass in bioeconomy sectors substitutes for residuals and pellets. Finally, waste collected by glass and paper collection is sent to recycling sector. Recycled paper and glass is then used in the paper and glass industry as a substitute for virgin materials. Incineration sector produces electricity using waste. Landfill is the only waste disposal option which does not provided any usable material or energy.

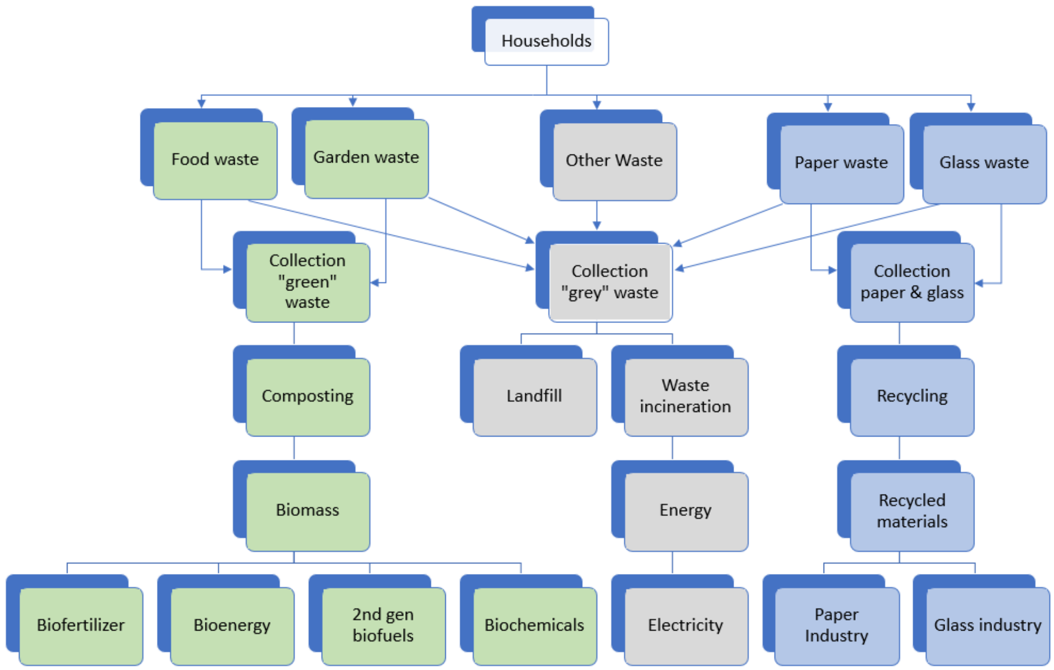

Figure 1. Waste stream schematic as implemented in MAGNET

2.3 Implication of waste generation for private consumption structure

The standard consumption expenditure allocation mechanism of the private household (as modelled in GTAP and MAGNET) is shown in Figure 2. Private households allocate expenditure between different commodities based on a Constant Difference of Elasticities (CDE) function. In region r, the value of private household's purchase of commodity c [$VPP(c,r)$] is given by the price of the commodity in the region [$PPA(c,r)$] and the quantity purchased [$QPA(c,r)$]. Each commodity is sourced partially from domestic suppliers [QPD] and partially from imports [QPM], and the price [PPA] of commodity is composite of the prices of domestic and imported commodity [PPD and PPM respectively]. The difference between basic/market prices [PMS, PDS] and price paid by consumer [PPM, PPD] are consumer taxes [$MPTAX, DPTAX$].

Figure 3 shows how private expenditure allocation mechanism is modified to accommodate waste streams. This mechanism uses 3 types of commodities: non-bundled, bundled, and composite commodities. A non-bundled commodity is essentially the same as a commodity in status-quo structure. A bundled commodity is a mix of non-bundled commodity and the waste collection services demanded to collect the waste generated as a result of consumption of said non-bundled commodity. Finally, just like the import and domestic composite quantity [qpa] in status-quo structure, the new structure includes an import-domestic composite demand [also called qpa] but instead of a composite of non-bundled quantities, it is now a composite of bundled quantity. There are similarly non-bundled, bundled and composite prices associated with these variables as depicted in Figure 3.

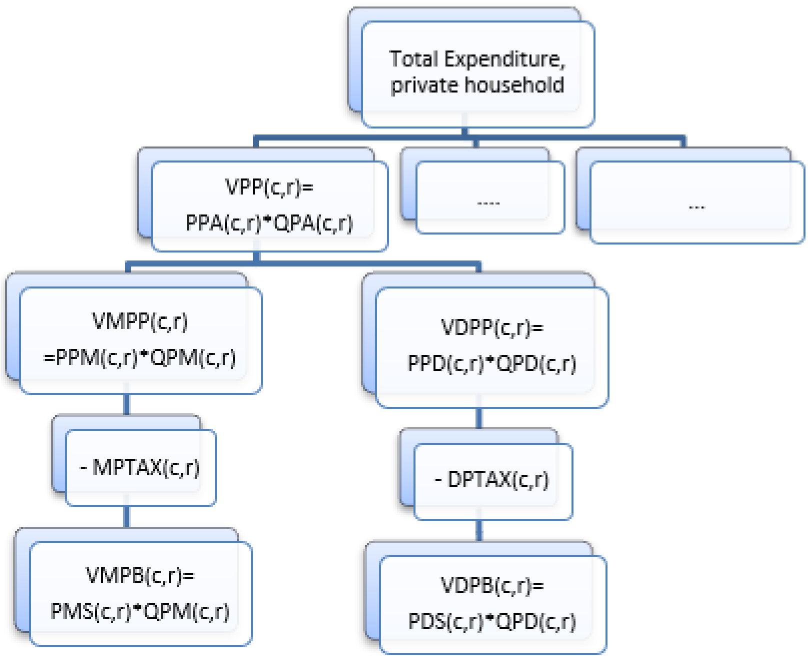

Figure 2. Status-quo private consumption treatment in GTAP and MAGNET.

Notes: VPP(c,r) i, the value of private household's purchase of commodity *c* in region *r*; PPA and QPA are respectively the price and quantity of the commodity; Each commodity is sourced partially from domestic suppliers [QPD] and partially from imports [QPM], and the price [PPA] of commodity is composite of the prices of domestic and imported commodity [PPD and PPM respectively]. The difference between basic/market prices [PMS,PDS] and price paid by consumer [PPM,PPD] are consumer taxes [MPTAX, DPTAX].

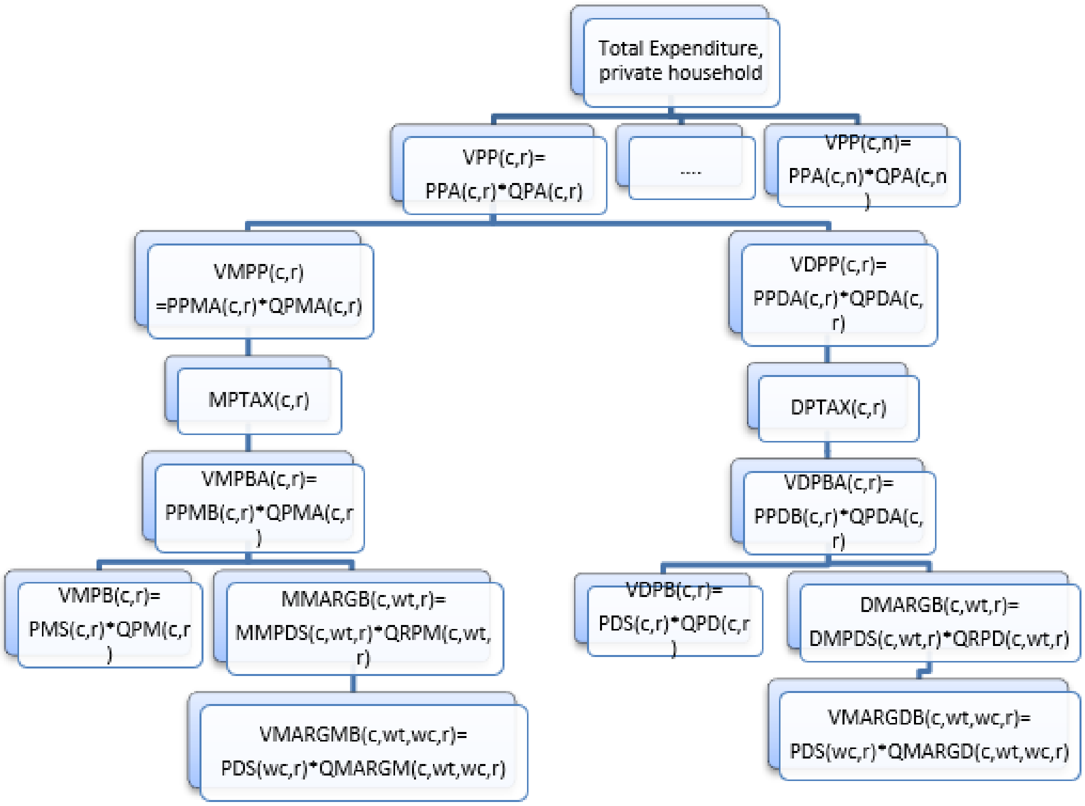

Figure 3. Consumption including waste margin commodity (bundled commodities).

Notes: VPP(c,r) is, the value of private household's purchase of bundled commodity *c* in region *r*. PPA and QPA are respectively the price and quantity of the bundled commodity. Each bundled commodity is sourced partially from domestic suppliers [QPDA] and partially from imports [QPMA], and the price [PPA] of bundled commodity is composite of the prices of domestic and imported commodity [PPDA and PPMA respectively]. The difference between basic/market prices [PPMB,PPDB] and price paid by consumer [PPMA,PPDA] are consumer taxes [MPTAX, DPTAX]. The bundled prices are weighted average of basic price for non-bundled commodity and price of waste collection service [MMPDS,DMPDS]. There is a bundled $[\mathrm{QPMA}, \mathrm{QPDA}]$ quantity where the latter is an aggregate of the non-bundled [QPM,QPD] quantity and an aggregate waste collection $[\mathrm{QRPM}, \mathrm{QRPD}]$ quantity. The bundled quantity has an additional index - waste type *wt*. There are basic prices for all non-bundled commodities and waste collection services [PDS,PMS]. Allocation of a given waste type to different collection services is denoted by $\mathrm{QMARGM}, \mathrm{QMARGD}$. These denote quantity variables for collection of waste type wt by service wc in region r, generated during consumption of imported and domestic commodity c respectively.

Instead of just two prices (basic and producer), the structure now has three prices: basic prices for all non-bundled commodities and waste collection services $[PDS, PMS]$, basic prices of bundled commodity $[PPMB, PPDB]$ and producer prices of bundled commodities [$PPMA, PPDA$]. The bundled prices are weighted average of basic price for non-bundled commodity and price of waste collection service [$MMPDS, DMPDS$].

Similarly, there are now two types of quantities: a non-bundled [QPM, QPD] and a bundled [QPMA, QPDA] quantity where the latter is an aggregate of the non-bundled quantity and an aggregate waste collection [$QRPM, QRPD$] quantity. Note that the bundled quantity has an additional index - waste type [wt], as consumption of each commodity can generate one or more types of waste. The aggregate demand for waste collection services [$QRPM, QRPD$] is allocated to three available waste collection services and the type of waste collection service demanded, depends on the type of waste generated. Allocation of a given waste type to different collection services is denoted by $QMARGM, QMARGD$. These denote quantity variables for collection of waste type wt by service wc in region r, generated during consumption of imported and domestic commodity c respectively.

$PDS(wc, r)$ denotes the basic market clearing price in region r. Note that waste collection services are not internationally traded[4]. These are domestic services provided by government to collect waste coming from region r's consumption of both imported and domestic commodities. The imported or domestic dimension in quantity variables [$QMARGM, QMARGD$] originates solely from source of origin of commodity c. The associated imported and domestic value coefficients are $VMARGMB$ and $VMARGDB$.

In this setup therefore the domestic market price [PDS] exists only for waste collection services and waste cannot be traded internationally. Value of aggregate waste collection [$MMARGB$ and $DMARGB$] is added to value of expenditure on the imported and domestic commodity purchased by private households [$VMPB$ and $VDPB$ respectively] to give the bundled expenditure on a commodity at basic prices [$VMPBA, VDPBA$]. Any consumption tax or subsidy [$MPTAX, DPTAX$] is added to this bundled expenditure to get the consumer expenditure on the imported and domestically procured commodity [$VMPP, VDPP$], to finally provide total expenditure on a commodity [VPP] in a region.

1.3 Equations to model changed consumption structure

The waste streams are implemented as a module in MAGNET which gives the user an option to choose one of the two consumption trees (represented in Figure 2 and Figure 3) for every model region. To model the tree represented by Figure 3, we need additional equations. This section provides details on these additional equations. The equations are provided in linearized form (in lowercase alphabet)

[4] In reality waste streams are traded internationally. However, we have not been able to model this yet due to unavailability of data.

corresponding to the level's coefficients and variables (in uppercase alphabet) in Figure 3.

1.3.1 Demand for the waste collection services

The nest at the bottom of Figure 3 deals with allocation of aggregate demand for waste collection services $[qrpm, qrpd]$ to individual services. The demand for collection service wc to collect waste associated with both imported and domestic commodities $[qmargm, qmargd]$ follows the same form given below:

$$\begin{aligned} qmargm(c, wt, wc, r) \\ &= qrpm(c, wt, r) - \varepsilon(c) \\ &* \left\{ pds(wc, r) - \sum_{wc} \theta q^{m}_{c,wt,wc,r} * pds(wc, r) \right\} \end{aligned} \tag{1}$$

$$\begin{aligned} qmargd(c, wt, wc, r) \\ &= qrpd(c, wt, r) - \varepsilon(c) \\ &* \left\{ pds(wc, r) - \sum_{wc} \theta q^{d}_{c,wt,wc,r} * pds(wc, r) \right\} \end{aligned} \tag{2}$$

The equations state that demand for individual waste collection service is increasing in demand for aggregate waste collection $[qrpm, qrpd]$ increases. Demand responds inversely to the difference in its price $[pds]$ relative to aggregate price index of waste collection. The elasticity of substitution is denoted ε_c ($> 1\ \forall\ c$)[5]. The shares $\theta q^{m}_{c,wt,wc,r}$ and $\theta q^{d}_{c,wt,wc,r}$ are the quantity shares of demand for waste collection service wc collecting waste type wt arising from consumption of commodity c, in the aggregate waste collection for imported and domestic consumption respectively.

The total demand for waste collection as an aggregate [equations 3 and 4], is increasing in demand for bundled commodity $[qpma, qpda]$ and decreasing in its price $[mmpds, dmpds]$ relative to basic price of the bundled commodity $[ppmb, ppdb]$. The elasticity of substitution between the non-bundled commodity and waste collection services components in an associated bundled commodity is denoted by $\sigma(c)$ (>0). This elasticity allows us to model the fact that consumption can be increased by reducing waste without requiring a consumer to increase their

[5] $\boldsymbol{\varepsilon(c)} = \frac{\rho}{\rho+1}$ since r<-1 therefore $\boldsymbol{\varepsilon(c)} > 1$, where ε_c is the elasticity of substitution and r is the substitution parameter of the underlying CET optimization function:

$Minimize\ \left[\sum_i (P_i * X_i)^{-\rho} * \delta_i\right]^{-\frac{1}{\rho}}$

demand for the bundled commodity. The new variable $arpd(c, wt, r)$ denotes technical progress in waste collection, and is modelled along the lines of the *ams* variable present in trade flow equations in the GTAP and MAGNET model.

$$\begin{aligned}\boldsymbol{qrpm(c, wt, r)} = \boldsymbol{qpma(c, r)} - \boldsymbol{\sigma(c)} \\ * \{\boldsymbol{mmpds(c, wt, r)} - \boldsymbol{arpd(c, wt, r)} \\ - \boldsymbol{ppmb(wc, r)}\} - \boldsymbol{arpd(c, wt, r)}\end{aligned} \tag{3}$$

$$\begin{aligned}qrpd(c, wt, r) = qpda(c, r) - \sigma(c) \\ * \{dmpds(c, wt, r) - arpd(c, wt, r) \\ - ppdb(wc, r)\} - arpd(c, wt, r)\end{aligned} \tag{4}$$

The formulation for individual waste collection demand [equations 1 and 2] is slightly different than ones for aggregate demand [equations 3 and 4], because of the need to meet the additivity constraint, namely that all waste generated in tons should equal waste collected in tons (Dixon et al, 1992).

1.3.2 Basic price of waste collection services

As there is no trade in waste collection services there is only one basic price for waste collection services in a country. This is the market clearing price for the waste collection service and is dictated by equating the supply of waste collection service [qc] to its domestic (and only) demand [qds].

$$qc(wc, r) \ = \ qds(wc, r) \tag{5}$$

The waste collection composite has two prices [$mmpds, dmpds$] depending on whether the waste collection services associated with consumption of imported (equation 6) or domestic (equation 7). The equations are again different than the simple share weighted form on account of additivity constraint (Dixon et al, 1992). The shares $\theta v^m_{c,wt,wc,r}$ and $\theta v^d_{c,wt,wc,r}$ are the value shares of demand for waste collection service wc collecting waste type wt arising from consumption of commodity c, in the aggregate waste collection for imported and domestic consumption respectively.

$$\begin{aligned}mmpds(c, wt, r) \\ = \sum_{wc} \theta v^m_{c,wt,wc,r} \\ * \{pds(wc, r) + qmargm(c, wt, wc, r)\} \\ - qrpm(c, wt, r)\end{aligned} \tag{6}$$

$$dmpds(c,wt,r) = \sum_{wc} \theta v^{d}_{c,wt,wc,r} * \{pds(wc,r) + qmargd(c,wt,wc,r)\} - qrpd(c,wt,r) \tag{7}$$

1.3.3 Demand for non-bundled commodity

The demand for non-bundled imported and domestic commodity $[qpm, qpd]$ follows a structure similar to that for waste collection service aggregate (see equations 3 and 4).

$$qpm(c,r) = qpma(c,r) - \varepsilon(c) * \{pms(c.r) - ppmb(c,r)\} \tag{8}$$

$$qpd(c,r) = qpda(c,r) - \varepsilon(c) * \{pds(c.r) - ppmb(c,r)\} \tag{9}$$

The demand for non-bundled commodity increases with that of bundled commodity and responds negatively to relative prices being higher than the basic price of the bundled commodity. This structure is similar to the import and domestic allocation of composite demand in standard model without waste.

Note that equations 8 and 9 do not apply to waste collection services commodities which are demanded only as waste margin commodities. The non-bundled demand variables $qpm(wc,r), qpd(wc,r)$ $(\forall\, wc)$ are essentially set to zero.

1.3.4 Basic price for non-bundled commodity

The price of non-bundled commodity is determined by market clearing condition for the commodities.

$$qc(c,s) = \alpha(c,s) * qds(c,s) + \sum_{d} \beta(c,s,d) \cdot qxs(c,s,d) \quad \forall\, c \in non - transport\ margin \tag{10a}$$

$$qc(c,s) = \alpha(c,s) * qds(c,s) + \sum_{d} \beta(c,s,d) \cdot qxs(c,s,d) + \gamma(c,s) \cdot qst(c,s) \quad \forall\, c \in\ transport\ margin \tag{10b}$$

Equations 10a and 10b basically state that the price of non-bundled commodity is determined at a level which equates supply of commodity *c* in region *s* to its sales in region *s*, its exports from region *s* to other regions, and its demand as transport margin if applicable. Equation 10, is very similar to equation 5, except that as waste collection services have only one source of demand (domestic sales, qds) the components representing sales to exports [qxs] and sales as transport margins [qst] do not appear in equation 5. α, β, γ represent the shares of domestic, export and transport margin demand in total demand for the commodity.

1.3.5 Demand for bundled commodity

Demand for the bundled commodity is determined the same way as the demand for imported and domestic components of composite consumption were determined in the status-quo structure (Figure 2). More specifically, the equations are

$$qpma(c,r) = qpa(c,r) - \mu(c,r) \cdot \{ppma(c,r) - ppa(c,r)\} \tag{11}$$

$$qpda(c,r) = qpa(c,r) - \mu(c,r) \cdot \{ppda(c,r) - ppa(c,r)\} \tag{12}$$

Demand for both domestic and imported bundled commodity [$qpma, qpda$] rises with a rise in composite demand for the commodity [qpa] and declines if import and domestic price [$ppma, ppda$] increase more than the composite price [ppa]. $\mu(c,r)$ denotes the elasticity of substitution possibility between the domestic and imported commodity c. To reiterate, the imported bundled commodity constitutes combination of imported non-bundled commodity and domestic waste collection services.

1.3.6 Basic price for bundled commodity

The price for the bundled commodity is a weighted average of the prices of bundle elements. The elements are the price of non-bundled commodities [pms, pds] and the price of the waste collection service aggregate [$mmpds, dmpds$] demanded as part of the bundle.

$$ppmb(c,r) = \varphi^{m}_{c,r} \cdot \sum_{wt} \tau^{m}_{c,wt,r} * \{mmpds(c,wt,r) - arpd(c,wt,r)\} + (1 - \varphi^{m}_{c,r}) \cdot pms(c,r) \tag{13}$$

$$ppdb(c,r) = \varphi^{d}_{c,r} \cdot \sum_{wt} \tau^{d}_{c,wt,r} * \{dmpds(c,wt,r) - arpd(c,wt,r)\} + (1 - \varphi^{d}_{c,r}) \cdot pds(c,r) \tag{14}$$

The share $\tau^{m}_{c,wt,r}$ and $\tau^{d}_{c,wt,r}$ denote the value shares of waste type wt in total waste generated by consumption of imported and domestic commodity c respectively, in region r. It is used to aggregate the waste collection prices [$mmpds, dmpds$] over their waste type dimension such that $\sum_{wt} \tau^{T}_{c,wt,r} = 1$, where $T \in (m, d)$. Note that the technical progress variable $arpd$ affects not only the aggregate demand for waste collection services (equations 3 and 4) but also the price of bundled commodity. A technical progress in waste collection would essentially lower the price of waste collection and thereby the price of bundled commodity.

This aggregated price is then calculated using value shares of the waste collection $[\varphi^{m}_{c,wt,r}, \varphi^{d}_{c,wt,r}]$ of the domestic and imported commodity waste and the non-bundled commodity $[1 - \varphi^{m}_{c,wt,r}, 1 - \varphi^{d}_{c,wt,r}]$ in the total value of the bundled commodity.

1.3.7 Tax inclusive price for bundled commodity

The relationship between basic $[ppmb, ppdb]$ and agent $[ppma, ppda]$ prices of a commodity are the same as in the standard model, except when the commodity in question is the bundled commodity.

$$ppma(c, r) = ppmb(c, r) + tpm(c, r) \quad (15)$$

$$ppda(c, r) = ppdb(c, r) + tpd(c, r) \quad (16)$$

The tax variables $[tpm, tpd]$ are now to be interpreted as consumer tax in region r on consumption of imported and domestic bundled commodity c respectively.

1.3.8 Total domestic sales

Total domestic sales $[qds]$ of non-bundled commodities and the waste collection services are modelled slightly differently depending on the source of demand. While the non-bundled commodity c can be demanded by firms as intermediate input $[qfd]$, private consumers $[qpd]$, government $[qgd]$ and investment $[qid]$ demand, the waste collection services have only one source of demand, namely from private consumers $[qmargm, qmargd]$. Accordingly, the domestic sales for the non-bundled commodity and waste collection services are given by equations 17a and 17b. The share of domestic sales of non-bundled commodity c as intermediate input to sector a in region r is denoted by $\omega^{f}_{c,a,r}$. The share of the sales to private consumption, government consumption and investment demand is denoted by $\omega^{F}_{c,r}$ where $F \in (p, g, i)$. Denoted by are $v^{m}_{c1,wt,c,r}$ and $v^{d}_{c1,wt,c,r}$ are the value shares of demand for waste collection c demanded to collect waste type wt generated in consumption of imported and domestic commodity *c1* respectively, in total demand for collection service to collect all waste types generated in total consumption (domestic and imported) of all commodities.

$$qds(c,r) = \left[\sum_{a} \omega^{f}_{c,a,r} \cdot qfd(c,a,r)\right] + \omega^{p}_{c,r} * qpd(c,r) + \omega^{g}_{c,r} * qgd(c,r) + \omega^{i}_{c,r} * qid(c,r) \quad \text{(17a)}$$
$$if\ c = non - bundled\ commodity$$

$$qds(c,r) = \sum_{c1}\sum_{wt} v^{m}_{c1,wt,c,r} * qmargm(c1,wt,c,r) + v^{d}_{c1,wt,c,r} * qmargd(c1,wt,c,r) \quad \text{(17b)}$$
$$if\ c = waste\ collection\ service$$

1.3.9 Price of composite commodity

Finally, the price of imported and domestic composite of the bundled commodities can be determined as a share weighted sum of the price of domestic and imported bundled commodities. The shares used for the purpose are the shares of consumption expenditure on composite commodity c in region r devoted to imported $[\vartheta(c,r)]$ and domestic $[1-\vartheta(c,r)]$ origins of the commodity. This equation is only valid for bundled-commodities.

$$ppa(c,r) = \vartheta(c,r) \cdot ppma(c,r) + [1-\vartheta(c,r)] \cdot ppda(c,r) \quad \text{(18)}$$

1.4 Data requirements

Implementing the waste streams in the model required undertaking the construction of a waste database. Relevant data gathered and its sources are described in subsections below. The waste data collected are in million tons as both the World Bank and Eurostat publish waste quantities in million tons.

1.4.1 Waste generation data

For all 141 countries in the GTAP 10.1 database, data was collected or compiled on the production and treatment of MSW. Data about waste generation are taken from the World Bank report (Kaza, et al. 2018). The World Bank presents a database with data on waste generation at the country level for 215 countries and economies. The World Bank database is the most extensive worldwide database available for municipal solid waste. This database collects and collates data from various sources in a balanced database.

The World Bank data relates to year 2016. As the GTAP 10.1 database corresponds to year 2014, the World Bank data is rescaled to 2014. To rescale the data, production of per capita MSW published by the World Bank is multiplied with the 2014 population from the GTAP database. This gives us the MSW produced per region for 2014.

Figure 4 shows the per capita waste generated for 141 regions in the world in 2014. Municipal waste accounts for about 10% of total waste generated when compared with the data reported according to the Waste Statistics Regulation (Eurostat, 2023).

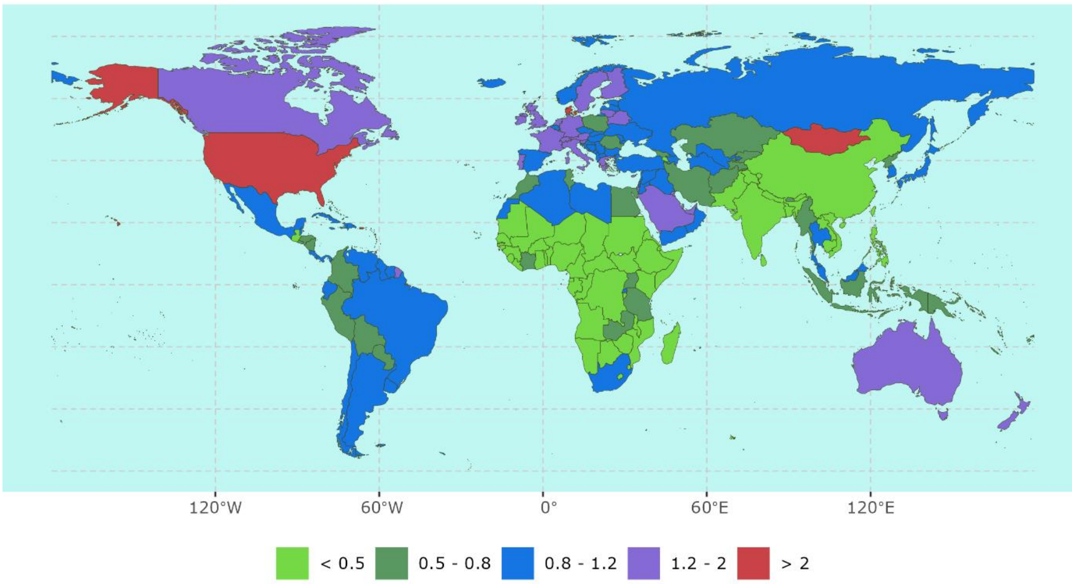

Figure 4. Per capita waste generation in 2014 (kg per capita per day)

Source: constructed using World Bank and GTAP data

1.4.2 Composition of MSW by type

Data on the composition of MSW (organic, glass, paper, metal, other) are also published by the World Bank (Kaza, et al. 2018). Figure 5 gives an overview of the different waste types present in the MSW for each continent.

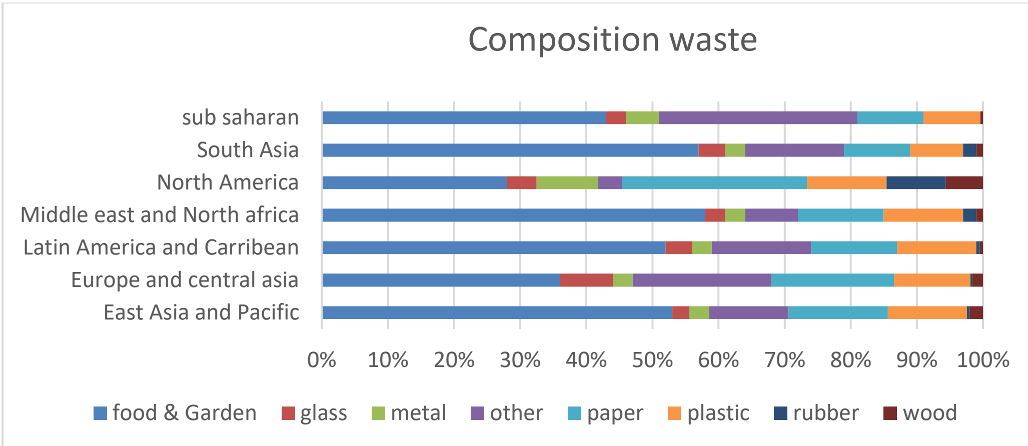

Figure 5. Waste composition by region (calculated as weight share of different types of waste in total tons of waste generated, 2014)

Source: World Bank

The World Bank (Kaza, et al 2018) only reports food and garden waste separately for 24 countries. For all other regions and countries, garden and food waste are reported as a single category. Food waste is important as an issue concerning global food security and good environmental governance. Therefore, it is preferable to treat food and garden waste as different waste types. However, as most municipalities collect food waste and garden waste together it is not easy to split these two waste streams. There is limited data available about the amount of food waste produced by households. In this study we used data from the World Bank (Kaza, et al. 2018) combined with Eurostat food loss and waste database (Eurostat, 2023) to determine the share of food waste in the total amount of green waste collected.

The Eurostat database provides food waste data for all 27 EU member states. Combined with the amount of green waste generated according to the World bank database, the share of food waste can be determined for the EU member states. Figure 6 below shows countries for which data is available to determine the food waste share. The food waste share varies between 10% to 98% around the world. For all regions with missing data, a world average food share of 58% is assumed.

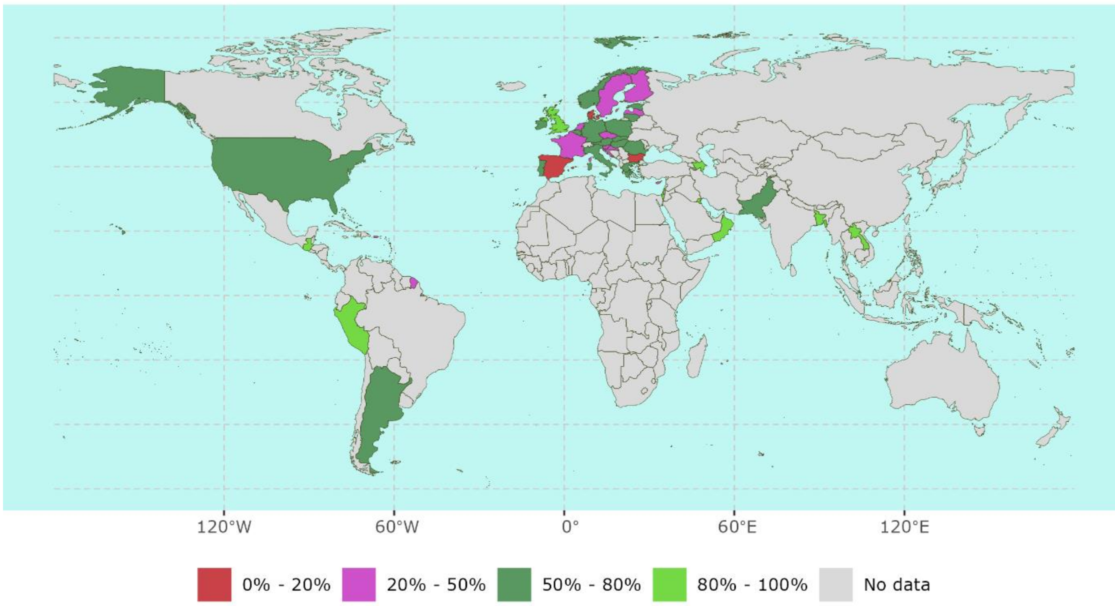

Figure 6. Share of food in food and garden waste aggregate (tons of food waste divided by tons of organic waste)

Source: constructed from World Bank and Eurostat

1.4.3 Waste generation by commodity

As waste generation is postulated to be based on consumption, the higher the consumption the higher the amount of waste generated. The composition of waste associated with a commodity should differ depending on the materials used to make the commodity.

A complete material-flows database however is not available. To link waste generation to consumption, we therefore assume that intermediate demand of materials for production of a commodity is a good approximation for composition of waste generated during the consumption of the said commodity. For example, paper is the most used input in the production of magazines so paper waste should be the biggest component of waste associated with magazine consumption. Based on the intermediate expenditure data from the GTAP database, shares for paper, glass, food and garden commodities are calculated. Figure 7 shows how much paper and glass is used by each of the aggregated sectors. For example, 32% of the demand for paper as intermediate input is accounted for by the paper industry, only 5% of paper is used in the agricultural sector. Therefore, when households consume commodities from the paper industry, they will generate more paper waste than when they consume commodities from the agricultural sector.

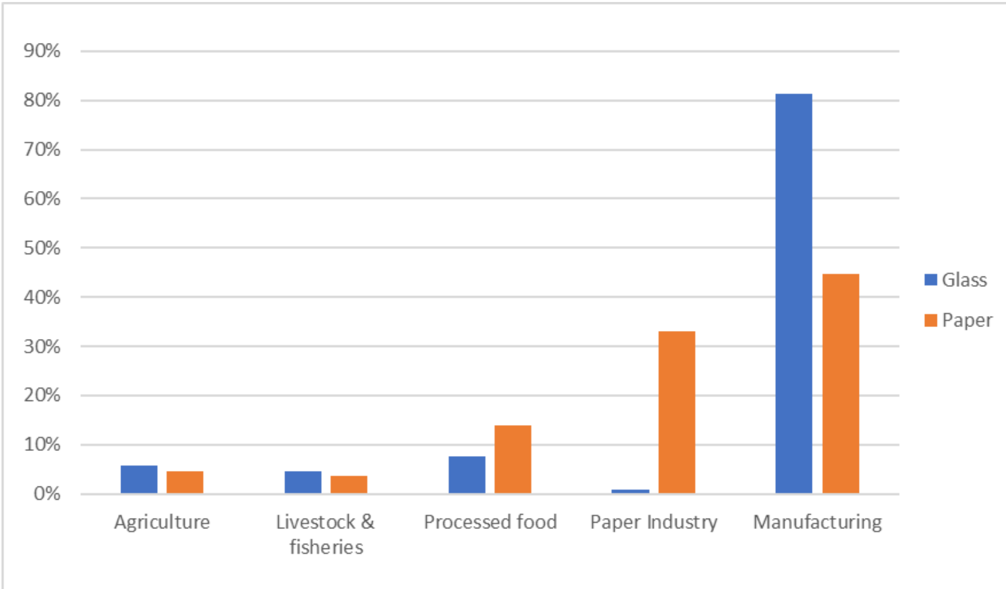

Figure 7. Glass and paper weights used to allocate waste to consumption (expenditure share calculated as million dollars spend on paper or glass by a certain activity divided by total expenditure of that activity)

Source: constructed from GTAP expenditure data

If better data becomes available, these assumptions should be replaced by estimates. Figure 8 shows the type of waste materials generated by consumption of certain product categories based on intermediate expenditure shares of virgin materials in the production process. Note that we assume that garden waste is linked to the GTAP sector dwellings. Services, which includes dwellings, is a big contributor of garden waste as is shown in Figure 8. This figure also shows that total MSW generated by commodity also differs between regions. Regional differences are predominantly due to different consumption patterns. For example, a large part of food waste in Europe is linked to the consumption of primary crops and fisheries. However, in North America and South and Central America, hardly any food waste is linked to the consumption of primary crops. This is because in these regions households consume very little primary crops. In North America much more food services are consumed and therefore food waste is mainly linked to food services. In South and Central America, the consumption of livestock is quite high which means that a larger share of the food waste is linked to livestock.

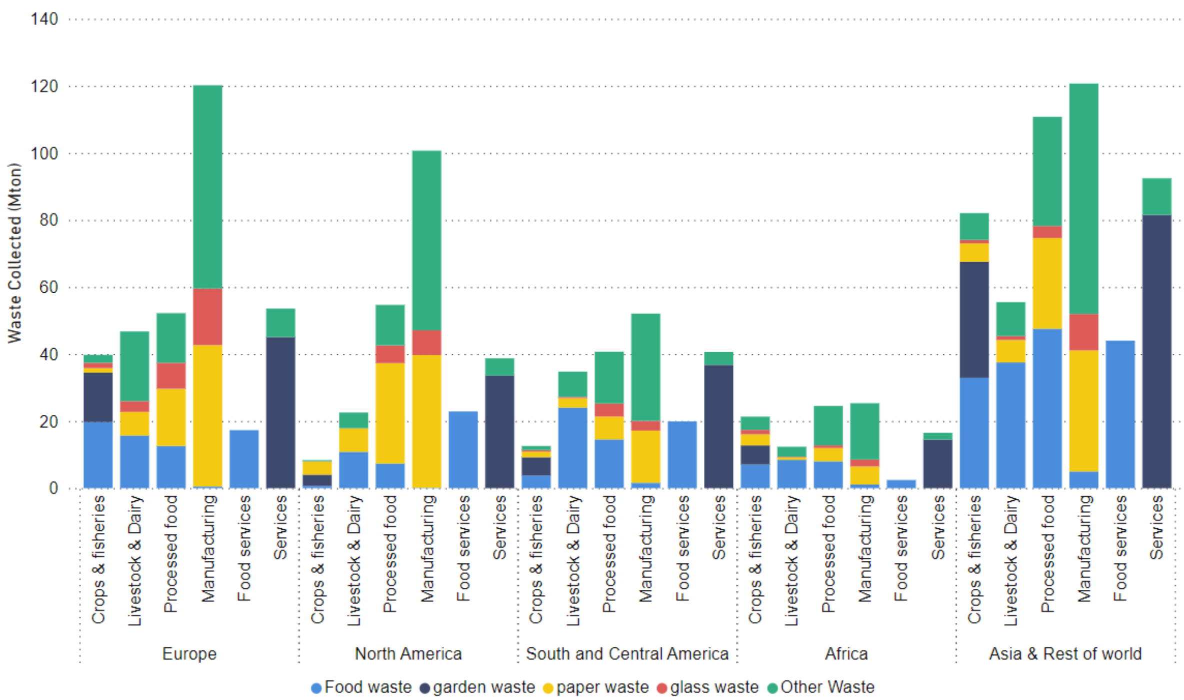

Figure 8. Waste composition/type by consumption category and region (in million tons)

Source: constructed based on intermediate expenditure data GTAP combined with World Bank data

1.4.4 Waste collection

Globally not all waste generated is collected. On average about 75% of waste generated worldwide is collected. The collection rates do differ a lot between different countries as shown in Figure 9. We do not model waste that is not collected. Only collected waste is included in the data. This underestimates the solid waste management problems in regions with low collection rates.

More often than not, waste is recycled or reused only if the different waste types are collected separately. While some countries are experimenting with separating waste after collection in so-called mixed material recovery facilities (MRF), in most cases, separation and sorting of organic waste, paper and glass is seen as too expensive and the quality of non-separated waste is too low to be reused, recycled or composted (Strange, 2002). Accordingly, the model assumes that only waste types that are collected separately can be recycled or composted. Based on average recycling and composting rates (Eurostat 2021, Chen et al, 2020) the amount of waste collected as green or paper and glass waste is imputed. More specifically, how much paper, glass and organic waste is collected is based on World Bank data (both as sperate waste streams or within the rest waste category). Combined with recycling and composting rates we can calculate the amount of waste that is collected separately as organic waste or as glass and paper waste. Recycling and composting rates are available for EU member states (Eurostat 2021) and per continent (David Meng-Chuen Chen et al, 2020).

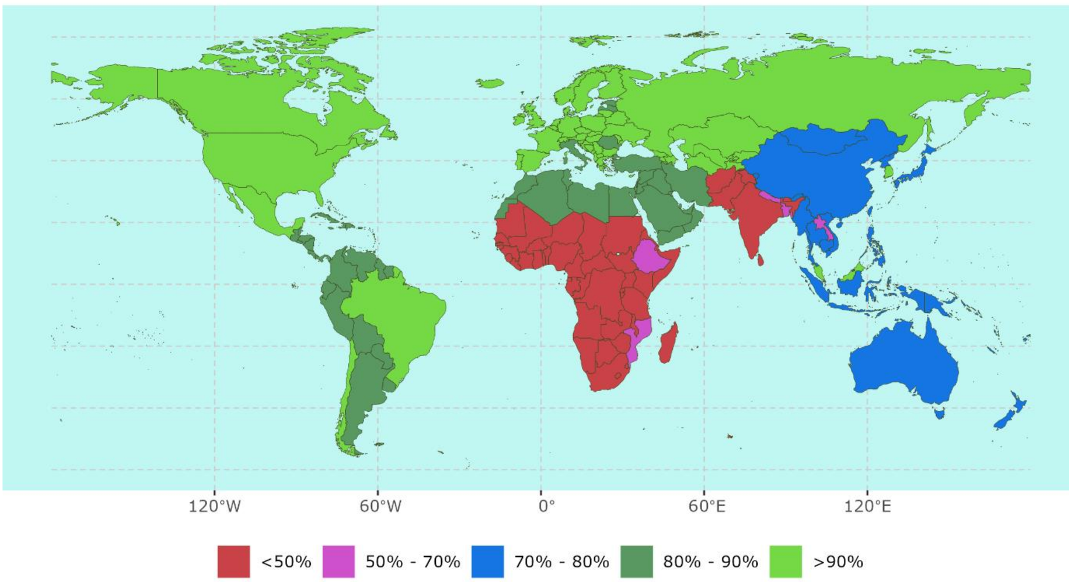

Figure 9. Waste collection rates (total waste collected divided by total waste generated, in percentage, 2014)

Source: constructed from World Bank

Figure 10 shows the global waste collection by waste type and provides insight into the extent of separated waste collection in 2014, which can be composted or recycled. The blue portion of the bars shows amount of the same waste type that is still collected as other/grey waste meant for landfills and incineration.

On average only a small percentage of global waste is collected as green waste (worldwide about 13% of organic waste is collected separately) or paper and glass waste (worldwide 45% of glass and paper waste is collected separately). These percentages do differ a lot between countries. Europe and Asia collect more organic waste separately. Glass and paper collection is higher in Europe and North America. Africa and South and Central America collect only a limit amount of waste separately.

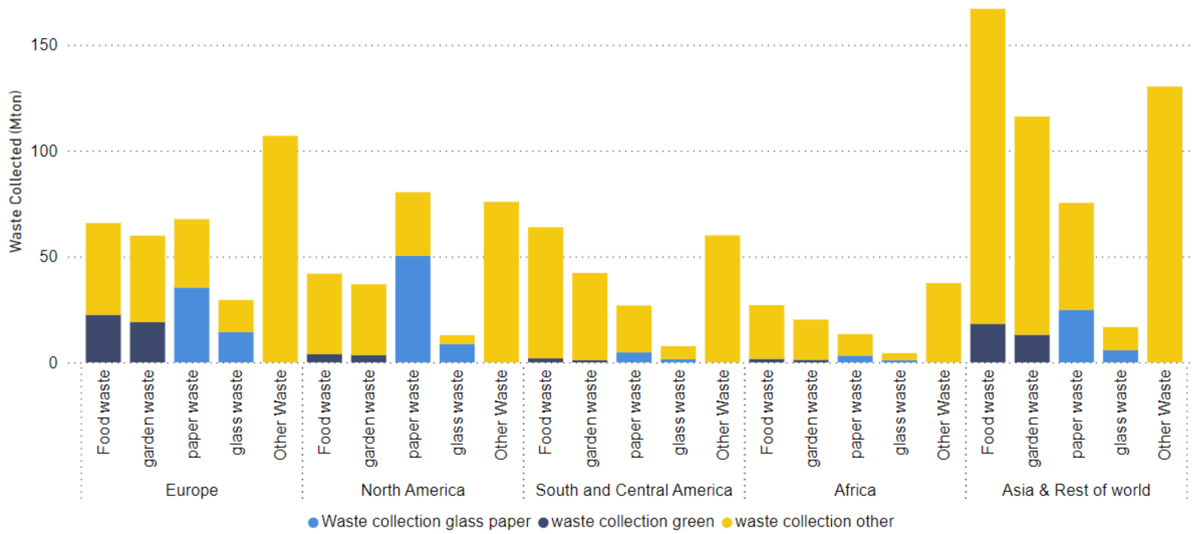

Figure 10. Extent of global waste separation (million tons waste collected)

Source: constructed from World Bank

1.4.5 Treatment of waste

Data on tons of waste treated per country is available from World Bank (Kaza, et al. 2018). Treatment methods included in data are: dumping and landfilling; incineration; recycling, and composting. The World Bank also publishes average waste treatment prices per category (landfill, incineration, recycling, composting) for 4 regions based on average income (low income, lower mid income, higher mid income, and high income). These data are combined with average cost structures published by RDC-Environment and Pira International (2003) to calculate the economic value of waste treatment options around the world (VDPB). Figure 11 shows the global average cost structures for the different waste treatment and waste collection sectors.

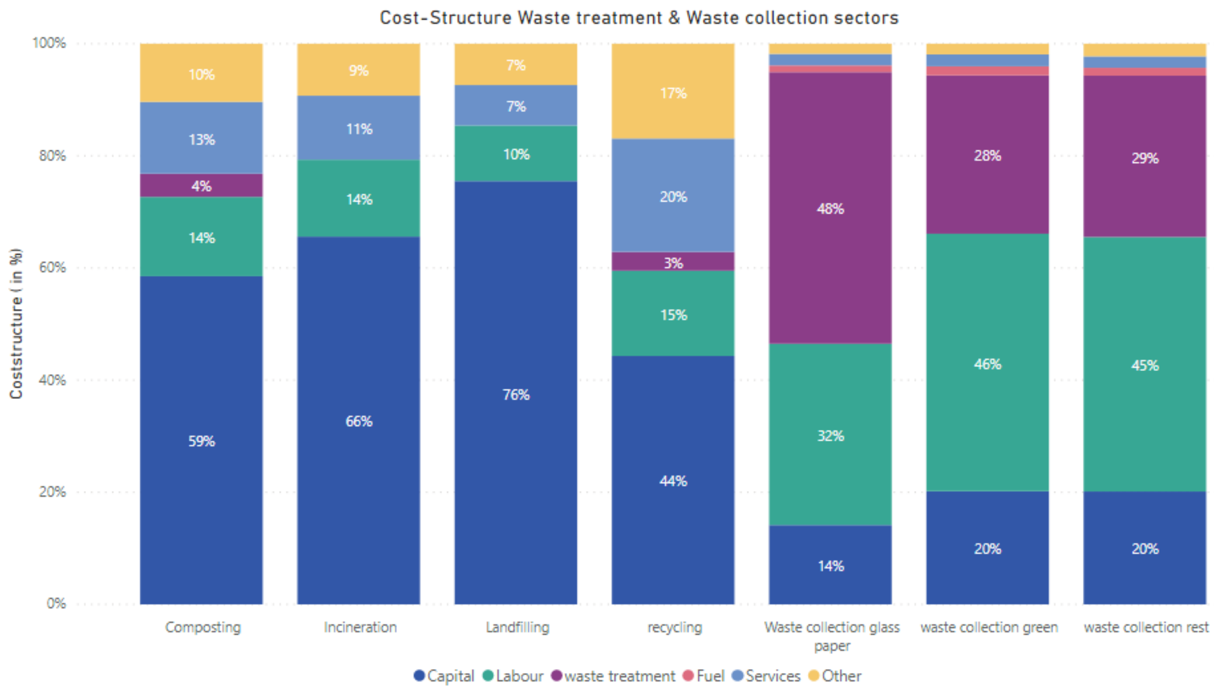

Figure 11. Cost structure Waste treatment and waste collection sectors (in%)

Source: Constructed from by RDC-Environment and Pira International (2003)

Figure 12 shows that European and Asian regions (within Asia and Rest of world) mostly use incineration as final disposal, while North America and Africa rely more on landfills. The initial share of composting and recycling also differs a lot between regions. Note that the figures below are based on actual collected data, home recycling and composting are not included in these numbers. Similarly, informal sectors engaged in waste collection (paper, plastic etc.) are not reflected in data used in this work.

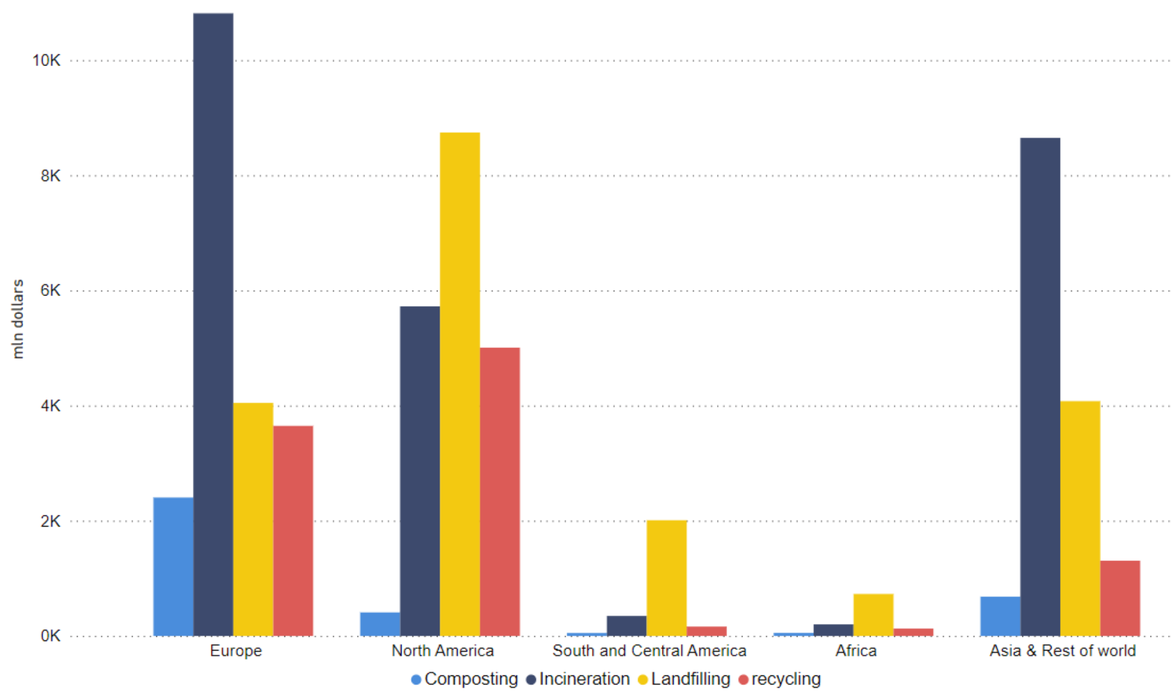

Figure 12. Value of waste treatment in various regions in million dollars, 2014

Source: Constructed from (RDC-Environment and Pira International 2003), World Bank (Kaza, et al. 2018)

1.4.6 Emissions from waste treatment/disposal

The Intergovernmental Panel on Climate (IPCC) publishes total emissions of landfilling, incineration, and composting arising from disposal of MSW, construction waste as well as industrial waste. For waste incinerated and composted, it is assumed that the emissions per ton of waste from IPCC are representative for MSW. However, for landfilled waste, this assumption does not hold. Several member states in Europe have either banned or severely taxed landfill as disposal option for MSW but landfilling of industrial and construction waste is still permitted. Using the IPCC data for landfill emissions in Europe therefore overestimates the emissions from landfill of MSW. As we could not find data of emissions of landfill for only MSW, we use the IPCC data from the USA to calculate the emissions per ton of MSW disposed at landfills. The USA emission factors are used along with tons of country specific landfill data to calculate emissions from MSW landfill for all countries.

As USA still landfills a substantial part of its MSW, the bias is much smaller than if EU data were used. However, this procedure may still lead to some overestimation of emissions of landfilling as we know that emissions from industrial waste are not exactly the same as emissions from municipal solid waste due to the consistency of the waste streams. The total emissions caused by waste treatment are shown for regional aggregates in Figure 13.

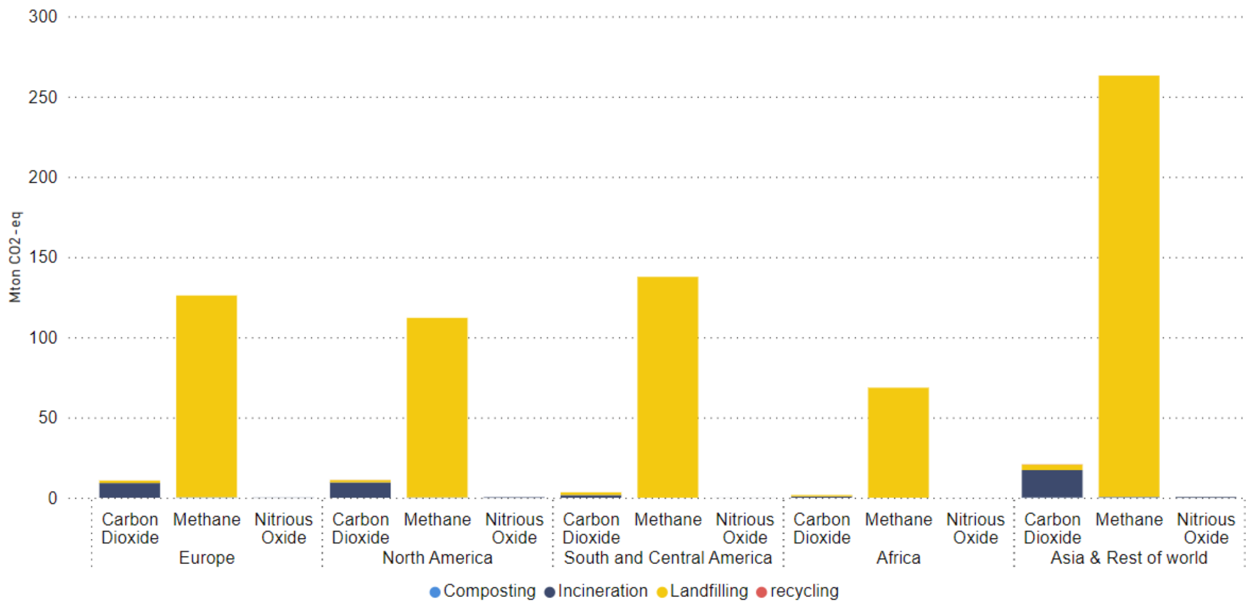

Figure 13. Emissions from waste treatment (million tons CO2 equivalent, 2014)

Source: constructed from World Bank and IPCC

1.4.7 Waste elasticities

There are two new substitution elasticities (one between consumption and waste generation and one between different types of waste collection services) included in the waste module. The first elasticity between consumption and waste generation has a low value of 0.1. Literature shows values between 0.06 and 0.47. While there is quite some variation in the estimated price elasticities, most literature agrees that the value is inelastic (Bel and Gradus, 2016). The second elasticity governs the substitution between the choice of waste collection services. As there is no literature available, we have set the elasticity at a level of 2 after a sensitivity analysis.

3. Baseline with waste module

The new waste module provides insights in directions previously outside the realm of MAGNET. To illustrate this, we run a simple baseline over 2014-2050 and look at the kind of details about waste generation and treatment that the model results can provide. We focus on how waste develops and not on having perfect baseline. Our baseline follows SSP2 assumptions (O'Neill et al., 2017). Figure 14 shows the expected growth in both GDP and population following SSP2. These changes in GDP and population are used as model inputs. According to the SSP2 assumptions, the highest GDP growth is expected in Asia and Africa and the highest population growth is expected in Africa. In Europe the population growth is expected to be slight or even negative in the case of eastern Europe. GDP growth will be moderate to average for most European countries.

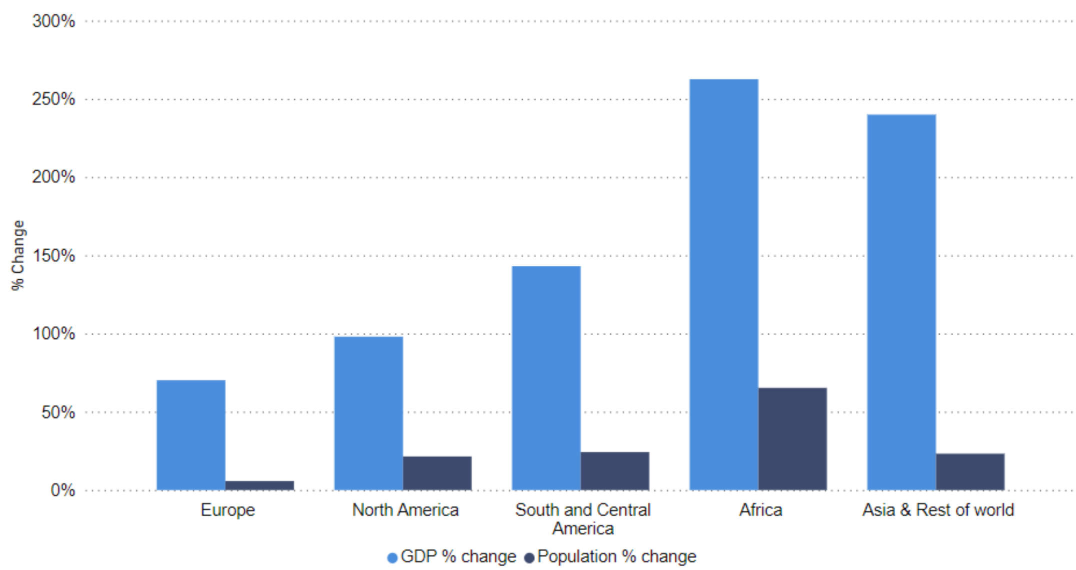

Figure 14. GDP and population development between 2014-2050

Source: MAGNET results

In addition to assumptions on GDP and population growth, we also use waste generation projections from World Bank (Kaza et al. 2018) as model input. The World bank provides projections on waste generation based on the relation between GDP per capita and waste generation (Figure 15). The base year is in line with real data and therefore not adjusted. However, the predictions about the development of municipal solid waste are shocked based on the relation between GDP growth per capita and waste generation. Within the model, the waste module would determine waste generation based on increased consumption due to GDP growth and population growth. However, without shocks, the module is more optimistic about waste generation development then the world bank observed on real data. Therefore, we adjust the trend downwards.

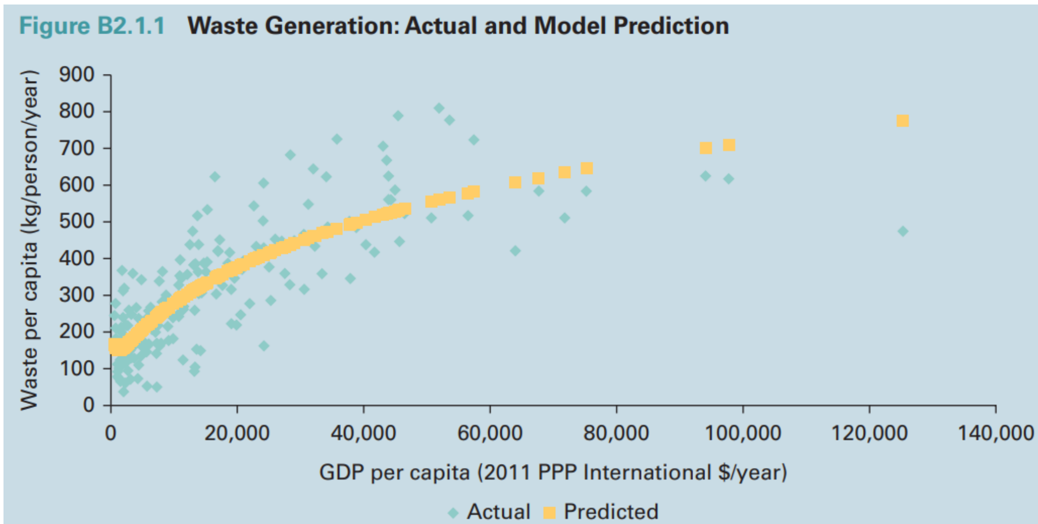

Figure 15. World bank projections: link between GDP and waste per capita

Source: Kaza et al. (2018)

MAGNET uses the relationship identified in Figure 15 to calculate amount of waste generated by a region in a given future year. Total waste generated and collected in various years and regions using this relationship, is shown in Figure 16. In all regions, waste generation and collection is expected to continue to increase. Worldwide the amount of waste collected increase by 0.6 billion tons. Most of the waste is collected as other waste. This is not expected to change in the period 2020-2050. Note that this path of waste generation development overtime can be altered in scenarios which focus on policy intervention aimed at waste generation, collection, treatment or use.

Without waste management policies, about 15% of the waste will be separately collected and be either composted or recycled. The remainder of the waste stream is collected as other/grey waste. Europe collects relatively a lot of green waste separately (on average about 30%). Northern America collects relatively more paper and glass. Separate collection is hardly present in South and Central America and Africa. Better waste management policies are needed to promote waste separation as both recycling and composting contribute to a circular economy and reduce the amount of greenhouse gas emissions associated with waste disposal. About 57% of the rest waste in 2050 will go to the landfills if current waste management trends continue. This is the least desirable option because landfills are the biggest contributor to greenhouse gas emissions.

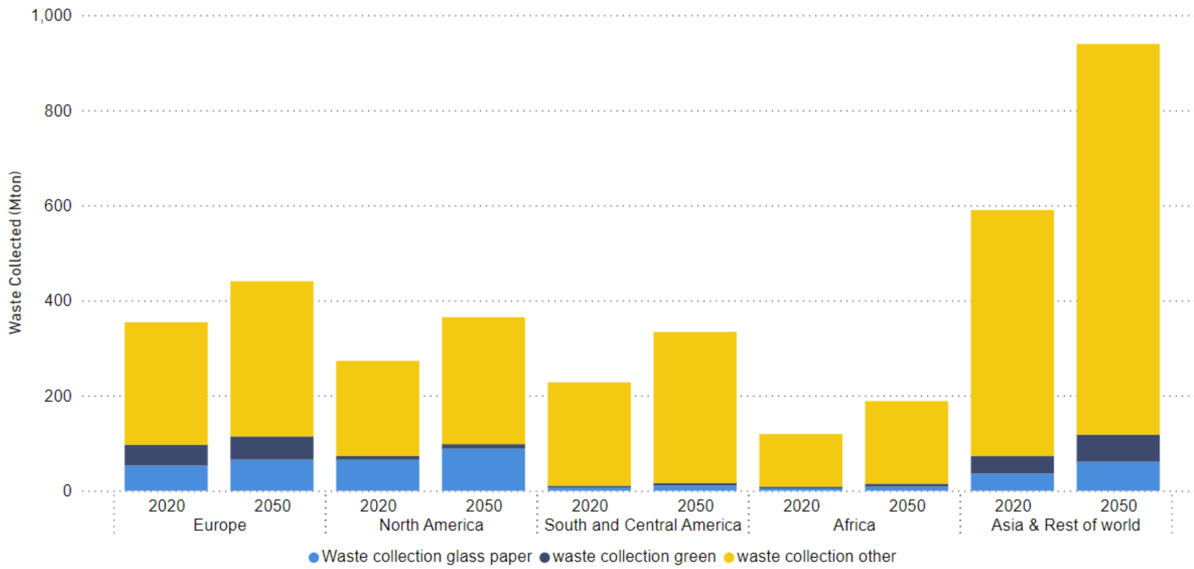

Figure 16. Waste collection 2020-2050 (in million tons)

Source: MAGNET results

Figure 17 shows the change in waste treatment production between 2020-2050. Overall, we see that final disposal (landfilling and incineration) increases the most. In the base year final disposal is the most popular waste treatment option and without waste policies this will remain the same. Composting increases the least of all waste treatment options. This is because food and garden waste are expected to increase the least of all waste types.

The extent of waste collection determines how the waste can be treated and disposed. Not all waste materials are collected in a way such that they can be recycled or composted. Figure 18 shows the share of the food and garden waste generated collected as green waste for composting and the share of the glass and paper waste generated collected for recycling. Worldwide only about 13% of all green waste is collected separately. The recycling rates of paper and glass are a bit higher. On average 44% is collected separately worldwide. Europe collects a relatively large share of green waste separately (35%). In Northern America a relatively large share of waste is collected for recycling (65%). Without further waste policies these recycling and composting shares are not expected to increase anymore in Europe and Northern America. Other regions that start with very low recycling and composting shares, are expecting to collect more organic waste, glass and paper waste separately mainly because virgin materials become more expensive in the future which makes recycling and to a lesser extent composting financially attractive.

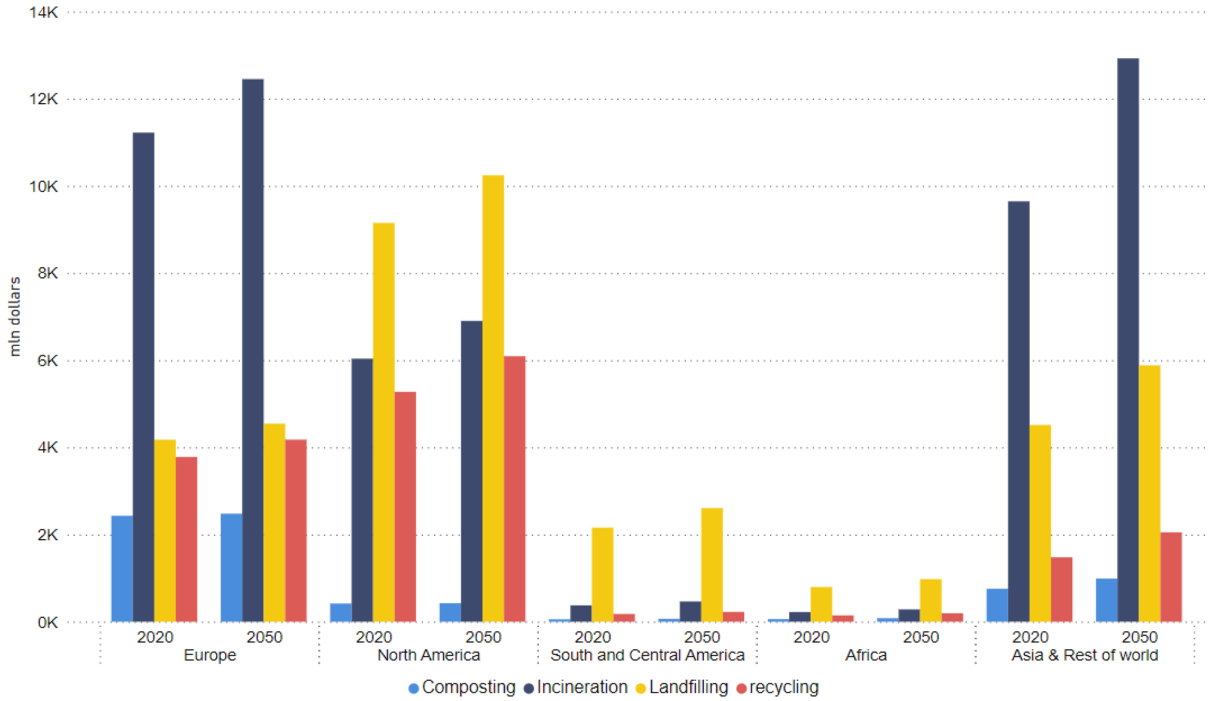

Figure 17. Waste treatment usage around the world (volume in constant 2014 prices, million dollars)

Source: MAGNET results

The results indicate that without any active efforts towards diverting more food, garden, paper, and glass waste away from grey waste collection towards green waste and recycling collection, the shares will not change much, suggesting inertia of consumer habits/attitudes.

Of the total green waste collected, between 50% to 60% comes as food waste with the rest coming from garden waste. The sources of green waste also differ across regions (Figure 19). While both food and garden waste are expected to grow, the model predicts that garden waste will grow faster than food waste. Food consumption is quite inelastic, whereas demand for dwellings and thus garden waste is expected to grow with an increase in GDP.

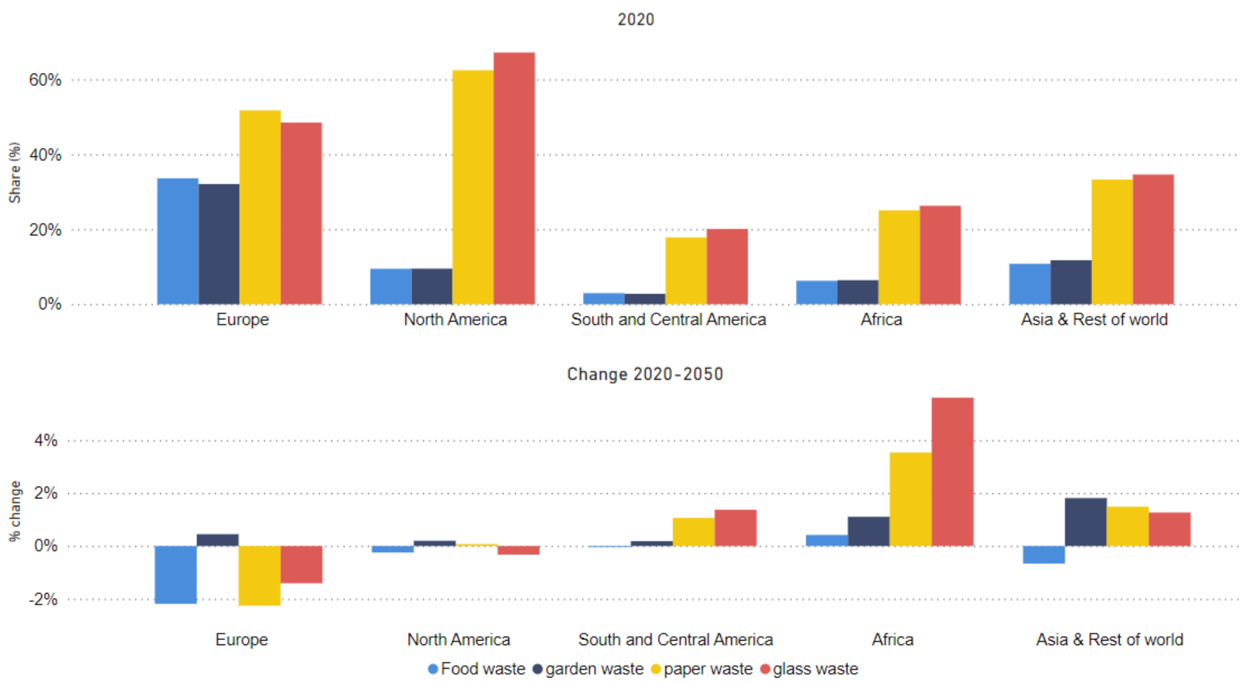

Figure 18. Share of organic waste composted and recycled in 2020 (upper graph) and % change of the share between 2020-2050 (lower graph)

Source: MAGNET results

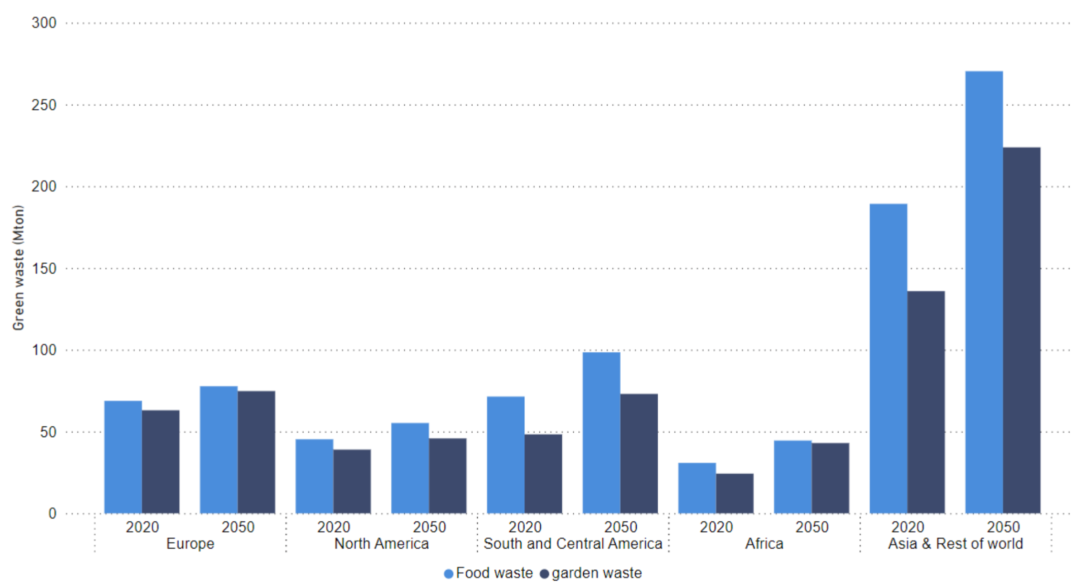

Figure 19. Composition of green waste collected (million tons)

Source: MAGNET results

As the composting service generates compost as an output, we now look at disposal of compost generated by composting sector. In the base year most of the compost produced by the composting sector is used as biofertilizer. In 2014 95% of the compost is used by the crop sectors (Figure 20). This is not expected to change a lot. As energy prices increase, the demand for bioenergy becomes a bit higher which also leads to some more use of compost in the bioenergy sectors however the change is minimal without any policies promoting the transition from fossil to bioenergy use.

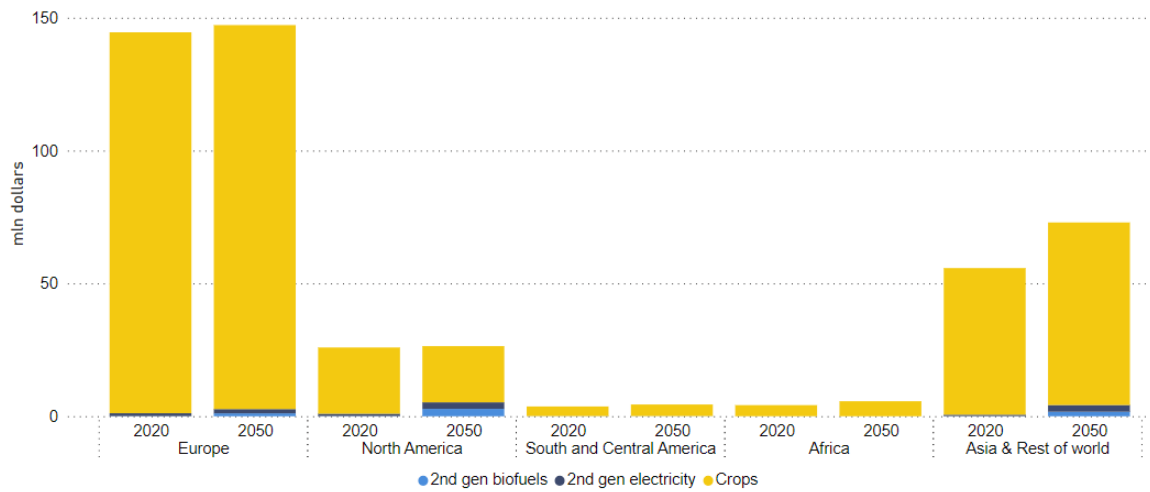

Figure 20. Demand for compost by different sectors (volume calculated in million dollars with constant 2014 prices)

Source: MAGNET results

Although the demand share of compost for biofertilizer and bio-electricity changes, this does not necessarily mean that total amount of compost used in the crop sectors declines as Figure 21 shows. Since crop production is expected to grow, both the demand for fossil fertilizers and biofertilizers increases. Overall, the share of biofertilizer in the total use of fertilizers decreases. The share of biomass use in the bio energy sector is expected to increase slightly however the use remains minimal.

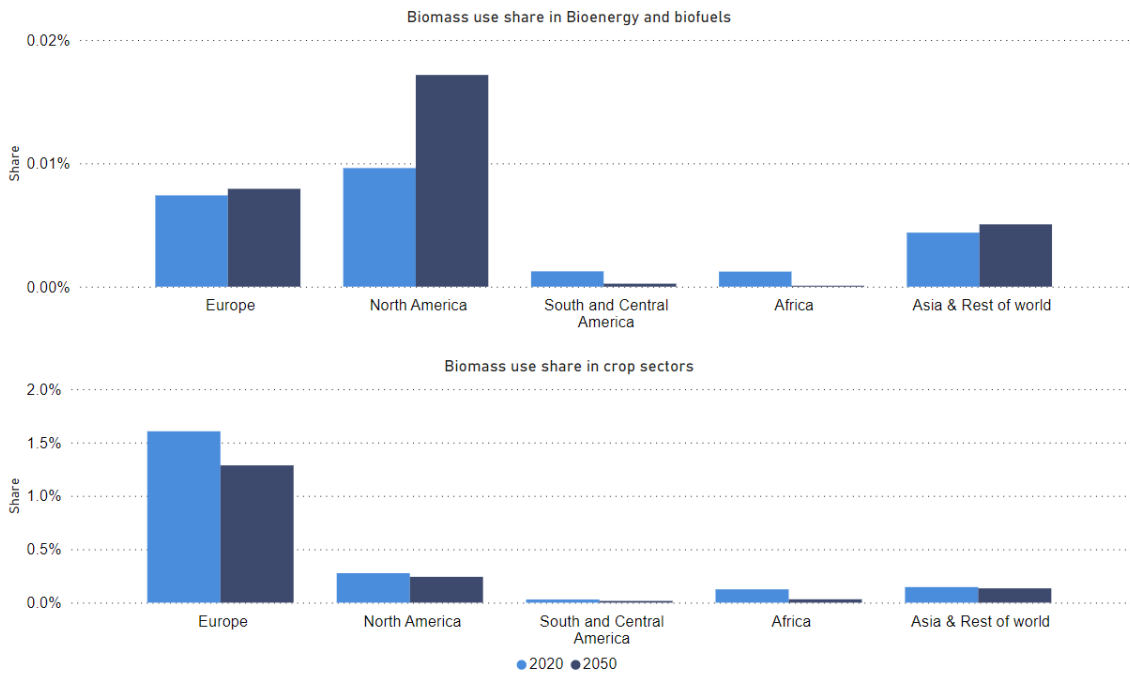

Figure 21. Demand share for biomass as feedstock energy (top graph) and biofertilizer (bottom graph)

Source: MAGNET results

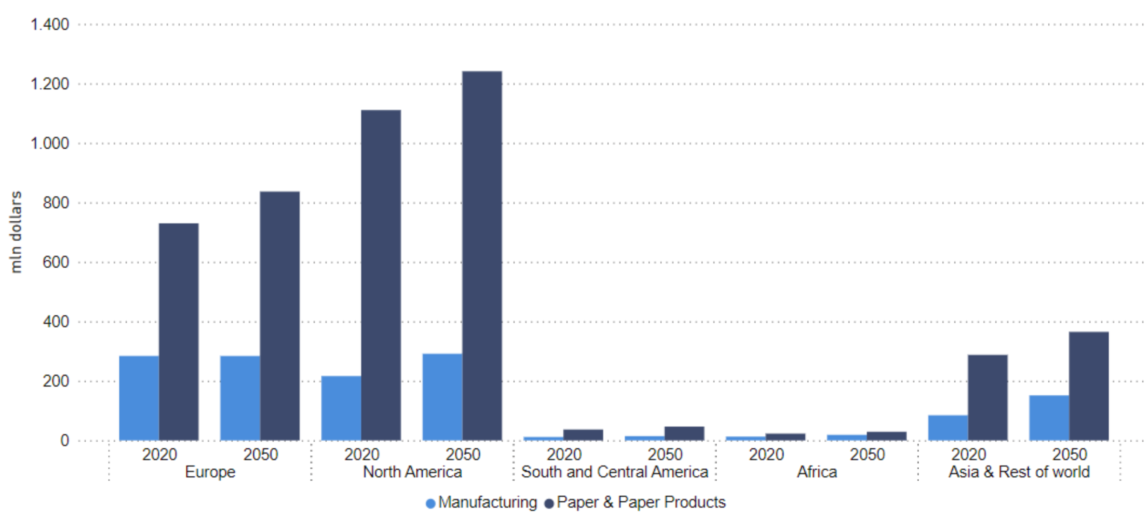

Figure 22. Demand for recycled paper and glass by different sectors (volume calculated in million dollars with constant 2014 prices)

Source: MAGNET results

While demand for compost is not expected to increase a lot, demand for recycled paper and glass is expected to increase worldwide with 15% for recycled paper and 25% for recycled glass. Figure 22 shows the demand for recycled glass and paper in the different regions. Europe and North America both use relatively large amounts of recycled paper and glass. Especially paper use is expected to increase in these regions.

Worldwide waste treatment and in this case mainly landfilling causes about 1.5% of all greenhouse gas emissions. In South and Central America which mainly uses landfilling as its preferred waste treatment option, the percentage is around 4% in 2020. As waste generation and collection is expected to increase, the number of emissions due to waste treatment will also increase in the period 2020-2050. However, waste treatment increases less than other polluting industries therefore Figure 23 shows that the share of waste treatment emissions in the total amount of emission produced falls in the period 2020-2050.

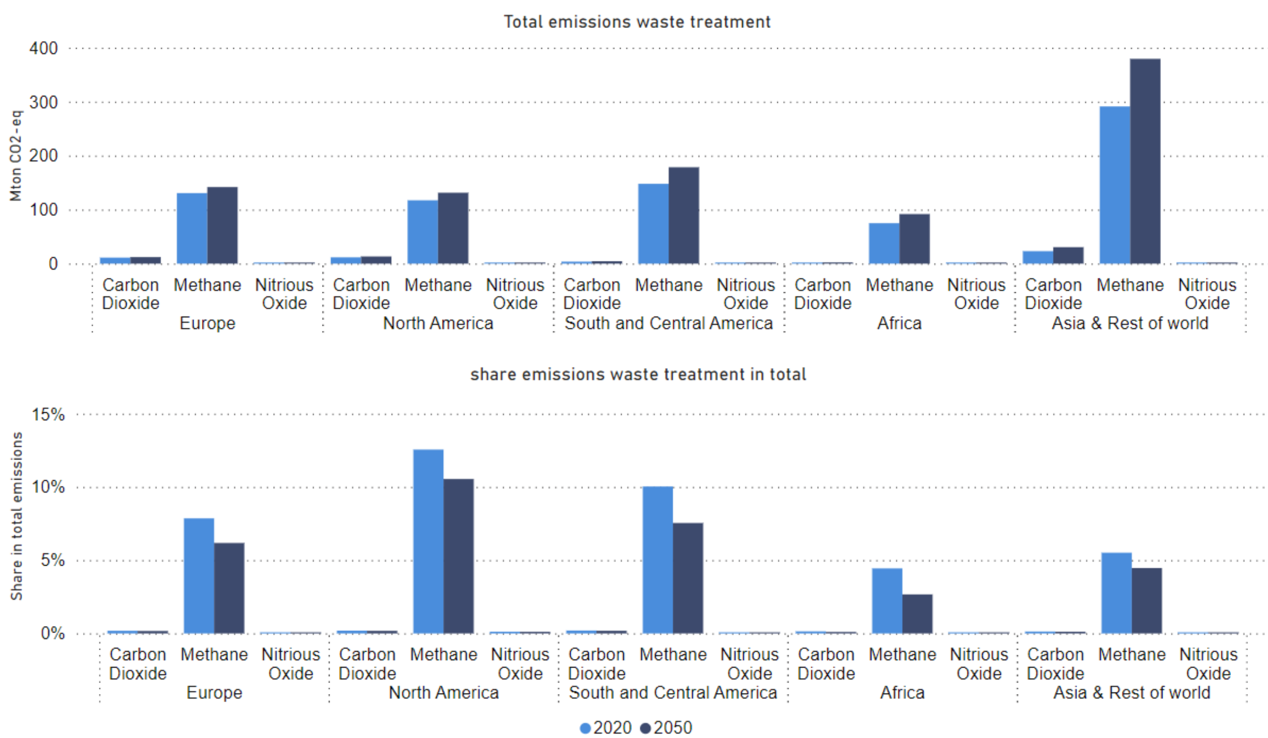

Figure 23. Emissions waste treatment in million tons CO2-eq (top graph) and as a % share in total emissions (bottom graph)

Source: MAGNET results

4. Concluding Remarks

This paper shows the first application of modelling municipal solid waste generation and treatment in a CGE framework. The MAGNET model has been adjusted to include five types of waste, three types of waste collection services and four types of waste treatment services. Both model and database updates were needed to properly integrate these new features into the model. We have chosen to model waste as a margin commodity to ensure that consumption and waste generation are linked. By modelling waste as a margin commodity, an extra price and quantity wedge is added between households and suppliers. The price consumers pay for a good includes both the market price plus the price of collecting and treating waste by the municipality. The coding changes needed to include waste as a margin commodity are described.

Data about waste generation, waste collection and waste treatment were collected and compiled into a consistent database. The data demand of this module is quite extensive and the availability of data is limited. For all 141 countries in the GTAP 10.1 database, waste data were collected. World bank data regarding production and treatment of Municipal Solid Waste (Kaza et al, 2018) were combined with data from various other sources (Eurostat 2023, RDC-Environment and Pira International 2003; Stenmarck et al, 2020). To create a complete database many data gaps had to be filled with simplifying and strong assumptions. As waste streams are important from a resource and environmental point of view, we strongly recommend enhancing data collection on waste streams in various continents. Especially a worldwide material flow database would be desirable to link waste generation to the consumption of commodities. Data about garden and food waste should be extended. In the World Bank database only 38 countries report garden and food waste separately. Garden and food waste data were estimated for all missing countries using a world average share. This split can be enhanced by using the food loss and waste database, recently published in Gatto (2024).

Matching waste types and consumption of GTAP commodities also proved difficult in some cases. For example, GTAP does not distinguish glass as a separate commodity but aggregates this in a sector called "Manufacture of other non-metallic mineral products (nmm)". This sector also contains among others production of cement. In this paper it is assumed that generation of glass waste can be linked to the consumption of nmm commodity. In a future expansion of the module it is recommended to separate glass as a distinct commodity. Garden waste is currently matched with the sector dwellings (dwe) in MAGNET. The sector dwellings does not differentiate between urban and rural dwellings, which regarding garden waste would be an important distinction to be made in the future.

A simplistic SSP2 baseline was constructed after including the new waste module. The baseline results show that waste generation and collection is expected to increase by 45% in the period 2014-2050. Other/Grey waste is expected to grow the most with 53%; food waste is projected to grow the least with 35%. Without waste management policies this will mean that more waste is incinerated or landfilled, therefore adding to climate change issues. Food, garden, recyclable glass and paper waste will continue to be thrown in with the grey waste streams and be send to final disposal options. The demand for recycled materials and biomass does increase but this will not influence consumer behavior regarding waste disposal. Therefore, additional waste management policies are needed and the new module in MAGNET can be used to evaluate the impact of these policies.

The current baseline is driven by SSP2 macros shocks (O'Neill et al. 2017) and waste generation trends provided by the World Bank (Kaza et al, 2018). The World Bank only provided the trends in the development of the total MSW waste but did not analyze development of different waste types. As a future extension it will be important to investigate waste development shocks per waste types instead of just the total. For example, Islam et al (2022) show that garden waste is expected to grow faster than other MSW types.

The benefit of modelling the cradle to grave flow of waste allows one to run simulations mimicking interventions at every stage of waste stream. The framework can be used to exogenously reduce consumer waste generation (as before) but it now provides a peek into the waste streams and the bio-economy sectors. Better still, we do not need to exogenously impose a change on consumer waste behavior but we can get these outcomes as a result of various policies instruments available such as – tax on other waste collection, subsidizing green waste collection and recycling, subsidizing composting sector, subsidizing use of bio-fertilizers in agriculture and so on. The call for a shift towards a more sustainable diet also implies a shift in the composition of food waste. Gatto et al. (2023) find that a substantial change in diet affects the composition and global flows of food loss and waste (FLW), creating environmental spillovers in terms of reuse possibilities. A reduction in total FLW generation is generally associated with a more sustainable diet (Willet et al. 2019, Springmann et al. 2018). Gatto et al. find that increased demand for plant-based foods commonly associated with high FLW shares increases FLW along global food supply chains. The framework developed in this paper can be used to evaluate the impact of policies, technical change and changes in consumer preferences to achieve these diet changes and their impact on emissions, biobased sectors and trade-offs in SDG terms.

This method also allows an analysis of the consequences of using flat fee pricing for waste collection as compared to using a pricing system based on the amount of waste generated. In many countries waste collection is still priced with a flat fee. A flat fee means that the fee households pay for waste collection is not related to the actual amount of waste produced. Therefore, the marginal price of waste collection for households is equal to zero. The impact of such a policy can be recreated by implementing a subsidy on the price of the margin commodity such that the cost of waste collection are again zero.

While the module presented in this paper already provides a lot of handles to analyze the issues related to municipal solid waste management, some extensions can still be explored. For one the current model only takes collected waste into account. A large number of regions in the world collect only part of their municipal solid waste. A significant part, for some regions over 50%, is (illegally) dumped. Dumped waste can cause pollution and social clean-up costs. Therefore, it would be important to extent the model to include the non-collected or dumped waste.

So far, the module only covers MSW. While MSW has a high political profile because of its complex character, its distribution among many sources of waste and its link to consumption patterns, it only covers about 10% of the total waste stream (Eurostat, 2023). Therefore, it is important to extend the module with waste generation along the supply chain. A first implementation of this was done for food waste generation in the EU (Bartelings and Philippidis, 2024) but this should be further extended to include also regions outside of the EU and other waste types.

Recycling is limited to paper and glass recycling in the current framework. Other waste materials like metal and plastics are left out of the analysis. By including these types in the model over 95% of the municipal solid waste stream would be included. These types however will need some further extensions to the model. For glass, paper and organic waste it is reasonable to assume that waste can only be recycled or composted if separated by the household as post-separation is not yet economically viable (IEA, 2013). Research shows that especially for plastics and metal, post separation instead of source separation can be a cost-efficient option (Dijkgraaf & Gradus, 2020). That would mean that post collection and cleaning need to be added as a sector in the model.

In the current setup of the module, it is assumed that waste cannot be traded and needs to be treated domestically. In reality waste is a traded commodity. A useful extension of the module would be to include trade in waste streams. Furthermore, the baseline could be enhanced by including more modules of the MAGNET model to better represent endogenous technical change by explicitly introducing R&D sectors (Smeets-Kriskova et al. 2017) or by including better empirical projections of sectors total factor productivity growth.

Finally potential innovations in the use of recycled and composted waste materials could be considered in the model. For example, while not currently legal in EU, Japan provides a good example of food waste use as animal feed. With increased demand for local sourcing (fueled also by COVID 19) legalizing use of swill as animal feed could be future possibility.

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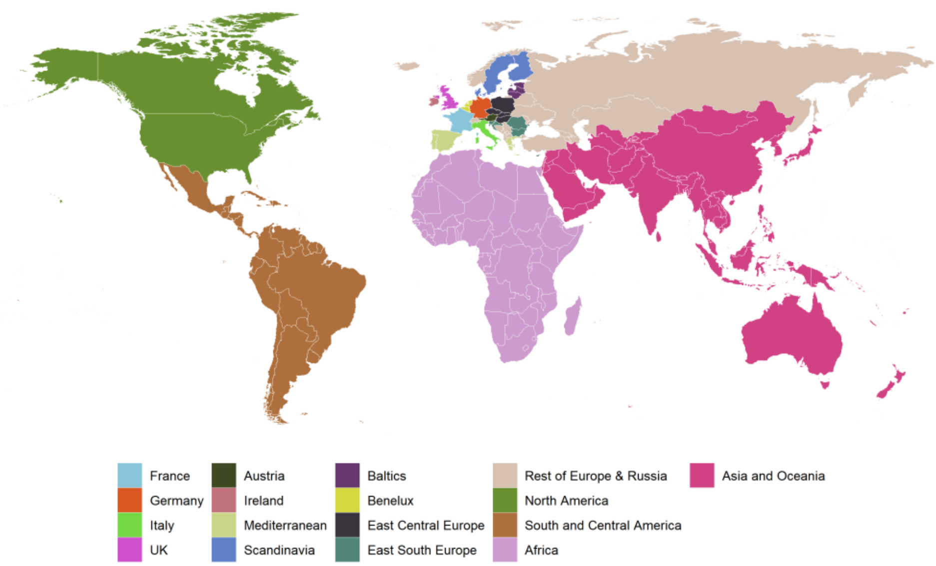
Appendix 1 Regional and sectoral aggregation



Sector type	Sector
Crop, forestry, fishery sectors (11)	Cereal grains; Crops; Energy crops from plantations; Fishing; Forestry; Oil seeds; Paddy and processed rice; Plant Fibers; Sugar cane, sugar beet; Vegetables, fruit, nuts; Wheat
Livestock sectors (6)	Animal products; Beef live animals; Cattle, sheep, goats, horses; Poultry live animals; Raw milk; Wool
Processed food sectors (10)	Beef meat; Crude vegetable oil; Dairy products; Meat products; Meat: cattle, sheep, goats, horse; Poultry meat; Processed food; Processed rice; Sugar and molasses; Vegetable oils and fats
Energy sectors (17)	Gas distribution; 2nd gen biofuel; Biodiesel; bioelectricity; biofuel kerosine; bio-gasoline; Coal; Crude oil; Electricity from coal; Electricity from gas; Electricity from hydro; Electricity from nuclear; Electricity from wind; Electricity transport; Ethanol 2nd gen biofuel; Fossil kerosine; Gas
Industry sectors (9)	Animal feed; Chemicals sector; Fertilizer; Manufacturing; Pellets sector; Residue sector;

	Textiles, leather and wearing apparel; Wood products; Paper products and publishing
Service and transport sectors (4)	Aviation; Food services (trd, ros, osg); Services; Transport excluding atp
Waste collection sectors (3)	Waste collection glass paper; Waste collection green; Waste collection rest
Waste treatment sectors (4)	Composting; Incineration; Landfilling; recycling