LCI calculation tools for regionalised waste treatment - General introduction

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Title picture Waste dump in Jefferson County, Denver county, CO, United States in April 1972. As a reminder that rather informal disposal methods were commonplace also in developed countries not so long ago. Photo by Bruce McAllister, U.S. Environmental Protection Agency from the Documerica-1 Exhibition. Public Domain from Wikimedia Commons https://commons.wikimedia.org/wiki/File:JEFFERSON_COUNTY_DUMP._(FROM_THE_DOCUMERICA-1_EXHIBITION_FOR_OTHER_IMAGES_IN_THIS_ASSIGNMENT,_SEE_FICHE_NUMBERS_38..._-_NARA_-_553039.jpg (10 Jul 2017)

Significant digits Figures in this report often feature several digits. This is not to imply that all the shown digits are really significant or that the data displayed is very precise. Showing several digits helps to minimise the avoidable accumulation of rounding mistakes along the chain of calculations performed here, and in possible future studies referring to this data.

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Contents

1 Summary

This report presents the calculation tools created to calculate waste-specific inventories of waste disposal in developing countries. Focus is on the disposal in open dumps, unsanitary landfills and open burning, but inventories for municipal incineration and sanitary landfills are also possible.

The underlying process models are built on the existing models already used for waste disposal in ecoinvent (Doka 2003) and the updates (Doka 2013, 2015). The technical details of the models are presented in separate reports.

The new tools allow calculation of inventories and produce Ecospold2 XML-Files (ES2) which can be read into EcoEditor(EE) and via that route become part of the ecoinvent database.

Waste-specific process inventories are complex as

- they usually inventory *a part* attributable to a specific waste material of a disposal process (so they represent a material-based subdivision of multi-input processes)
- they can *produce usable recyclates* or useful energy apart from providing disposal services (so they are multi-output processes)
- they can incorporate *disposal of secondary wastes* further downstream, e.g. bottom ash landfilling from waste incineration (so they encompass more than one real-world activity)
- they can represent treatment of *complex waste* composed of dissimilar materials, e.g. paper laminated with plastic, or wooden window frames with metal fittings.

Apart from information characterising the waste (composition, heating values, degradabilities, burnabilities), the regionalisation requires that the local circumstances of a disposal site are described using local parameters like climate – e.g. temperature, precipitation – and technical parameters like landfill height or gas collection rates. This increases the complexities and raw data demand necessary for disposal inventory calculation even more. The tools present a vehicle to apply all these different aspects in a consistent manner. Nevertheless it is recommended that for transparency authors not only create process inventories, but write also conventional text reports detailing the raw data, choices, assumptions and sources.

The present tools were developed 2016–2017 by Gabor Doka in a project for Sustainable Recycling Industries SRI, financed by the Swiss State Secretariat for Economic Affairs SECO, commissioned by the Swiss Federal Laboratories for Materials Science and Technology EMPA, mandated by the ecoinvent Association. The reports were reviewed by Ivan Muñoz of 2.-0 LCA consultants.

2 Introduction

2.a A look back

Inclusion of waste disposal processes in life cycle inventory data has a long history. The ecoinvent database featured waste disposal activities since its very first implementation in 1994 – then created by Martin Ménard (ESU 1994). Already in these instalments, disposal activities were *waste-specific* and were aimed to depict end-of-life for individual waste materials and products and not merely an average input of treated waste. But as at that time the database was targeted at Swiss foreground processes, the disposal methods were those used in Switzerland: municipal incineration and sanitary landfilling. Also in later instalments of ecoinvent, modern waste disposal as performed in Europe was inventoried, and to avoid data gaps those treatments were used as approximation for disposal in the whole world. The need to look at less managed disposal activities, which might perform significantly differently from an environmental viewpoint, was noted previously (Doka 2003-I:15). With the present report and accompanying calculation tools, more basic and low-tech disposal methods, as they are frequent in many parts of the world, can be inventoried for LCA.

2.b Waste generation and treatment in developing countries

2.b.1 Waste generation in developing countries

The magnitude of solid waste generation is commonly linked to economic development and urbanization (Hoornweg et al. 2012:2). As countries increase in economic wealth they tend to get more urbanized. With rising standards of living and disposable incomes, consumption of goods and services increases, which commonly increases the generated amount of wastes.

The annual waste generation can be as low as 100 kg per capita in economically poorer countries and rises to five times that amount or more in rich countries, see Fig. 2.1.[1] Waste generation rates can also be large in small island nations, like the Maldives, Antigua & Barbuda, or Bermuda. Presumably dependence on imported goods, dominance of tourism and associated goods is a factor in this finding. There are however also small, tourist destination islands like Saint Lucia or Dominica with lower reported waste generation rates than their economic wealth would suggest.

[1] Gross National Income per capita (GNI) is used here as parameter for a nation's economic wealth. Other parameters such as share of urban population, life expectancy, or literacy could be used for these plots. All these are usually highly correlated. GNI is the parameter with the widest coverage for the world's nations and using it as the x-axis value minimizes data gaps in the correlation plot.

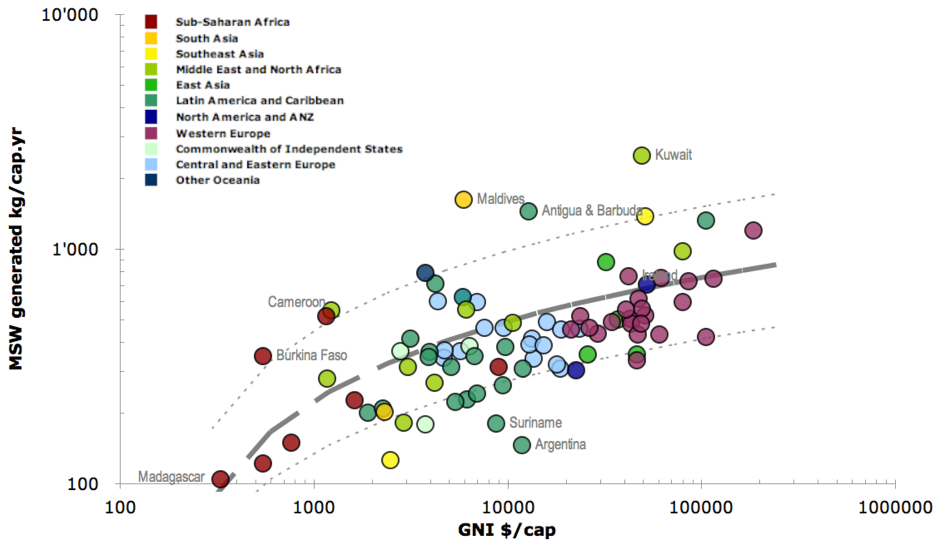

Fig. 2.1 **Solid waste generation in various countries per capita plotted against Gross National Income (GNI) per capita.[2] Colours indicate world regions. Lines indicate a logarithmic growth according to MSW = a*ln(GNI) – b, with the mean values a = 115 and b= 570.**

Though there is large variation between nations, there is no indication of a turnaround with economic wealth. An Environmental Kuznets effect is not visible at this stage (waste mass), though when heeding effects from the waste's treatment there might be, as treatment types tend to become more vigilant and sophisticated.

Frequently there are heterogeneities within countries – especially in large countries. These heterogeneities can be caused by differences in urbanisation, income levels or other factors. An example is displayed for the nine provinces of South Africa. Waste generation rates from a 1998 publication (DWAF 1998) are plotted against the per-capita Gross Domestic Product attributed to that region, based on 2002 data given in (DEA 2012:Tab.3+4).

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2 Data on GNI is from World Bank using the Atlas method and expressed in current US$ http://databank.worldbank.org/data/reports.aspx?source=world-development-indicators (10 Dec 2016). Data on MSW generation was calculated from UN Statistics Division data on "Municipal Waste Collected" (kg/yr) divided by "total population served by municipal waste collection" (%) and divided by population (https://unstats.un.org/unsd/ENVIRONMENT/Time%20series.htm#Waste , released Nov 2016). GNI data was matched to the year the MSW data was measured.

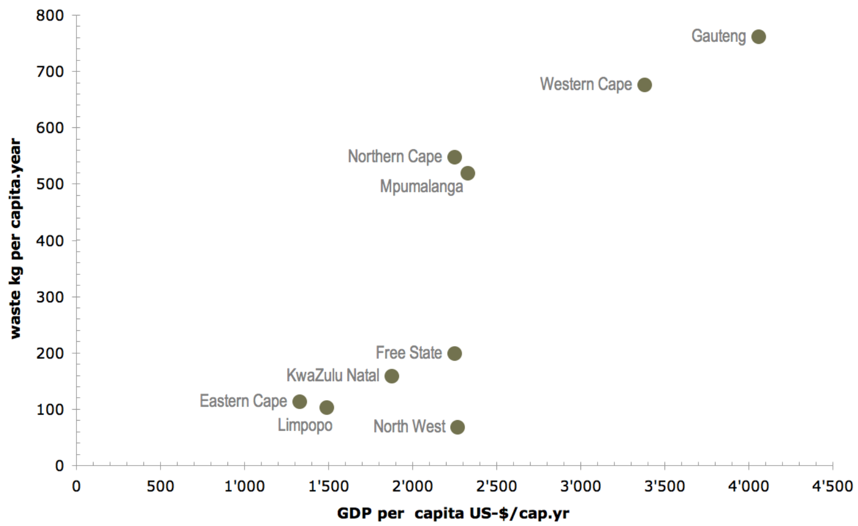

Fig. 2.2 Municipal waste generation in nine South African provinces plotted against Gross Domestic Product (GDP) per capita.

Also here a coarse trend is apparent that waste generation increases with economic wealth. Per-capita GDP is used in Fig. 2.2 as opposed to per-capita GNI in Fig. 2.1. GDP measures all economic activities within a geographic area, while GNI measures income of inhabitants ("nationals") regardless of where it is generated. It is also visible that even at this level of detail and even within country, economic wealth is obviously not the only determining factor. Four provinces show very similar per-capita GDP, but have very different waste generation by almost one order of magnitude (Northern Cape 547 kg/cap.year, Mpumalanga 518, vs. Free State 199, North West 68).

2.b.2 Waste composition in developing countries

A change in waste composition with economic development is also observable, see following figures, which were based on United Nations statistical data. Low-income regions have solid waste with a high content of putrescibles (fresh biomass and food waste). With increasing income the relative share of paper and plastic increases, while content of putrescibles decreases. One reason for this is the increased consumption of manufactured, store-bought and convenience goods, with its associated packaging waste (Hoornweg et al. 2012:3). Please note that these charts show relative shares in waste composition, not absolute masses.

While some trends of waste composition change with income level emerge, it is also evident that large differences and variabilities remain. These differences can be attributed to differences in consumption patterns and culture, as well as dissimilarities in statistical coverage.

Waste materials reflect the consumption patterns and differences in consumed products will therefore have influence on average waste composition. If for instance houses are frequently built from wood and not bricks or concrete, more wood will be found in waste. Heating sources can also influence waste composition. Where coal or wood fuel is frequent, more ash will be present in waste than with gas, oil or electrical heating. This could contribute to the decreasing trend observed for "other inorganic material" in Fig. 2.3, i.e. solid fuels are probably more frequently used in low-income countries. Geography and climate can influence city areas, e.g. amount of greenery, parks, gardens etc and their resulting wastes. In dry locations street sweepings – presumably wind-blown – can be as much as 10% of a city's waste stream (Hoornweg et al. 2012:17).

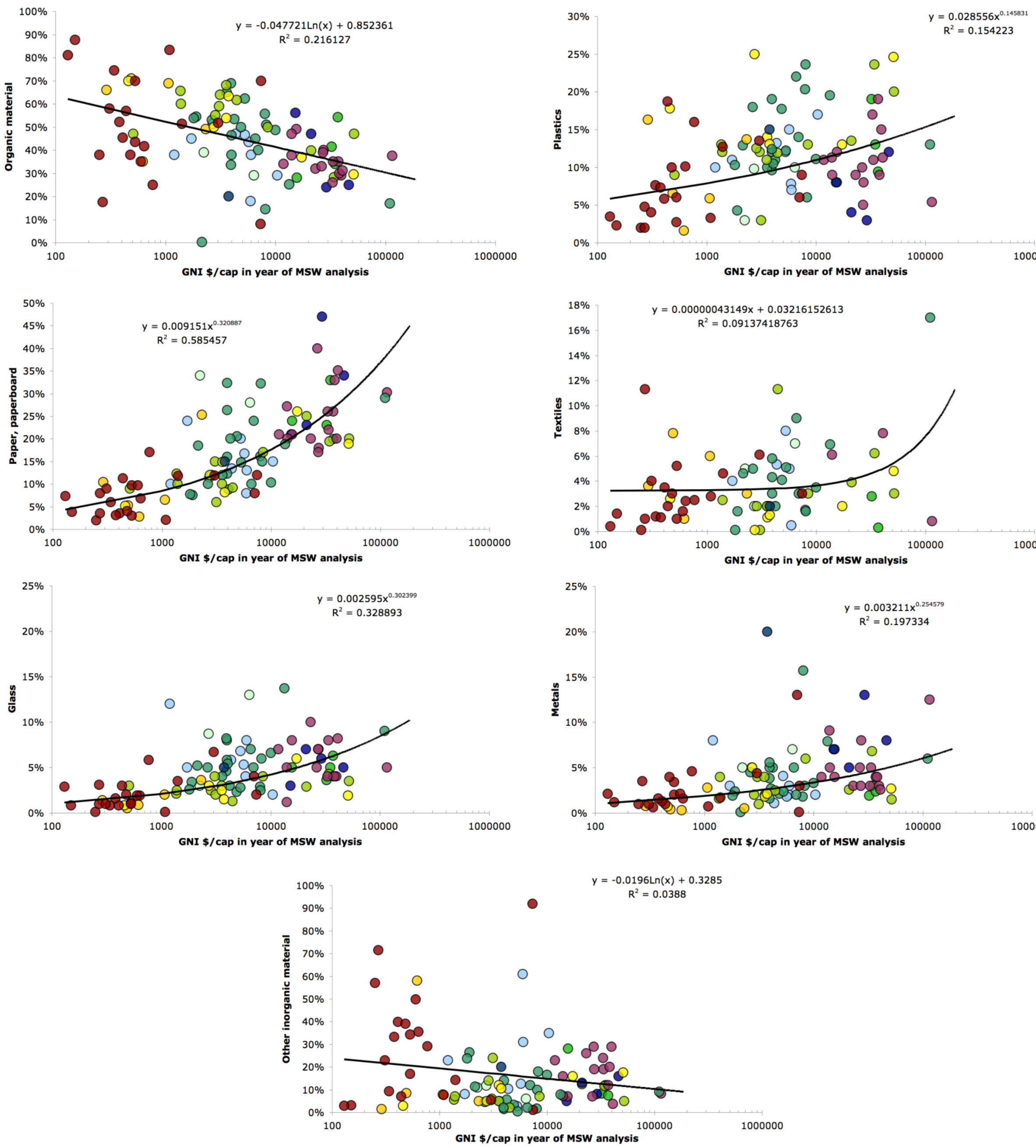

Fig. 2.3 Fractions in solid waste in various countries per capita plotted against Gross National Income (GNI) per capita.[3] Colours indicate world regions cf. Fig. 2.1. Some data relating to separate collection only was not included (Thailand, Kazakhstan, Denmark, Germany, Ireland, Italy, Luxembourg, Sweden) as was obviously incomplete data (Monaco). Regression lines with different approaches were used (linear, exponential, potential, logarithmic) and the one with the best fit is shown.

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3 Data from UN Statistics Division, based on UN questionnaires, EU or OECD statistics, "Composition of municipal waste" (https://unstats.un.org/unsd/ENVIRONMENT/Time%20series.htm#Waste, released Nov 2016). GNI data was matched to the year the composition data relates to. Data on GNI is from World Bank using the Atlas method and expressed in current US$ http://databank.worldbank.org/data/reports.aspx?source=world-development-indicators (10 Dec 2016).

2.b.3 Waste collection in developing countries

Waste collection is the transport of solid waste from the waste-producing activity to the point of treatment or disposal. Collection can include street pickup from waste bins placed outside residences, pickup from community bins at formal collection points or from waste dumped at informal heaps, e.g. end of the street heaps. Collection includes waste source-separated at the waste-producing activity to be recycled, e.g. glass, paper etc. according to local collection schemes.

For average national waste collection rates an increasing trend with growing economic wealth is apparent in Fig. 2.3. The saturating plateau, i.e. collection rates close to 100%, is reached for GNI values above 10'000 $/capita.year. Waste collection is usually more abundant in urban areas, as wild dumping and littering leads more quickly to complaints and a communal response than in rural areas.

In low-income countries waste collection services make up the bulk of a municipality's solid waste management budget (Hoornweg et al. 2012:14).

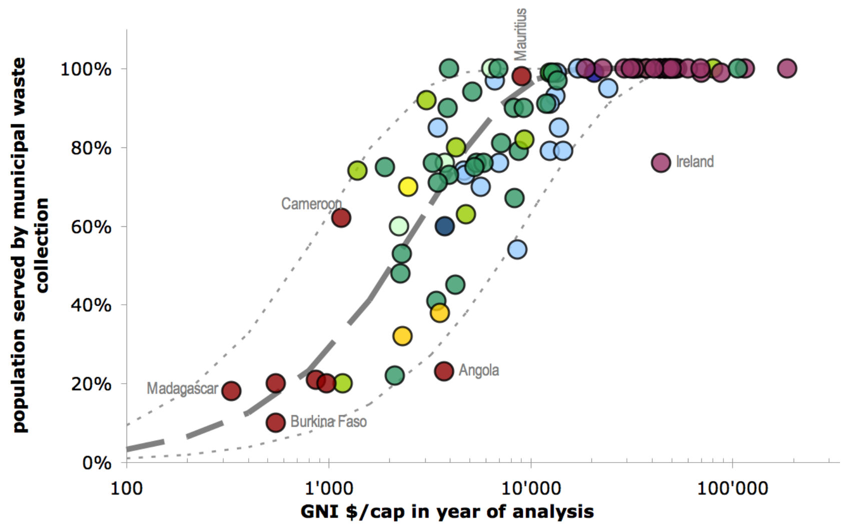

Fig. 2.4 Municipal waste collection in various countries plotted against Gross National Income (GNI) per capita.[4] Colours indicate world regions, cf. Fig. 2.1. Lines indicate a logistic growth according to coll = 1–exp(–k* GNI) with a median of k=3.32E-4. Some data relating to urban areas only was not included (Kenya, Tunisia)

The separation of waste by waste generators themselves is not commonplace in developing countries (Wallace 2015). The mixing up waste materials of makes potential recycling options more difficult.

2.b.4 Waste pickers, scavengers and informal recycling

Some waste might be diverted from final disposal through recycling. This depends not only on the material but also the form and state the material was used in the waste product. For instance a paper label on a glass bottle will hardly find its way into paper recycling. While formal recycling is often not established in developing countries, there can be considerable circumstantial informal recycling. Hoornweg et al. (2012:VII) estimate that there are more than two million informal waste pickers or

[4] Data on MSW collection is from UN Statistics Division, based on UN questionnaires, EU or OECD statistics, "Total population served by municipal waste collection" (https://unstats.un.org/unsd/ENVIRONMENT/Time%20series.htm#Waste, released Sept 2016). GNI data was matched to the year the collection data was measured. Data on GNI is from World Bank using the Atlas method and expressed in current US$ http://databank.worldbank.org/data/reports.aspx?source=world-development-indicators (10 Dec 2016).

scavengers worldwide. This can include a variety of activities, like door-to-door collection of special items, or waste picking from curbside depots or street dumps, or waste picking from dumps and accessible landfills.

Some aspects of informal waste recycling, e.g. burning off insulation from electrical cables to obtain recyclable copper, can be inventoried with the open burning model presented. The calculation models are focused towards final waste treatment in dumps, landfills, incinerators. Simple diversion of material to recycling processes should be heeded in the production volumes.

2.b.5 Waste disposal in developing countries

Patterns of household waste disposal methods in developing countries vary according to climate, housing conditions, availability and cost of waste collection services, local regulations, cultural and other factors. Also the characteristics of the waste itself (smell, attractiveness to flies and rodents) determines disposal habits. Households in hot, humid climates have incentive to dispose of waste immediately. In lower income countries a city's single largest budgetary item is often solid waste management (Hoornweg et al. 2012:1).

In communities where the primary waste collection does not exist – like in many rural areas – open burning is a common disposal method.

Where collection exists, the collected waste is usually hauled to open dumps. These open dumps are often uncontrolled landfills without leachate collection and often pose hazards in the form of vermin, uncontrolled fires and unsanitary conditions. In this environment waste scavengers – often children – pick out reusable material.

Energy production from waste via incinerator or landfill gas capture is very uncommon in developing countries. UN data suggests that significant shares of waste going into energy production might be expected in countries with average per-capita income of significantly larger than 10'000 US$.[5]

What is a developing country?

Though there is no unanimous definition, a developing country is a nation or state with a less developed industrial base relative to other countries. Often gross national income (GNI) per capita is employed as a metric to discern state of development. In the classification of the International Monetary Fund IMF, all except the highly industrialised countries are labelled "developing", which includes for instance Russia and a majority of the Commonwealth of Independent States and Eastern Europe, while Northern America, Japan, Australia, New Zealand and the majority of Western Europe are "developed". The IMF excludes many oil exporting countries, a high GNI notwithstanding, from being classified as developed on the grounds that export trade is not diversified, i.e. too reliant on one branch alone. IMFs classification therefore presupposes that a varied and heterogeneous export trade is also a defining requirement of a developed country. Another classification, e.g. by the UN, employs the Human Development Index (HDI) which is an aggregate indicator combined from life expectancy, education, and per capita income.

The term "developing" has been criticised as implying inferiority and a paradigm of Western economic development. Suggested alternative terms like "periphery country" do not seem to alleviate

[5] See data from United Nations Statistics Division, Energy Statistics Database, Municipal Wastes for energy produced from municipal waste. http://data.un.org/Data.aspx?q=waste&d=EDATA&f=cmID%3aMW (19 May 2016).

this. Sometimes a third category "newly industrialized country" is used for countries in an intermediate position.

The term "developing country" might be obsolete for present times. Only in the period of approximately mid-1950s to mid-1990s the world income distribution (population vs. income per day) had *two* local maxima, cf. Fig. 2.5. From this observation it can appear as understandable that a desire arose in the past to classify countries into "developing" and "developed". Both these local maxima continued to increase between 1955 and 1995 – i.e. also the already developed nations were progressing further economically. Since then the developing nations completely merged into the group of more developed countries. For the most recent data (2015) the two maxima have been entirely fused again into a single maxima distribution and a distinction between two discrete classes "developing" and "developed" has become quite arbitrary. In 2016, the World Bank has discontinued the classification of countries into "developing" and "developed", but still uses a flexible four-step classification according to per-capita income levels. Notably, there are also movements of countries into lower income classes, e.g. in January 2016 Venezuela, Equatorial Guinea, and Russia were moved from the "high income" to the "upper middle income" group.[6]

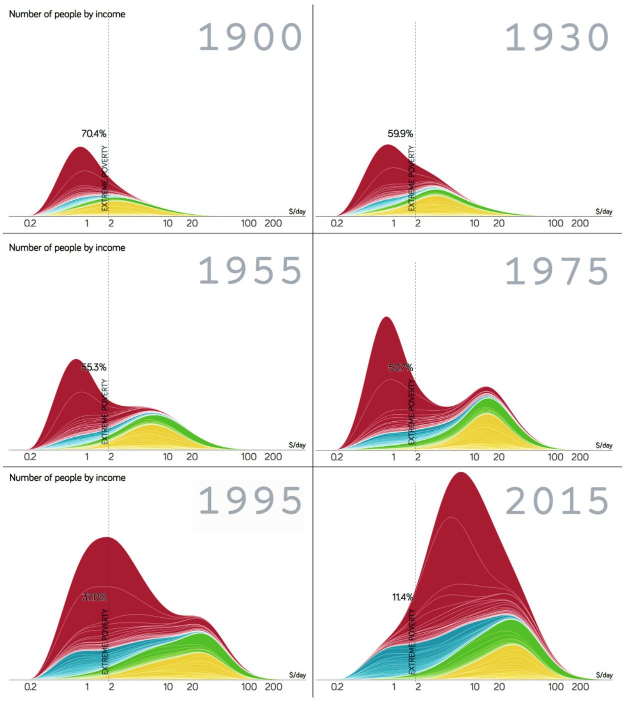

Fig. 2.5 Income distribution of the World population in 1900, 1955, 1975, 1995 and 2015 according to Gapminder in Dollars per capita and day, adjusted for inflation and prices.[7] Please note logarithmic x-axis. Colors denote world regions: red for Asia and Australia, blue for Africa, green for the Americas, yellow for Europe & CIS

6 World Bank Data Blog "New country classifications by income level" http://blogs.worldbank.org/opendata/new-country-classifications-2016 (21 Feb 2017)

7 See Gapminder tool https://www.gapminder.org/tools/#_locale_id=en;&state_time_value=1954;;&chart-type=mountain (7. June 2017)

3 Brazil

In 2015 the total annual municipal waste generation in Brazil amounted to 79.9 million tons (ABRELPE 2016:18). Of the generated amount 90.8% were collected by municipalities or other services. However collected waste is not necessarily disposed of properly: an amount of 30 million tons of collected waste is estimated to be disposed in inadequate treatments.[8] Assuming inadequate treatment also for any uncollected waste, a total rate of 47% of all generated waste can be estimated to be disposed of inadequately in 2015, or 37 million tons annually. Of the total of 5'570 Brazilian municipalities 3'326 (60%) use inadequate treatment sites (ABRELPE 2016:18).

The standards of what comprises a sanitary landfill in Brazil are very diverse. Data for 2015 based on questionnaires give a very varied picture (SNIS 2017). Of 679 sites listed as sanitary landfills, which in total were disposing an estimated 14 million tons of waste annually[9], only 60% (406) stated that the landfill has a base seal . Therefore 40% of the responding "sanitary landfills" probably do not have a base seal, but leach pollutants directly into the subsoil.[10] Only 47% (317) of the sanitary landfills had gas collection pipes installed; the remainder emits landfill gas directly. Only 55% (374) had leachate collection pipes installed. Only 51% (347) reported to have any kind of external or internal leachate treatment, including recirculation; the remainder apparently emits any leachate untreated. Of 577 supposed sanitary landfills listing corresponding details, 25% (147) reported to have *neither base seal, nor gas collection pipes, nor any form of leachate collection and treatment*. These sanitary landfills thus reportedly show the characteristics of unsanitary landfills, where merely covering of the waste is the chief mitigating measure. Sanitary landfills lacking important features are more prominent in landfills of smaller size, but even large landfills up to 100'000 tons per year estimated annual deposition rate can be found amongst the sanitary-by-name-only landfills. These findings might also highlight problems in accuracy of data retrieval caused by different understanding of used terms by respondents and government.

The rate of waste collection in the five Brazilian regions ranges between 78.5% (North East) and 97.4% (South East). Collection rate is higher in regions with larger per-capita GDP. Also open dumping practices decrease with larger per-capita GDP of a region, see Fig. 3.1. With growing economical wealth, waste is preferentially disposed in sanitary landfills. Frequency of unsanitary (controlled) landfills seems not clearly affected by economical wealth. The Central-West region exhibits waste disposal choices that would fit the trends of a less wealthy region than the actual GDP of this region suggests.

8 Inadequate treatments include dumpsites and so called "controlled landfills" (*aterros controlados*), which according to ABRELPE "lack the necessary array of systems to protect public health and the environment". ABRELPE distinguishes the controlled landfills from sanitary landfills in their questionnaires. Brazilian controlled landfills can therefore be best categorised as what in this report are called unsanitary landfills. For uncollected waste it is also likely that some open burning is taking place.

9 Annual deposition rate was estimated by dividing the total deposited waste (given in table "Planilha_Unidades_Fluxos_RS_2015.xls") by the duration of operation, assuming constant operation since the facility's startup date (given in file " Planilha_Unidades_Cadastro_Nacional_RS_2015.xls") (SNIS 2017).

10 One might surmise that his figure is dominated by *older* sanitary landfills, which did not adhere yet to more modern standards. But this explanation is not supported by the data. In fact quite the opposite is happening: the *more recent* "sanitary landfills" more frequently have no base seal than the previously built landfills. Of the sanitary landfills built in the period between 1981 and 1993 (10 plants) *all* featured base seals. But of the sanitary landfills started up between 2011-2015 only 49% (177) featured base seals. These figures heed only landfills giving a specific answer regarding the presence or absence of a base seal and exclude any non-responding facilities. There is a clear trend in recent years to have *increasingly* no base seals in Brazilian sanitary landfills.

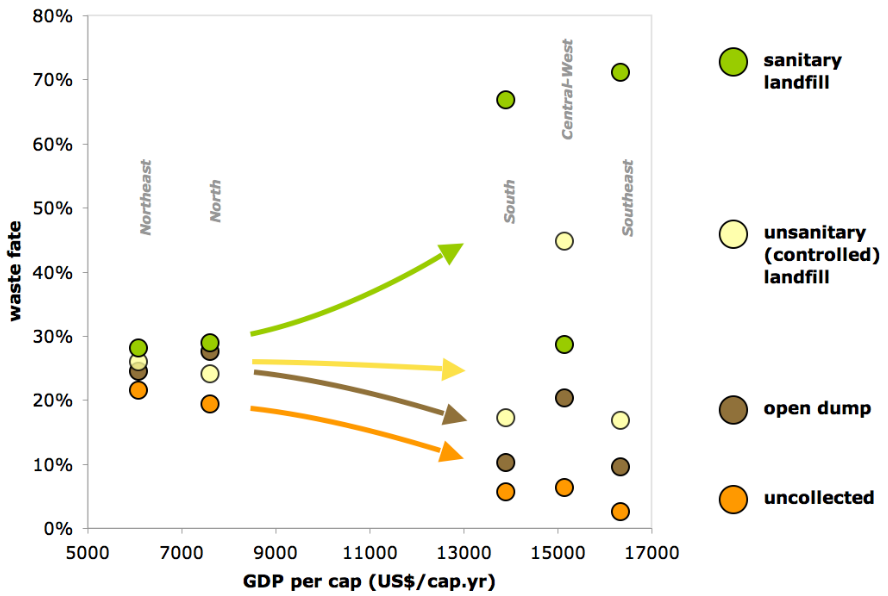

Fig. 3.1 Fate of municipal waste in 5 Brazilian regions plotted against per-capita-GNP. From ABRELPE (2016:Fig.3, Fig. 11ff.). 100% is total waste generated calculated from sum of all four fates, neglecting a minor amount of recycling.

A new Brazilian policy on Solid Waste Management (Política Nacional de Resíduos Sólido PNRS, law 12.305/2010, the National Solid Waste Policy) came into effect in 2010. Similar to the EU waste hierarchy (EU 2008:§4) it targets waste avoidance, waste recycling and appropriate treatment of not recycled waste. Appropriate treatment of not recycled waste is considered to be landfilling, but not incineration without energy recovery. Incineration is not a targeted treatment for municipal waste and sanitary landfilling is even prioritised before recyclables sorting (Jacobi & Besen 2011). Incineration is only a targeted treatment for health care waste, septic waste and food waste from ports and airports (Jacobi & Besen 2011:138).

Although waste incinerators have been built in Brazil as early as 1896 (in Manaus), the only currently existing incineration facility for household waste is the Usina Verde plant on Ilha do Fundão near Rio de Janeiro; an experimental prototype which started up in 2005. It burns a pre-sorted MSW mixture of organics, contaminated paper and plastic and features an energy recovery boiler (UV 2012). Morgado & Ferreira (2012) note that the plant *dries the waste* prior to incineration, bringing up the calorific value from 2.52 to 9.58 MJ/kg. The plant's capacity is 30 t per day (MyClimate 2004) which would therefore be able to process around 0.4% of the total waste mass of Rio de Janeiro city, or 0.014% of all Brazilian waste – assuming no maintenance downtime. Incineration of household waste can therefore be considered negligible in the current Brazilian situation.

Waste incineration is usually not practiced in all of Latin America. Only Brazil and some Caribbean islands have experience with urban solid waste incinerators (PAHO 2010:130). In waste statistics for Brazil of 2015, waste incineration is only listed as treatment for health care waste (*resíduos de serviços de saúde, RSS*) (ABRELPE 2016:69). The Brazilian Association of Waste Management Companies notes that incineration with energy recovery does not yet exist in Brazil, apparently discounting the experimental Usina Verde plant mentioned above (ABRELPE 2012:21).

In 2010 an estimated number of 132'600 persons worked as waste separators in Brazil.[11] This includes all manners of recyclers and waste pickers, formal and informal. Around 98'500 of those are informal waste pickers and 43'000 of those are working directly on landfill sites.

The are some landfill gas capture projects in Brazil. MCTI (2016:74) states that by November 2014 50 CDM activities of landfill gas capture were established reducing GHG emissions. However a study by the Brazilian Association of Waste Management Companies estimating the greenhouse gas emissions of the Brazilian waste sector during 2009-2039 employed a landfill gas capture rate of 0%, suggesting a negligible occurrence on a national scale (ABRELPE 2013:66).

4 India

Official data on waste generation in India is based on a limited survey conducted 2004-05 in 59 cities[12] by the National Environmental Engineering Research Institute NEERI. This measured data from urban areas has been extrapolated to create the offical statistics on more recent waste generation figures for the whole country (Narain & Sambyal 2016:4). Such an offical report listed the 2014 total municipal waste generation in India as roughly 52 million tons.[13] The same source suggests an average national waste collection rate of 90%, i.e. 127'531 tonnes per day collected over 141'064 tons per day generated. At a GNI of 1560 $ in 2014 a collection rate of 90% would render India a positive outlier in Fig. 2.4 on page 9. The accuracy of these figures for the whole country may therefore be questioned. Maurya & Goswami (2017) quote a waste collection rate in India of only 68%, which appears still high, but more probable in regard of the correlation in Fig. 2.4.

Using the extrapolation from Fig. 2.1 and a GNI for 2014 of 1560 $/capita.year, a mean waste generation of 275 kg/capita.year can be estimated at a range of 161 to 551 kg/capita.year. With a population of 1'267.4 million – for the end of 2014 – this totals to a mean of 349 million tons of MSW generated annually, with a range of 204 to 698 million tons per year. This approximation presumes that India behaves in a similar manner as the other countries depicted in Fig. 2.1. The resulting estimate suggests that the official statistics are off by a factor of 4 to 13. Officially a waste generation of only 41 kg/capita.year is implied (CPCB 2016:61), while 275 kg/capita.year is estimated based on the GNI. Khajuria et al. (2010) estimate a waste generation of 288 kg/capita.year for 2010, which also makes the official figure appear much too small.[14]

The following description of urban waste management in India is from (CED 2011:7). Urban households and businesses usually collect waste in a single bin. Waste separation at the source is not commonly performed. Waste is then brought to community collection points situated at street corners and at specific intervals. If the convenience of this arrangement is perceived as too low residents will

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11 Calculated from a total population of 192.76 million in 2010 and a figure of 6.88 separators per 10'000 inhabitants from the (AIDIS 2010) database, see following tabs: Brasil → Tamaño de población → Disposición final → Presencia de segregadores. Please be aware that the total displayed in the source table (5.11) *excludes formal separators organised in groups* and therefore relates only to the total of *informal* workers.

12 There are about 300 Indian cities with populations over 100'000 and a total of about 8000 cities and towns in India.

13 Derived from data listed for a total of 35 member states and union territories of 141'064 tons per day and quoted to be from annual reports of the period 2013-14 and 2014-15 (CPCB 2016:61).

14 It might be argued that India has its population majority in rural areas, which will tend to produce less waste per capita and year. Variation from rural vs. urban lifestyles are already covered by the range of values in Fig. 2.1 as it covers countries with rural populations between 80% and 0%. India has 68% rural population. A country similar to India regarding rural population and GNI is the Yemen (71% rural, 1180 $/capita.year). Although both these parameters would suggest a waste generation rate below that of India, the Yemen produced 279 kg/capita.year and had a collection rate of 20% (data for 2012 from UN 2016).

discard waste directly in the street curb from where it removed by street sweepers. In either case waste can be picked apart by waste scavengers and stray animals. Waste is hauled from collection points using open trucks; waste compactor trucks are not common, but exist in a few cities.

In most of Indian cities no systematic disposal of waste is maintained. According to the Indian Government landfills are not properly constructed; operation and maintenance of the landfills is poor (MOEF 2012:76). Recently efforts are being made to increase waste segregation at the source and composting (CED 2011:8).

Maurya & Goswami (2017) give figures of unhygienic waste treatment versus treated waste for the 35 member states. "Treatment" here means composting, recycling or sanitary landfills, while unhygienic treatment is open (or marine) dumping. From this data a share of unhygienic treatment of collected waste can be derived. This data is plotted against the individual states GNI per capita in Rupees per year in Fig. 4.1.[15] Although this data is based on official statistics, whose absolute tonnages were doubted above, it is assumed here that the relative shares of treatment are more reliable.

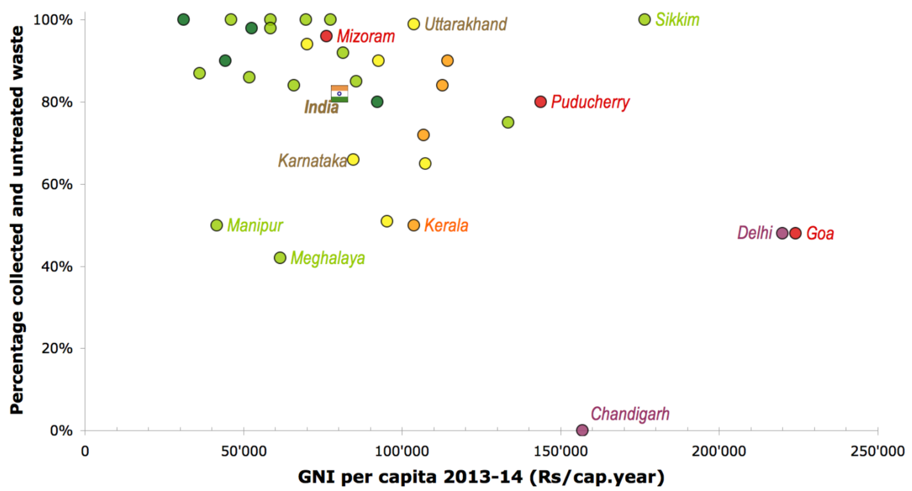

Fig. 4.1 Percentage of unhygienic treatment of collected waste in 35 Indian member states in 2015 plotted against their per-capita-GNI in Rupees. Derived from (Maurya & Goswami 2017). Colours denote percentage of urban population: ●dark green 10-20%, ●light green 20-30%, ●yellow 30-40%, ●orange 40-50%, ●red 50-80%, ●purple ~97%

There is large variation between member states even with similar economic wealth. There is however an apparent affinity of more wealthy states to have less unhygienic treatments. There is also a tendency for states with large rural populations (green dots) to have higher percentages of open dumping, even if the waste is collected. In turn the more urban states (red dots) tend to have lower percentages of open dumping of collected waste. There are limitations to these trends and several outliers can be observed: Sikkim, a comparatively wealthy, but rather rural state, has only open dumping. On the other hand Manipur and Meghalaya, two states equally rural as Sikkim, but much less economically wealthy feature open dumping rates which are similar to the much more wealthy and much more urban states Goa and Delhi. These outlier states however have relatively small populations and produce only a small fraction of the waste in India. They hardly affect the national average, which is indicated in the plot with an Indian flag (at 82% open dumping and 80'388 Rs/cap.year).

15 State-wise GNI data for 2013-14 (latest available complete year) is from the Indian Ministry of Statistics http://pib.nic.in/newsite/PrintRelease.aspx?relid=123563 (27 Jun 2017).

Maurya & Goswami (2017) quote an average waste collection rate of 68% in India, which means 32% of the waste will be not collected and probably disposed in open dumps. With the 82% of collected waste also ending up in open dumps, a rate of 88% all generated municipal waste will probably end up in open dumps and other unhygienic treatments, and only 12% will reach more hygienic treatments. As these figures are based on reporting municipalities, which end to include the more populous and urban ones, and disposal in rural areas is usually more unhygienic, the rate of 12% hygienic treatment might even be too high.

The Indian national average landfill gas capture rate estimated for 2007 was very close to zero, as only a few small pilot projects in large cities exist. For the national Indian greenhouse gas inventory from waste management activities a landfill gas capture rate of zero was employed (INCCA 2010:39).

According to official data 6 waste incinerator plants existed in India in 2015, three each in the states of Maharashtra and Delhi (CPCB 2016:3). Twelve facilities for refuse derived fuels (RDF) were set up. In Kerala state 600 digester plants for biowaste existed, and a further 48 in the states of Karnataka and Maharashtra. Also 95 local bodies of a total of 203'700 have set up sanitary landfills. This number might include older and already closed landfills (CPCB 2016:54). Almost 600 local bodies are known to have established composting facilities for treatment of organic waste. The actual number and operation status of these facilities is not known. No data on actually processed waste in these plants is available.

5 South Africa

Official data for masses of reported waste in South Africa are available online from the South African Waste Information Centre (SAWIC 2017). This is detailed, but incomplete data, as it looks only at wastes delivered to waste facilities and therefore neglects any uncollected waste with informal disposal. The data available from waste facilities is also incomplete, as not all facilities are required to report and for instance in 2011 only 13% of all landfills required to submit data to the official authorities did so (DEA 2012:6). The sum of waste in 2016 from (SAWIC 2017) was about 33.1 million tons.[16] This translates to a per capita mass of 592 kg annually. At a GNI of 6050 $/capita.year in 2015 this seems to fall well into the range of the trend found in Fig. 2.1. The point falls above the average trend for most countries, which might be explained by a relatively large degree of urbanisation in South Africa, where two thirds of the population lived in urban areas in 2015, and a large amount of mining, metal and resource wastes.

The range of the waste generation rate in several provinces is presented in Fig. 2.2 on page 7. Please note that this refers to older data.

In 2014 municipal waste collection services were performed for 66% of all households in South Africa (SSA 2015:51).[17] Other households had no collection services and had chiefly an own informal refuse dump, or alternatively had to bring their waste to a communal waste dump (no collection service) or simply littered their waste. This average national figure has large variations depending on type of settlement, cf. Tab. 5.1. In rural areas only 7% of all households receive waste collection services, while for urban or metropolitan areas this figure is around 90% (SSA 2015:51). There is also heterogeneity between the provinces: While in the Northern Cape province there is no collection at all

[16] Sum of all general waste, excluding separately collected hazardous waste.

[17] Sum of "Removed at least once a week" and "Removed less often than once a week" referring to municipal collection services. Please note that this is a rate *per households* and does neither reflect *population* serviced by collection, nor the rate of *waste mass* collected, as waste generation per household is diverse.

in rural areas the North West province reaches a collection rate even in rural areas of 31.5%. While most provinces achieve collection rates in urban areas over 87%, the KwaZulu-Natal province achieves only 74.8% in urban areas and 56.6% in the whole province.

Province	**Rural**	**Urban**	**Metro**	**Total**
Western Cape	–	95.9%	93.3%	**90.7%**
Eastern Cape	0.7%	80.8%	98%	**44.7%**
Northern Cape	0%	87.3%	–	**70.9%**
Free State	0.8%	92.8%	–	**81%**
KwaZulu-Natal	2.8%	74.8%	91.7%	**56.6%**
North West	31.5%	90.9%	–	**59.1%**
Gauteng	–	92.8%	90.9%	**90.1%**
Mpumalanga	5.8%	80.4%	–	**40.3%**
Limpopo	6.5%	91%	–	**22%**
South Africa	**7.6%**	**87.1%**	**91.8%**	**66.3%**

Tab. 5.1 Percentage of households serviced by waste collection in 2014. By province and settlement area type. Data from (SSA 2015:51). Cf. footnote 17. Settlement area types not occurring within a certain province are shown as "–".

Overall national waste collection rates develop only slowly and increased from 59% in 2002 to 66% in 2014 (SSA 2015:Fig.38). Between 2006 and 2009 the waste collection rate even *decreased* from 63.3% to 62.1%.

Fig. 5.1 Mariannhill sanitary landfill near Pinetown, KwaZulu Natal, in 2005, left (MLC 2010) and New England Road landfill near Msunduzi, KwaZulu Natal ca. 2014 right (Lewis 2014)

According to latest data for 2016 the vast majority of disposed waste goes to landfills (SAWIC 2017). The statistics distinguish between two classes of landfills, which are listed below with their official designation:

- *"D1: Disposal of waste to land (e.g. specially engineered landfill)"*
- *"D2: Disposal of waste to landfill (e.g. non-engineered landfill)"*

Thus a "disposal *to land*" signifies an *engineered* landfill, while "disposal *to landfill*" is coined for more specific disposal in a *non-engineered* landfill. In 2016 a total of 84% of the recorded non-hazardous waste ("General waste") was disposed in engineered landfills (D1) while the remainder was going to non-engineered landfills (D2) (SAWIC 2017). The non-engineered landfills can apparently be assumed to represent informal and open dumps. A definition what exactly is included in an engineered landfill vs. an non-engineered landfill could not be found. Even the registration form for the SAWIC database leaves it open to the applicant to pick a disposal type, without any kind of guidance or explanation beyond the wording listed above (SAWIC 2012). It is unclear, whether for instance an intentionally excavated pit, but without any liners, collection systems nor waste compaction would qualify as an engineered landfill. Within the modelling choices of this project such a landfill would not perform differently than an open dump, even if the pit itself was engineered perfectly.

As national information on sanitary landfills is not complete, so is information on capture and utilisation of landfill gas. A 2015 report on climate change response notes that even for reporting landfills there is no record on the annual amount of energy generated from landfill gas (DEA 2015:43). The 2000-2010 national greenhouse gas inventory did not heed any methane recovery from landfills, but notes some landfill gas capture project had been begun after the year 2000 (DEA 2014:238). The 2016 annual climate change report states that source-specific activity data for the waste sector still need to be developed in a project foreseen to end in 2018 (DEA 2016:B.33).

Some limited information on landfill gas capture in South Africa is available. In 2011 the eThekwini district in the KwaZulu-Natal province owned four landfills and three of them featured landfill gas capture: Bisasar, Mariannhill, and the closed La Mercy landfill (Morgan 2013:10). According to (Lombo et al. 2016:33) Bisasar and Mariannhill landfills produced 6.5 MWh and 1 MWh electricity from landfill gas utilisation, respectively.

All three gas capturing landfills in the eThekwini district are registered with the Clean Development Mechanism (CDM). Several other landfills were registered as of 2012 with the Clean Development Mechanism: five landfills situated in the Ekurhuleni municipality near Johannesburg, Gauteng province (Simmer and Jack, Weltevreden, Rooikraal and Rietfontein) (Petterson 2016) as well as the privately owned Enviroserv Chloorkop.

6 Modelled waste treatment activities

The goal of this project is to provide calculation tools to create waste-specific inventories for waste disposal in developing nations.

A distinction is made between following treatment options:

- Open, uncontrolled dumping
- Semi-controlled unsanitary landfilling
- Controlled sanitary landfilling
- Open, uncontrolled burning
- Controlled waste incineration (municipal incineration)
- Tailings impoundment (landfill for metal ore beneficiation waste)

The assumptions of the models for open dumping and unsanitary landfilling are detailed in a separate report (Doka 2017a). The open burning model is described in (Doka 2017b). The tailings impoundment model is described in (Doka 2017c). Sanitary landfilling and controlled municipal waste incineration are the models described in (Doka 2009, 2013), including the dependence on local climate for the sanitary landfill as described in (Doka 2017a).

These models were implemented in a set of Excel workbooks, where the user can choose and define a waste input, a specific location and specific disposal technology parameters. These tools are available as free, open-source software (GPL) from the authors webpages. [18] The tools can create process treatment LCIs in Ecospold2 format directly. These LCI can be submitted to the ecoinvent database using the EcoEditor software. The detailed usage of these tools is described in a Calculation Manual (Doka 2017d).

6.a Granularity of data

Information on the waste situation in developing countries is presented in chapter 2.b 'Waste generation and treatment in developing countries' on page 5. The large variabilities even within one country are apparent, cf. Fig. 2.2, Fig. 3.1, and Fig. 4.1 in that chapter. A typical generic national average might therefore be unrepresentative for a more confined specific area. This sort of granularity problem – whether the level of detail is appropriate to a certain LCA study – appears in a lot of applications of LCI data. Since the models presented here are for a *backgrounds LCI database*, ecoinvent, generic, national averages are the oftentimes sufficient and appropriate as the waste producing activities are usually not smaller than national levels.

Targeting geographically more finely resolved data might not succeed in reducing the encountered variability. For instance in Switzerland – a country many factors smaller than India, Brazil or South Africa – the waste incinerators feature a diverse range of energy recycling characteristics regarding the trade-off between heat and electricity production (see Doka 2013: Fig.2.3). Although this might influence LCI study results depending on their goal and scope, this diversity was "flattened" to employing a generic Swiss average in the ecoinvent datasets for Swiss waste treatment.

It might be worth to emphasize that such variability in base data is not unique to waste treatment activities. For instance, several thousand of lorry and car models are in use in the world, but the ecoinvent database features only a few typical models based on EURO norms. Or several thousand of steel alloys exist in the world, yet ecoinvent has only six: unalloyed carbon steel, unalloyed converted steel, low-alloyed converter steel, low-alloyed electric (secondary) steel, high-alloyed 18/8 Cr/Ni converter steel, high-alloyed 18/8 Cr/Ni electric (secondary) steel.

The treatment models presented allow the user to detailing parameters at the level seen fit for the purpose. In this, it is not mandatory to operate with national averages. It is possible to calculate detailed specific regional parameters and create inventories for sub-regions, provinces or even single facilities. It must be kept in mind though that impact assessment in LCA is usually generic, not site-specific and often based on developed nations. So even if a treatment inventory is very detailed and site specific, the results might still lack proper geographical granularity. The goal of LCA is to assess overall life cycle burdens, not only locally occurring burdens, and has therefore a much wider focus than for instance the more confined Environmental Impact Assessment (EIA) studies, see (Doka 2008:5), and care must be exercised to recognize these different purposes. With today's state of the art results of LCA and EIA are not necessarily mutually compatible. I.e. although one might conceptually think so, EIA results are not simply a subset of LCA results.

[18] See http://www.doka.ch/publications.htm . The open source license is meant to prevent incorporation of the provided free software tools into closed, proprietary and commercial applications. Such applications must also remain free. However, the data and datasets you create with the tools are of course your creation and can be used for any kind of projects, also confidential and commercial ones.

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