# ZERO WASTE TO ENERGY

*Identifying opportunities for spatial intervention to address overcapacity of Waste-To-Energy plants in the Netherlands*

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***ABSTRACT***

*This paper explores the potential to adapt Dutch Waste-To-Energy plants in the context of the transition to a circular economy. It strives to identify entry points for architectural intervention, in order to tackle the country's overcapacity of waste incinerators and dependency on waste. The Netherlands' largest incinerator, AEB Amsterdam, is taken as a focal point. The site is first considered against the city's performance on Raworth's doughnut model. This reveals its position within a complex system, where it plays a role in meeting societal needs as well as transgressing planetary boundaries. A Material Flow Analysis is used to identify critical flows and processes, and scenarios are developed to understand how these are likely to change in a system with shifting values. Unused flows and processes which are prone to redundancy are identified, both of which could act as a starting point for design.*

***KEYWORDS:*** *Waste-to-Energy (WTE), Waste-to-Power, overcapacity, waste management, circular economy, doughnut economics, Amsterdam Westpoort*

## I. INTRODUCTION

The Netherlands is considered a world leader in waste management, largely because of their Waste-To-Energy (WTE) infrastructures. These WTE plants convert combustible waste into electricity, heat and raw materials. This recovers around 50% of energy content, and represents one of the least effective R-strategies set out within a circular economy: recovery (Minguez et al., 2021). The country is home to 12 waste incineration plants, and these infrastructures represent the last part of the "make-use-lose" linear economic model.

Together, these plants have an annual processing capacity of 8 megatons of waste, and produce roughly 10% of the country's "renewable" energy. These plants need to run at near full capacity to be financially viable, but the Netherlands only produces 5.7 megatons of waste each year, and has circularity goals that will reduce this number significantly by as soon as 2030. To remediate this overcapacity, about 1.5 megatons of combustible residual waste is imported from other EU countries annually. This means that we have a dependency on waste. This dependency is becoming increasingly problematic, as international goals to tackle climate change mean the trade of waste is becoming more heavily taxed (van Santen & Kooiman, 2019).

Population growth, urbanization trends and a scarcity of space mean there is increasing pressure on areas surrounding cities to become livable and accommodate a mixed program of functions. Industrial areas - where most WTE plants are located - are among these. Populations are concentrating in cities, and as a result, so are resources and waste. Amsterdam has more citizens than any other Dutch city, and it has chosen to respond to these increasing pressures by expanding the city towards the port, home to the country's largest WTE plant: Afval Energy Bedrijf (AEB) Amsterdam. The city has also committed itself to becoming fully circular by 2050 by incorporating Kate Raworth's *Doughnut model* into its municipal vision (Nugent, 2021). This model outlines a social foundation, as well as an ecological ceiling, and proposes that a thriving society will function in the "sweet spot" between these two boundaries (Raworth, 2017).

At the heart of Amsterdam's waste, energy and heat networks, AEB has a critical role to play within this transition. Because of this, it is chosen as a focal point for this research paper. Though it is expected that the results could be extrapolated to all WTE plants because of the many similarities that are often present within industrial infrastructures. This problem statement provokes the research question:

***Which processes within AEB Amsterdam are most suitable for architectural adaptation to create a future-proof closed-loop waste management facility that helps Amsterdam achieve it's doughnut economy municipal vision by 2050?***

This question is broken down into three sub-questions:

1. What significance does AEB have for Amsterdam's *doughnut model*?
2. What are the processes taking place inside the WTE plant, how are they organized spatially, and what are their respective contributions to the *doughnut model*?
3. How are these processes expected to change in a closed-loop system?

## II. Method

The research was carried out using a balance of approaches. A Material Flow Analysis (MFA) forms the foundation. This quantitative approach is complemented by more traditional qualitative research approaches, namely literature review and site analysis. The research is broken down into three parts corresponding to the sub-questions:

I. The relevance of AEB for Amsterdam's doughnut model
II. The processes and flows on site (MFA)
III. How this MFA could look in the future

In the first chapter AEB and Amsterdam are considered against an adapted version of Raworth's doughnut model. This version by O'Neill et al. uses the *safe and just space* (sjs) framework with downscaled planetary boundaries and social indicators. It was chosen because it is the most current model with defined and measurable indicators, for which much data is available. The Amsterdam doughnut for this research was made by scaling O'Neill et al. Dutch data per capita, unless more specific information was available, as was the case with $CO_2$ emissions.

Several documents published by AEB, the municipality of Amsterdam and the national statistics authorities (CBS) provide in depth information for all three parts of the research. In particular the company's annual reports are consulted. In 2019, AEB was at the heart of a national waste crisis when it temporarily lost most of its incineration capacity. Because of this, there are also several insight reports, reviews and newspaper articles available that offer complementary information to the research. The year 2015 is used for both the doughnut research and MFA. This is because the most comprehensive data is available for this year.

Understanding the spatial layout and routes of flows on site would have been most easily done through a site visit and interviews. Due to the corona crisis this has not been possible. Instead a collection of photos and videos from the site, and mapping, is used. These were sourced from YouTube, social media, AEB's website and contact persons.

The final chapter builds two MFA scenarios for the site for the years 2030 and 2050. It does this by considering each flow within the MFA and anticipating its changes based on national and municipal goals and forecasts. These years are chosen as they align with critical national and international climate goals.

It important to note that AEB is also responsible for running six waste collection points spread throughout the city. To maintain relevance for potential architectural intervention, the research is limited to one physical location in Amsterdam Westpoort, so these are not considered. More detailed information on how estimates are reached can be found in the appendix.

## III. Results

### 3.1. AEB and the Doughnut Model

Research revealed that AEB Amsterdam has several significant influences on the city's doughnut model. These are both direct and indirect, and affect the transgression of ecological ceiling as well as the city's ability to reach its social foundation. The direct, measurable contributions are shown on the diagram below:

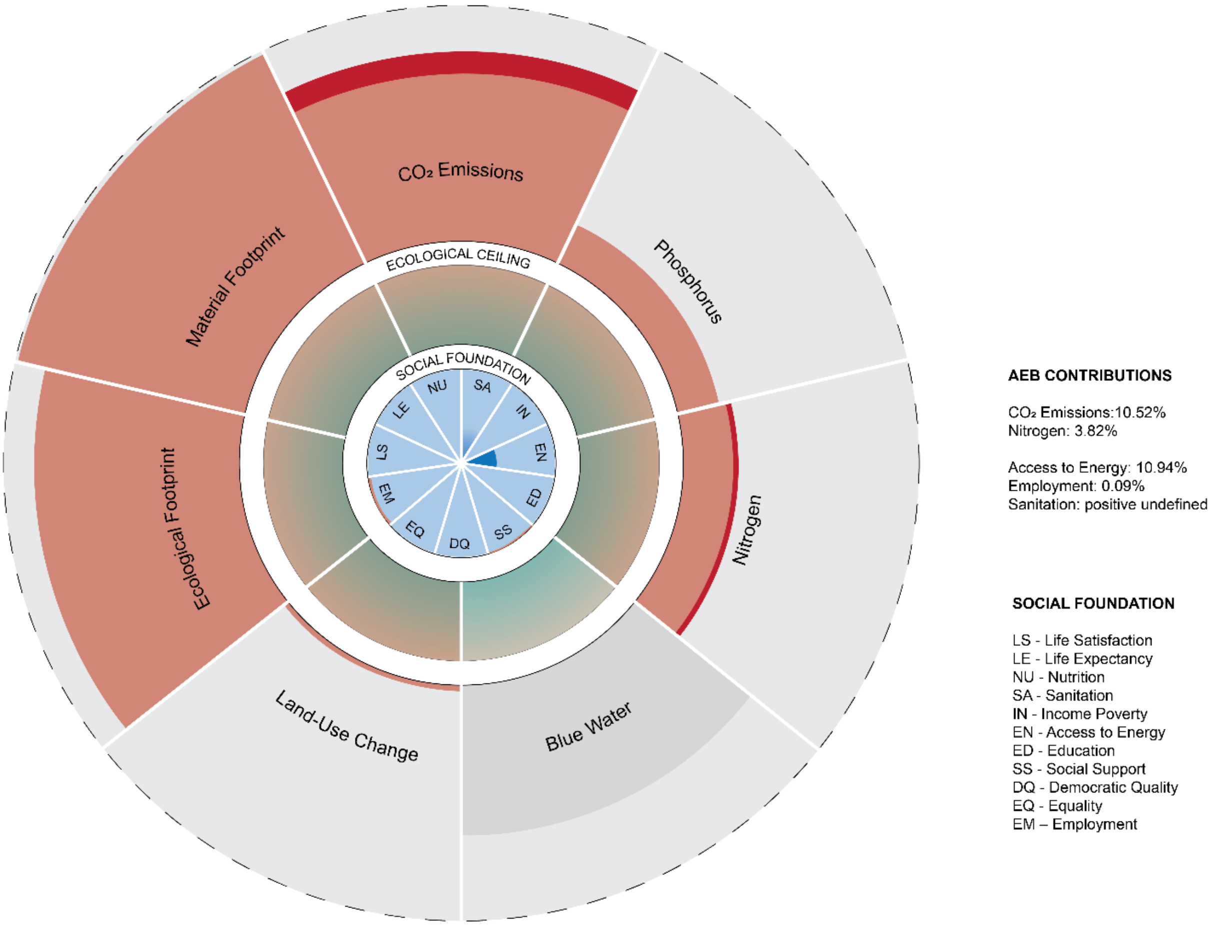


Figure 1. AEB impact on the Amsterdam city doughnut (own creation based on O'Neill et al., 2021).

#### 3.1.a Ecological Ceiling

The doughnut segments of the ecological ceiling that AEB showed measurable contributions to are those of Carbon Dioxide (10,52%) and reactive Nitrogen (3,82%).

The $CO_2$ emissions considered here are limited to those emitted directly from the burning of waste. Emissions caused by, for example, diesel garbage trucks are not included as these take place outside the site boundaries. Despite the high amount of $CO_2$ produced, AEB is considered to be a $CO_2$ saver, having a net $CO_2$ balance in the negatives. This is because it produces energy and raw materials that would alternatively be sourced with more resource intensive means, for example mining. This net value is calculated by AEB using a universally recognized method called the EpE-protocol, and in 2015 came to a total of about 215 kilotons $CO_2$ reduction (AEB Amsterdam, 2016). However for this paper the gross $CO_2$ emissions are used, as these are the ones linked directly to the physical boundaries of the site.

Nitrogen oxides ($NO_x$) are most often released into the environment through the use of fertilizers, but are also released in small quantities during incineration processes. An estimated 470.000kg are likely released each year, although the company's emissions are well below national and EU regulatory levels. It is also emitting trace amounts of polluting substances such as dust, carbon monoxide, and heavy metals (cadmium, lead, nickel, mercury) (AEB Amsterdam, 2016).

Other segments on the doughnut that AEB is likely linked to indirectly include Blue Water, Material and Ecological Footprint. Blue water refers to fresh water withdrawals, and methods of measurement are often disputed and evolving. It is clear that AEB uses large amounts of surface water from the nearby harbor within cooling processes, and releases this water back into another part of the harbor, but detailed information about quantities and processes is not available (AEB Amsterdam, 2006). Material and Ecological footprints are consumption based measurements, which do not take source location into account. As AEB is such a critical part of the linear economy, it could be considered an enabler for the city's enormous consumption of goods.

### 3.1.b Social Foundation

AEB's most tangible impact in providing for Amsterdam's citizens is as a heat and electricity source, producing almost 11% of the city's power. It is especially valuable in being a source for the HT (high temperature >90˚C) thermal network for the city (Ruijs, 2019).

Sanitation is another important segment. Although within the doughnut framework this focuses exclusively on processes related to water. AEB is positioned immediately next to Waternet, and is responsible for incinerating the city's sewage sludge. It is therefore playing an important role, but how this weighs into the segment is unclear. This is therefore shown as a gradient.

Alongside these two segments, AEB hires about 400 employees - a small fraction of Amsterdam's working population (AEB Amsterdam 2016). This is interesting as employment (as well as social support) are the only thresholds that are not fully met. Although waste management itself is not an aspect of the doughnuts social foundation, it is likely that the services AEB provides enable a certain quality of life within the city. Perhaps influencing in some intangible ways the life satisfaction of residents.

### 3.2. Processes within AEB

A Material Flow Analysis was carried out to gain an understanding of the scale, processes and flows taking place on site. Net values were used for clarity, for example a large amount of ambient air (nitrogen) flows through the system, but much of it is unreactive.

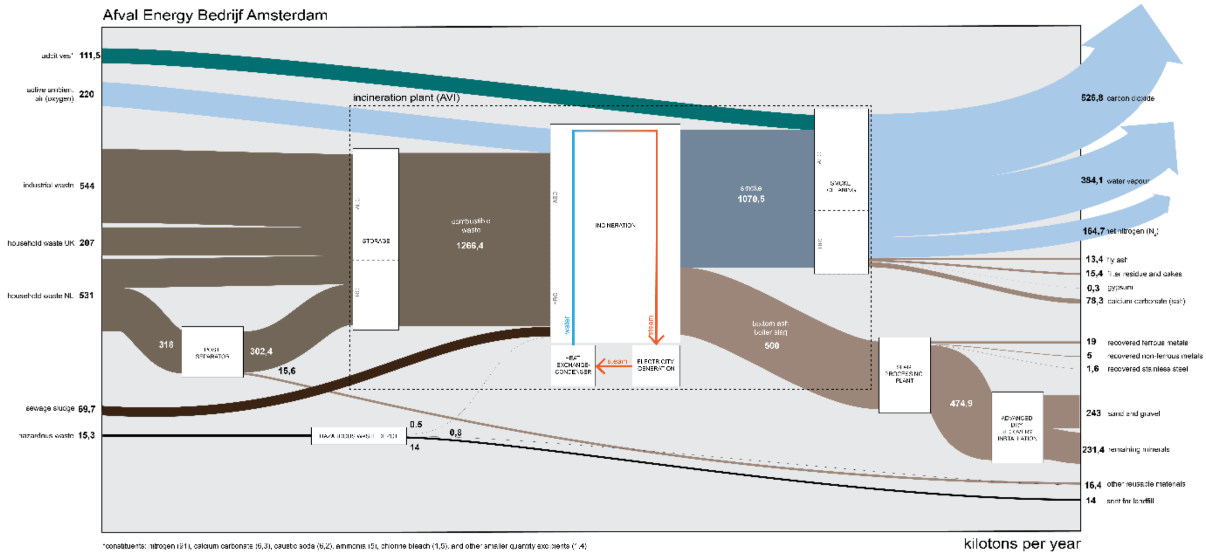


Figure 2.  AEB Material Flow Analysis (own creation, 2021).

Research for the MFA showed that there are often quite significant fluctuations in the quantities of waste for a variety of reasons, particularly in regard to imported and hazardous waste. Storage on site in the “afval bunker” is necessary to enable a continuous supply to keep the incineration lines running 24/7 (AEB Amsterdam, 2006).

The post separator was added at the end of 2017 to increase waste separation and recycling. The data in the MFA are based on its pilot phase where it was not yet running optimally. Under ideal conditions it would sort about 300 kilotons annually, from 12 municipalities (see appendix C), saving 105kton organic material, 30kton of plastic and 30kton of paper from incineration (AEB Amsterdam, 2018). Separating streams is the critical first step to creating opportunities to close resource loops. Streams released here include: drink cartons, paper/cardboard, organic material, metals, rigid and malleable plastics.

The incineration process itself is the largest on site and, with the smoke cleaning, is responsible for AEB’s most significant contributions to the doughnut model. It is comprised of six incineration lines within two parallel connected building sections. Each section has its own chimney. The AEC (Afval Energie Centrale) houses four of these lines and two turbines. It has a capacity of 850 kton annually, and an energy efficiency around 71%. The HRC (Hoogrendement Centrale) houses the two newest and most efficient incineration lines and turbine. Each year it can process 530kton with an energy efficiency of about 94% (Lysias Advies, 2020). A closed loop water system inside these incinerators powers turbines for electricity generation. The remaining heat is then used for district heating (AEB Amsterdam, 2016). The quantity of water used is unknown.

In recent years AEB has begun venturing into biogas, with a small new biogas plant completed in 2020 at a separate location (AT5, 2020). The connection between the processes associated with this and those happening on site remains unclear.

The filter residues have as yet no useful purpose found for them (AEB Amsterdam 2018).

The flows through the site can also be understood spatially through the diagram below:

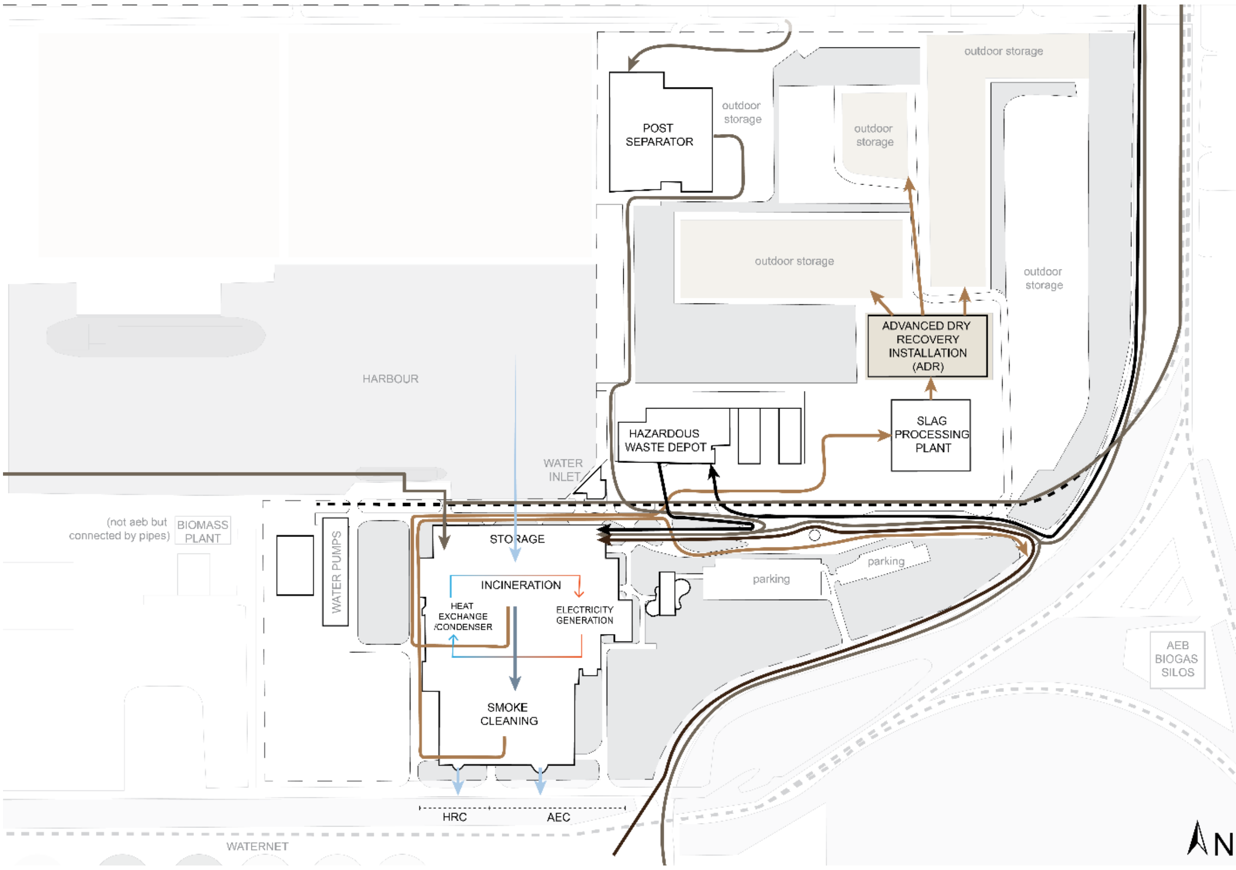


Figure 3. spatial configuration of MFA flows on site (own creation, 2021).

Flows travel to and from the site by boat, train, and road. About 600 garbage trucks arrive each day (NH Nieuws, 2016). The layout seems somewhat illogical, and uncertainty remains over the exact location of some installations (slag recovery, ADR, biogas). Within the AVI the incineration and smoke cleaning process runs linearly from north (where waste, cooling water and ambient air are brought in) to south (where emissions are released through the chimneys).

### 3.3. Scenarios

The flows on site are considered against municipal and national forecasts and goals.

### 3.3.a 2030

Amsterdam's population is expected to grow to 936,000 (Gemeente Amsterdam, 2021). It is assumed that national goals of halving raw material use have succeeded. Top-down this could be achieved using market incentives, stronger legislation, circular product/component design and innovative technologies. Bottom-up, this could mean citizens better sorting waste, opting for alternatives to single-use items or fast fashion, using online platforms to buy and sell used products and reducing their overall consumption. Combined, these approaches would result in the recirculation of many materials in the economy, and a decrease in those being sent for incineration. The Dutch transition agendas also layout some specific goals, such as organic waste streams being sent to biomass plants, and 44% less plastics sent for incineration, which will directly impact the waste streams flowing to AEB (Government of the Netherlands, 2018).

Two streams which may be less affected are sewage and hazardous waste. This is because the treatment of sewage in Amsterdam is already relatively optimized. New city districts will likely work with decentralized sanitation models, such as in Buiksloterham (Concept Innovation, 2022). However more pressure could be put on the existing network as density and tourism increase. Hazardous waste includes items such as batteries, paints, light bulbs and more. Although new alternatives may be more sustainable, there are constantly new end-of-life challenges. For example lithium-ion batteries (in Tesla's, laptops, cellphones and more). There is a growing stock present in the city, with lifespans that mean they will still need to be processed in the coming decades. Additionally, this waste often needs to be dismantled by hand, and is sometimes sent abroad where labor is cheaper (Baldé & van den Brink, 2021). It is assumed that more of this will be done domestically to reduce transport emissions.

AEB itself could also see some changes. For example the post separator running with projected efficiency, as its staff become more experienced and its technology is refined. Waste is also no longer imported, as the disadvantages now outweigh the benefits.

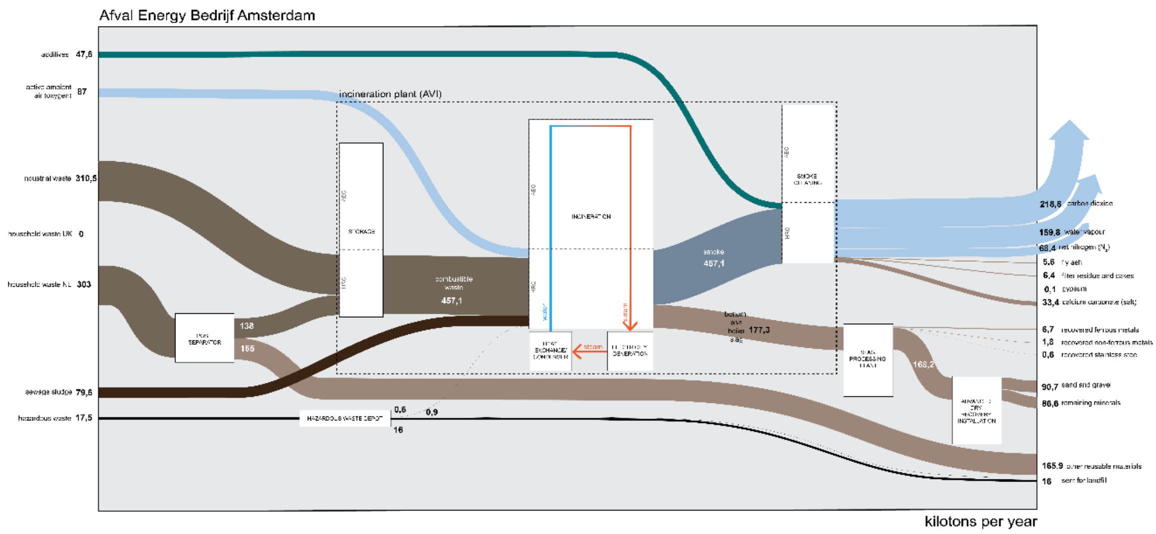


Figure 4. AEB Material Flow Analysis 2030 (own creation, 2021).

### 3.3.b 2050

Amsterdam's population is expected to grow to 1,081,000 (Gemeente Amsterdam, 2021). It is assumed that it has achieved complete circularity. Here it is taken that the city has refined the approaches laid out in the previous scenario, resulting in a zero-waste society, where the only flows remaining for incineration are hazardous waste and sewage sludge.

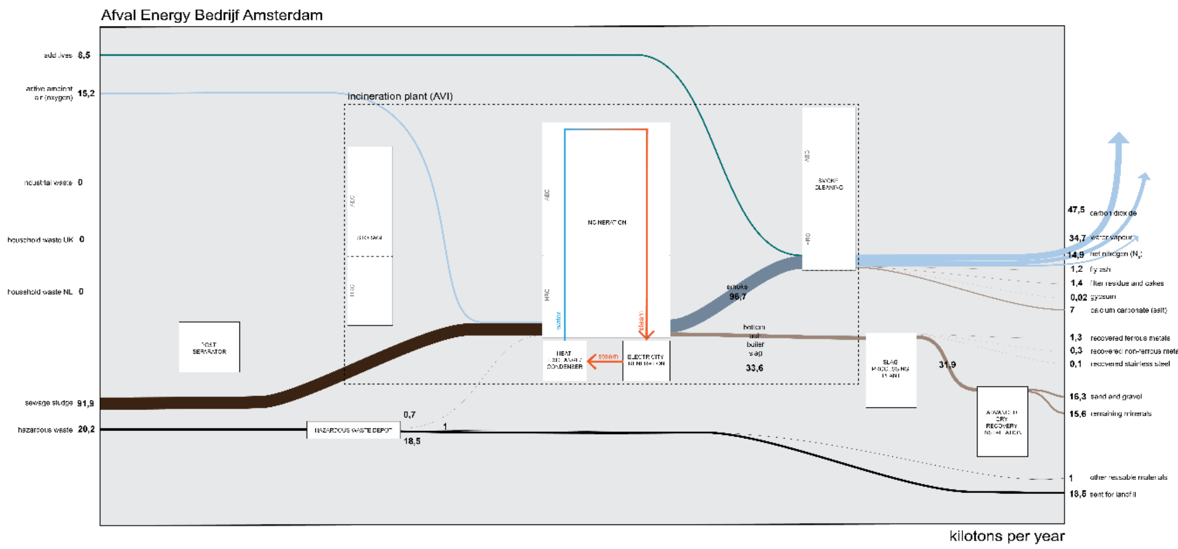


Figure 5. AEB Material Flow Analysis 2050 (own creation, 2021).

There are also several relevant goals set out by the city and AEB for the coming years. By 2025 AEB intends to have a carbon capture installation running, harnessing 450kton $CO_2$ a year from emissions for greenhouses in Westland or chemical production. It is also exploring possibilities for supplying steam to nearby industry to use as a substitute to natural gas (AEB Amsterdam, 2021). Much hope is also being placed on biomass for heat, energy and aromatics generation. Considerations are being made to convert the AEC lines into a biomass plant (AT5, 2020). Amsterdam intends to have all transport running emission-free by 2030, and be natural gas free by 2040, putting greater demand on the district heating and energy networks. It also intends for the harbor and industry to be climate neutral by 2050 (DEAL, 2020).

## IV. Conclusion

This paper revealed four potential starting points for design intervention. The first, and probably most urgent, being limiting the transgression of planetary boundaries, by addressing the $CO_2$ and nitrogen emissions. The second being supporting the city's social foundation, by strengthening existing roles on the doughnut or offering new ones, likely focusing on employment. The third entry point is closing loops by addressing unused waste streams on site, such as filter residues and emissions. The final point is exclusively spatial, and should be combined with one or more of the other points for a comprehensive strategy. It focuses on spaces that are likely to become available for adaptation based on the MFA, such as the post-separator or AEC.

Tackling emissions on site is a direct way of addressing AEB's contribution to the doughnut as well as closing loops. AEB already intends to do this with their $CO_2$ capture. However installing a carbon capture system at the site will likely strengthen the dependency on waste and perpetuate the overcapacity problems. Because of the uncertainty of future waste flows, it should either be considered a short term facility, linked only to the HRC, or coupled with a strategy for alternative sources. For example adaptability to potential biomass processes would be critical. It is also unusual that AEB intends to send the captured $CO_2$ so far away, to Westland, instead of local greenhouses. Perhaps the $CO_2$ could be used on site to produce biomass (with crops, trees, algae). This could then be used to fuel AEB's own biomass plants. AEB can also play an indirect role in reducing emissions, by inviting citizens to experience and interact with the impact and scale of their own lifestyles. Industrial areas concentrate "dirty" processes that enable luxurious lifestyles away from the people. It is easy to live an unsustainable lifestyle when you are never confronted with its costs and consequences. In the same way that it is easy to eat meat when you are not the one butchering the animal. Architectural design could play a very interesting role here down to the smallest scale.

The site has potential for increasing employment by adding new programs or expanding existing ones. For example hazardous waste flows are likely to increase with growing amounts of e-waste, and this flow requires careful and labor intensive work.

Closing loops on site should be considered a temporary or cautionary approach. As seen with potential $CO_2$ capture, it exacerbates existing problems in the face of dwindling waste streams. Interventions addressing these can be seen as a *phase* of the adaptation, or stepping stone, during a complex transition for both AEB and the city. This approach includes not only unused waste streams, but also those that are sent away for further processing. For example plastics from the post separator. Further research into exactly where these are sent, and the spatial requirements of their processing would be an interesting next step here.

The spatial analysis revealed that the post separator and storage will likely become redundant. However the interdependencies between processes means that it would not be possible for the plant to function efficiently without the storage process. It is more likely that the processes would be scaled down, for example removing the AEC and leaving the HRC. Or removing two conjoined incineration lines at a time. Because of this further research into the spatial qualities specific to the incineration building would be interesting, as it is the largest, most complex, and most relevant process to the doughnut model.

Overall this research method has offered a more dynamic and quantitative approach than typical architectural research methods. As many industrial infrastructures face uncertain futures in the face of the economic transition, this approach has allowed us to acknowledge the complexity of the systems they operate in, before considering their adaptation. However, the overall relevance and strength of the scenario-based results is rather dependent on the thoroughness, quality and depth of available data.

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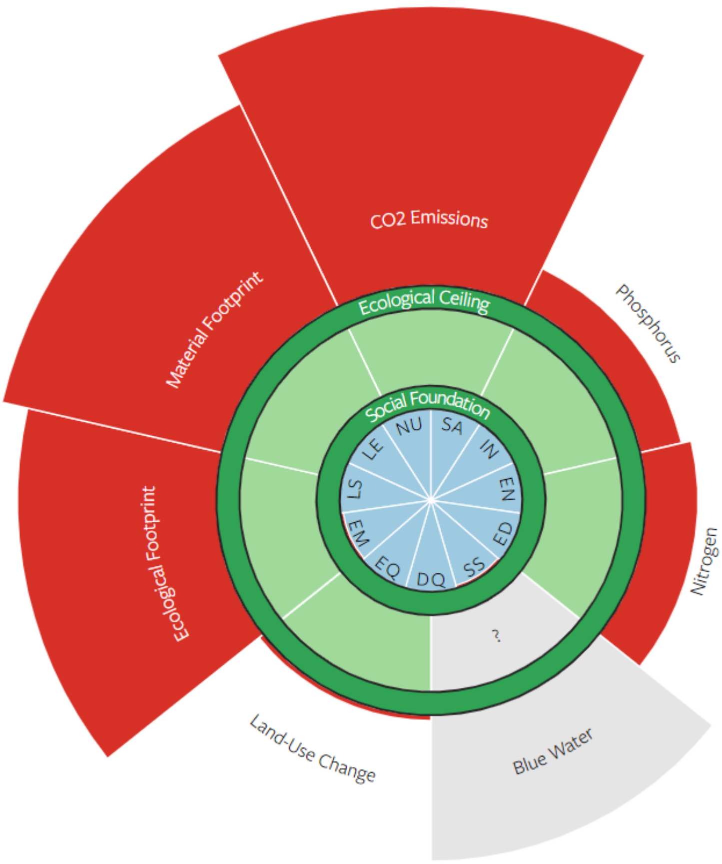
## Appendices

### A. O'Neill et al. Dutch doughnut data

Retrieved from: https://goodlife.leeds.ac.uk/national-trends/country-trends/#NLD




| | | | |
|---|---|---|---|
| LS - Life Satisfaction | LE - Life Expectancy | NU - Nutrition | SA - Sanitation |
| IN - Income Poverty | EN - Access to Energy | ED - Education | SS - Social Support |
| DQ - Democratic Quality | EQ - Equality | EM - Employment | |

| 2015 | Value | Threshold | Unit |
|---|---|---|---|
| CO2 Emissions | 11,093 | 2,397 | cumulative megatonnes CO2 |
| Phosphorus | 1.3 | 0.8 | kilograms P per capita |
| Nitrogen | 14.2 | 8.4 | kilograms N per capita |
| Land-Use Change | 2.6 | 2.4 | tonnes C per capita |
| Ecological Footprint | 6 | | global hectares per capita |
| Material Footprint | 26.7 | 6.8 | tonnes per capita |

| 2015 | Value | Threshold | Unit |
|---|---|---|---|
| Life Satisfaction | 7.3 | 6.5 | [0-10] Cantril scale |
| Life Expectancy | 81.5 | 74 | years of life |
| Nutrition | 3,222.6 | 2,700 | kilocalories per capita per day |
| Sanitation | 97.7 | 95 | % with access to improved sanitation |
| Income Poverty | 99.5 | 95 | % who earn above $5.50 per day (2011 PPP) |
| Access to Energy | 100 | 95 | % with access to electricity |
| Education | 133.6 | 95 | % gross enrolment in secondary school |
| Social Support | 87.9 | 90 | % with friends of family they can depend upon |
| Democratic Quality | 8.9 | 7 | [0-10 scale] |
| Equality | 72.9 | 70 | [0-100] scale (Gini index of 0.3) |
| Employment | 93.1 | 94 | % of labour force employed |

## B. AEB doughnut calculations

| | AEB | SOURCE | BOUNDARY | AMSTERDAM | AEB SHARE % |
|---|---|---|---|---|---|
| **$CO_2$ EMISSIONS** | 525.823ton | AEB Jaarverslag 2015 | 1.392.000 | 5.000.000 | 10,52% |
| **PHOSPHORUS** | 0 | | 783.000 | 1.131.000 | 0 |
| **NITROGEN** | 471.720kg | estimate elaborated below | 7.743.000 | 12.354.000 | 3,82% |
| **BLUE WATER** | - | | - | - | - |
| **eHANPP** | 0 | | 2.088.000 | 2.262.000 | 0 |
| **ECOLOGICAL FOOTPRINT** | 0 | | 1.479.000 | 5.220.000 | 0 |
| **MATERIAL FOOTPRINT** | 0 | | 6.264.000 | 23.229.000 | 0 |
| | | | | | |
| **LIFE SATISFACTION** | 0 | | 6,5 | 7,3 | 0 |
| **HEALTHY LIFE EXPECTANCY** | 0 | | 65 | 74 | 0 |
| **NUTRITION** | 0 | | 2700 | 3222,6 | 0 |
| **SANITATION** | | | 95 | 97,7 | |
| **INCOME** | 0 | | 95 | 99,5 | 0 |
| **ACCESS TO ENERGY** | 10,94% | AEB Jaarverslag 2015, The Amsterdam heat guide 2019 | 95 | 100 | 10,94% |
| **EDUCATION** | 0 | | 95 | 133,6 | 0 |
| **SOCIAL SUPPORT** | 0 | | 90 | 87,9 | 0 |
| **DEMOCRATIC QUALITY** | 0 | | 7 | 8.9 | 0 |
| **EQUALITY** | 0 | | 70 | 72.9 | 0 |
| **EMPLOYMENT** | 400 | | 451.200 | 446.880 | 0,09% |

Based on nitrogen oxide emissions given per cubic meter of emissions. Emission volume estimated using known $CO_2$ emissions, with:

$$volume = \frac{mass}{density}$$

Using a standardized density and composition of flue gas (from Aouini et at., 2014). This gives $1{,}91 \times e^{12}$ $m^3$ at standard pressure and temperature. Assuming flue gas is emitted at 150˚C, we determine emission volume with:

$$\frac{P_1 \cdot V_1}{T_1} = \frac{P_2 \cdot V_2}{T_2}$$

Where P = pressure, V = volume and T = temperature.

Giving $1{,}23 \times e^{12}$ $m^3$. In 2015 AEB released 64,94 + 92,3 mg of Nitrogen Oxides from the AEC and HRC per cubic meter of emissions (from AEB Jaarverslag 2015).

## C. Municipalities participating in the use of the post separator

Amsterdam, Aalsmeer, Amstelveen, Bloemendaal, Diemen, EdamVolendam, Haarlem, Heemstede, Landsmeer, Ouder-Amstel, Waterland en Zandvoort (AEB Amsterdam, 2018).

## D. MFA quantities 2015*

| 2015 "now" | | | | | Population: 820.000 |
|---|---|---|---|---|---|
| **PROCESS** | **IN (kilotons)** | | **OUT (kilotons)** | | **NOTES** |
| post separator | NL household waste | 318 | for incineration | 302,4 | added November 2017 |
| | | | for reuse | 15,6 | estimate based on 12x data given (only known December 2017) |
| | | **318** | | **318** | |
| hazardous waste depot | hazardous waste | 15,3 | for incineration | 0,5 | estimate based on balancing MFA |
| | | | for reuse | 0,8 | |
| | | | for landfill | 14 | estimate based on 1% of received waste going to landfill |
| | | **15,3** | | **15,3** | |
| storage | industrial waste | 544 | combustible waste | 1266,4 | |
| | NL household waste | 531 | | | |
| | UK household waste | 207 | | | |
| | minus post separator | -15,6 | | | |
| | | **1266,4** | | **1266,4** | |
| incineration | combustible waste | 1266 | smoke | 1070,5 | estimate based on balancing MFA |
| | sewage sludge | 69,7 | bottom ash | 500 | estimate based on 1/3 remaining (source AEB YouTube) |
| | hazardous waste | 15,3 | boiler slag | 0,5 | |
| | oxygen from ambient air | 220 | | | estimate based on molar mass of emissions vs ambient air ($CO_2$ known)** |
| | | **1571** | | **1571** | |
| smoke cleaning | smoke | 1070,5 | fly ash | 13,4 | |
| | additives | 111,5 | cloth residues | 15,4 | |
| | | | salt | 78,3 | estimate based on balancing MFA |
| | | | gypsum | 0,3 | |
| | | | $CO_2$ | 525,8 | |
| | | | water vapour | 384,1 | estimate based on molar mass of emissions vs ambient air ($CO_2$ known)** |
| | | | net nitrogen | 164,7 | estimate based on molar mass of emissions vs ambient air ($CO_2$ known)** |
| | | **1182** | | **1182** | |
| slag processing plant | bottom ash | 500 | ferrous metals | 19 | added 2017? |
| | boiler slag | 0,5 | non-ferrous metals | 5 | |
| | | | stainless steel | 1,6 | |
| | | | remaining slag | 474,9 | estimate based on balancing MFA |
| | | **500,5** | | **500,5** | |
| advanced dry recovery installation | remaining slag | 474,9 | sand and gravel | 243 | |
| | | | remaining minerals | 231,9 | estimate based on balancing MFA |
| | | **474,9** | | **474,9** | |

*Figures shown in blue are estimates, those in black are given.

** estimating quantities of gases in MFA given the mass of $CO_2$ output:

$$\text{Where } relative\ mass = atomic\ mass \times volume,$$

$$\text{And } total\ mass = percentage\ mass \times \left(\frac{total\ mass\ CO2}{percentage\ mass\ CO2}\right):$$

| flue gas | atomic mass (g mol$^{-1}$) | % vol | relative mass (g mol$^{-1}$) | % mass | total mass (kton) |
|---|---|---|---|---|---|
| $CO_2$ | 44 | 14% | 6,16 | 22,05% | 525,823 |
| $H_2O$ | 18 | 25% | 4,50 | 16,11% | 384,124 |
| $N_2$ | 28 | 56% | 15,68 | 56,12% | 1338,459 |
| $O_2$ | 32 | 5% | 1,60 | 5,73% | 136,577 |
| **total** | **122** | **100%** | **27,94** | **100,00%** | **2384,983** |

Based on average volumetric flue gas constituents (from Aouini et at., 2014). [highly dependent on fuel]

Where ambient air mass quantities are determined by balancing the MFA,

$$\text{And } relative\ mass = atomic\ mass \times volume,$$

| ambient air | atomic mass (g mol$^{-1}$) | % vol | relative mass (g mol$^{-1}$) | % mass | total mass (kton) |
|---|---|---|---|---|---|
| $N_2$ | 28 | 79% | 22,12 | 76,70% | 125,019 |
| $O_2$ | 32 | 21% | 6,72 | 23,30% | 37,981 |
| **total** | **60** | **100%** | **28,84** | **100,00%** | **163** |

Based on average volumetric ambient air constituents [likely variable in an industrial area].

Therefore net emissions:

| flue gas | in (kton) | out (kton) | difference (kton) |
|---|---|---|---|
| $CO_2$ | 0 | 525,823 | 525,823 |
| $H_2O$ | 0 | 384,124 | 384,124 |
| $N_2$ | 1173,459 | 1338,459 | 164,725 |
| $O_2$ | 356,577 | 136,577 | -220,000 |

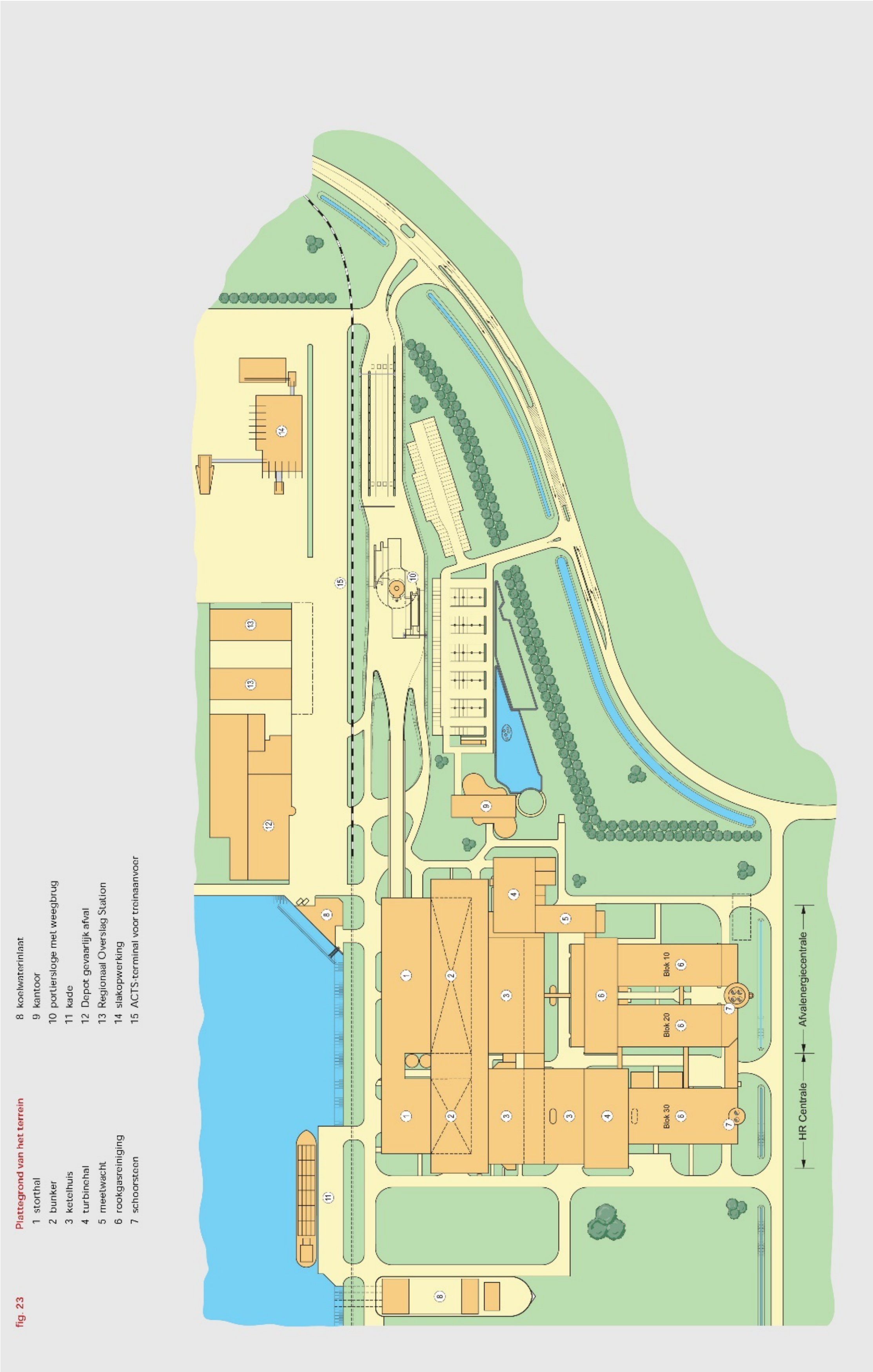
## E. MFA estimated quantities 2030

| **2030** | | | | | Population: 936.000 |
|---|---|---|---|---|---|
| **PROCESS** | **IN (kilotons)** | | **OUT (kilotons)** | | **NOTES** |
| | | | | | |
| post separator | NL household waste | 303 | for incineration | 138 | scaled for population growth, then halved |
| | | | for reuse | 165 | based on 2018 projections (ideal performance) |
| | | **303** | | **303** | |
| | | | | | |
| hazardous waste depot | hazardous waste | 17,5 | for incineration | 0,6 | scaled for population growth |
| | | | for reuse | 0,9 | maintaining existing proportions |
| | | | for landfill | 16 | maintaining existing proportions |
| | | **17,5** | | **17,5** | |
| | | | | | |
| storage | industrial waste | 310,5 | combustible waste | 448,5 | scaled for population and halved |
| | NL household waste | 303 | | | |
| | UK household waste | 0 | | | import no longer affordable/permitted |
| | minus post separator | -165 | | | |
| | | **448,5** | | **448,5** | |
| | | | | | |
| incineration | combustible waste | 448,5 | smoke | 457,1 | scaled for population and halved |
| | sewage sludge | 79,6 | bottom ash | 177,1 | scaled for population |
| | hazardous waste | 17,5 | boiler slag | 0.2 | scaled for population |
| | oxygen from ambient air | 87 | | | maintaining existing proportions |
| | | **634,4** | | **634,4** | |
| | | | | | |
| smoke cleaning | smoke | 457,1 | fly ash | 5,6 | maintaining existing proportions |
| | additives | 47,6 | cloth residues | 6,4 | maintaining existing proportions |
| | | | salt | 33,4 | maintaining existing proportions |
| | | | gypsum | 0.1 | maintaining existing proportions |
| | | | $CO_2$ | 218,8 | maintaining existing proportions |
| | | | water vapour | 159,8 | maintaining existing proportions |
| | | | net nitrogen | 68,4 | maintaining existing proportions |
| | | **504,7** | | **504,7** | |
| | | | | | |
| slag processing plant | bottom ash | 177,1 | ferrous metals | 6,7 | maintaining existing proportions |
| | boiler slag | 0,2 | non-ferrous metals | 1,8 | maintaining existing proportions |
| | | | stainless steel | 0,6 | maintaining existing proportions |
| | | | remaining slag | 168,2 | maintaining existing proportions |
| | | **177,3** | | **177,3** | |
| | | | | | |
| advanced dry recovery installation | remaining slag | 177,3 | sand and gravel | 90,7 | maintaining existing proportions |
| | | | remaining minerals | 86,6 | maintaining existing proportions |
| | | **177,3** | | **177,3** | |

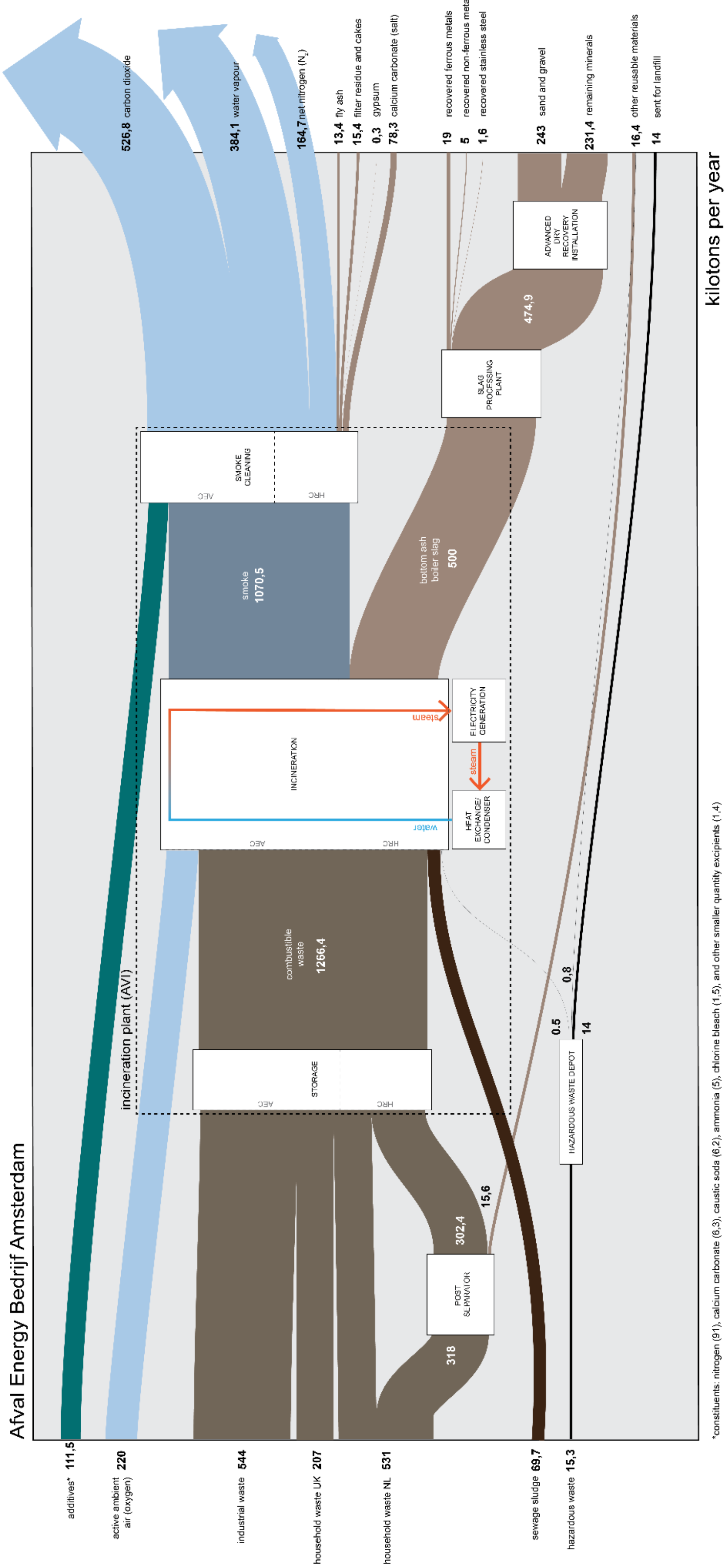
# F. MFA estimated quantities 2050

| 2050 | | | | | Population: 1.081.000 |
|---|---|---|---|---|---|
| **PROCESS** | **IN (kilotons)** | | **OUT (kilotons)** | | **NOTES** |
| | | | | | |
| post separator | NL household waste | 0 | for incineration | 0 | based on achieving a fully circular economy |
| | | | for reuse | 0 | |
| | | **0** | | **0** | |
| | | | | | |
| hazardous waste depot | hazardous waste | 20,2 | for incineration | 0,7 | scaled for population growth |
| | | | for reuse | 1 | maintaining existing proportions |
| | | | for landfill | 18,5 | maintaining existing proportions |
| | | **20,2** | | **20,2** | |
| | | | | | |
| storage | industrial waste | 0 | combustible waste | 0 | based on achieving a fully circular economy |
| | NL household waste | 0 | | | |
| | UK household waste | 0 | | | import no longer affordable/permitted, other EU countries also achieving circular economies. |
| | minus post separator | 0 | | | |
| | | **0** | | **0** | |
| | | | | | |
| incineration | combustible waste | 0 | smoke | 96,7 | maintaining existing proportions |
| | sewage sludge | 91,9 | bottom ash | 33,6 | scaled for population |
| | hazardous waste | 20,2 | boiler slag | 0,03 | scaled for population |
| | oxygen from ambient air | 18,2 | | | maintaining existing proportions |
| | | **130,3** | | **130,3** | |
| | | | | | |
| smoke cleaning | smoke | 96,7 | fly ash | 1,2 | maintaining existing proportions |
| | additives | 10 | cloth residues | 1,4 | maintaining existing proportions |
| | | | salt | 7 | maintaining existing proportions |
| | | | gypsum | 0,02 | maintaining existing proportions |
| | | | $CO_2$ | 47,5 | maintaining existing proportions |
| | | | water vapour | 34,7 | maintaining existing proportions |
| | | | net nitrogen | 14,9 | maintaining existing proportions |
| | | **106,7** | | **106,7** | |
| | | | | | |
| slag processing plant | bottom ash | 33,6 | ferrous metals | 1,3 | maintaining existing proportions |
| | boiler slag | 0,03 | non-ferrous metals | 0,3 | maintaining existing proportions |
| | | | stainless steel | 0,1 | maintaining existing proportions |
| | | | remaining slag | 31,9 | maintaining existing proportions |
| | | **33,7** | | **33,7** | |
| | | | | | |
| advanced dry recovery installation | remaining slag | 31,9 | sand and gravel | 16,3 | maintaining existing proportions |
| | | | remaining minerals | 15,6 | maintaining existing proportions |
| | | **31,9** | | **31,9** | |

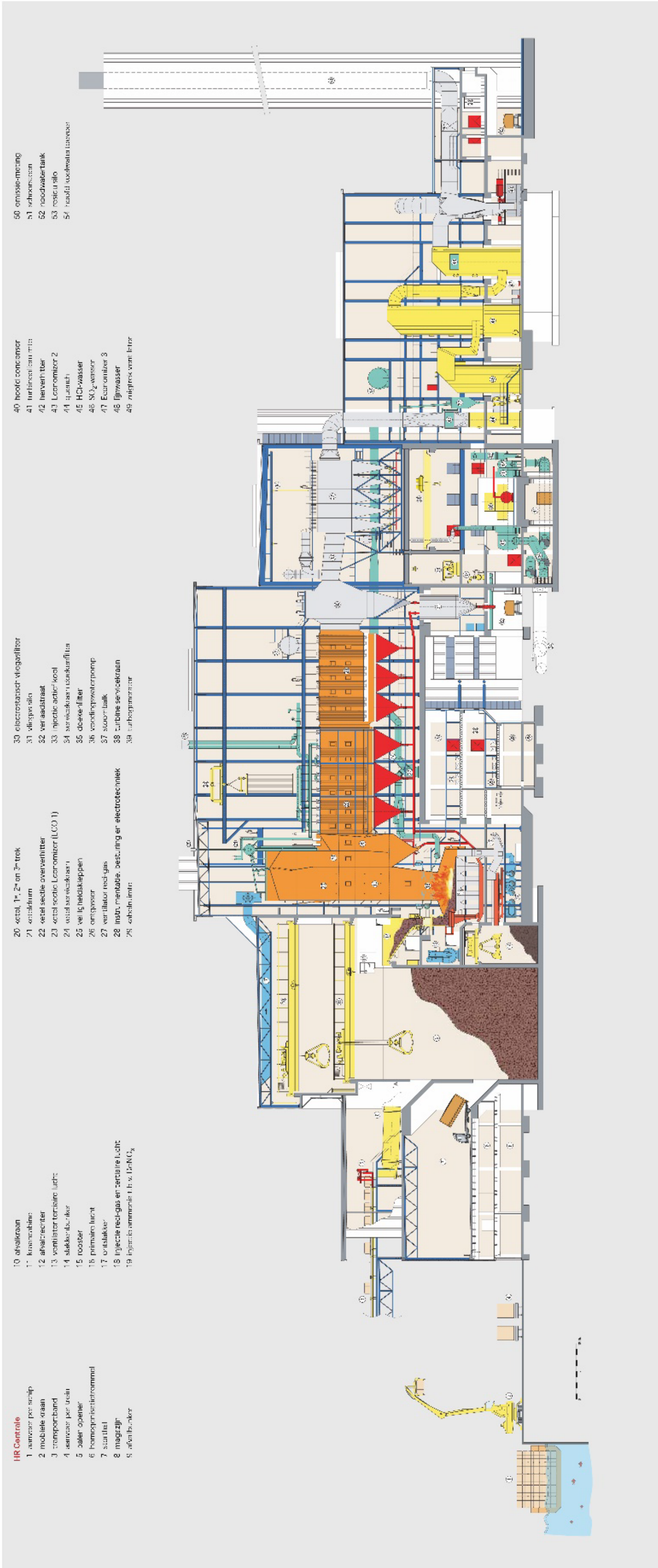
## G. Site plan (AEB Amsterdam, 2006)



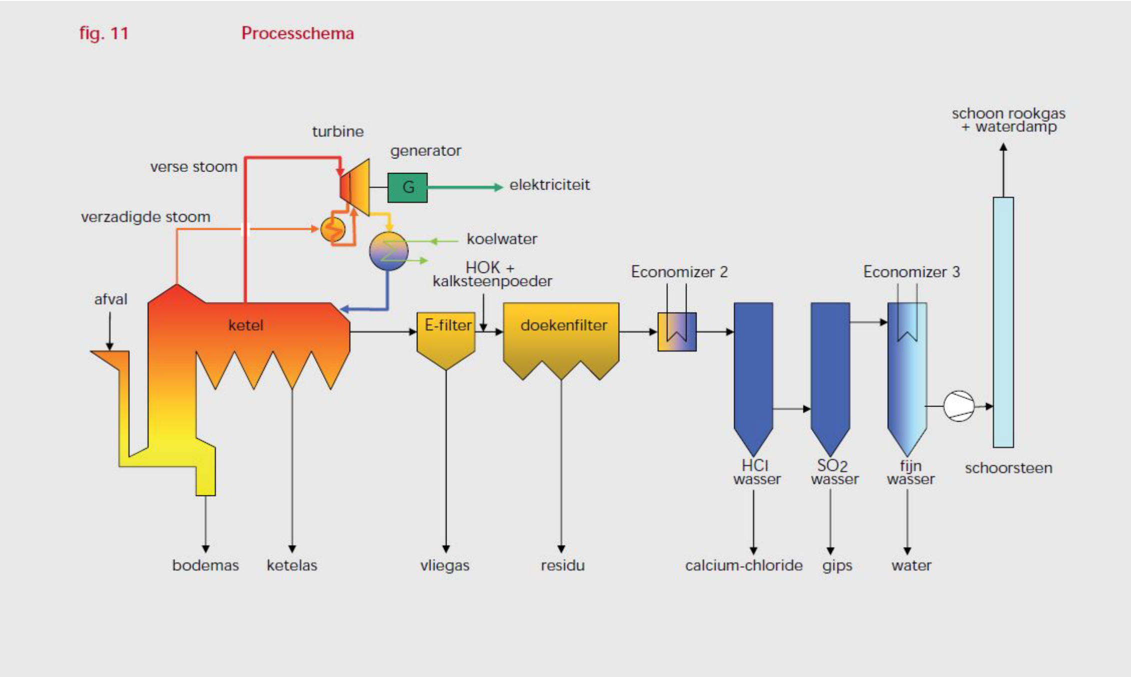
# H. Large Scale MFA (own creation, 2021)



# I. Section of AVI (AEB Amsterdam, 2006)



## J. Process diagram AVI (AEB Amsterdam, 2006)




## K. Post separator diagram (AEB Amsterdam, 2021)

L. Aerial photo of site (adapted from Google Earth, 2021)